DOCTORAL THESIS

Smart Energy System Efficiency Improvement Through Combined Heat and Power Production Flexibility

Kertu Lepiksaar

TALLINNA TEHNIKAÜLIKOOL
TALLINN UNIVERSITY OF TECHNOLOGY
TALLINN 2024

TALLINN UNIVERSITY OF TECHNOLOGY
DOCTORAL THESIS
24/2024

Smart Energy System Efficiency Improvement Through Combined Heat and Power Production Flexibility

KERTU LEPIKSAAR

TAL TECH PRESS

TALLINN UNIVERSITY OF TECHNOLOGY
School of Engineering
Department of Energy Technology
This dissertation was accepted for the defence of the degree 29/04/2024

Supervisor: Tenured Associate Professor, PhD Anna Volkova
School of Engineering
Tallinn University of Technology
Tallinn, Estonia

Co-supervisor: Senior lecturer, PhD Igor Krupenski
School of Engineering
Tallinn University of Technology
Tallinn, Estonia

Opponents: Senior researcher, PhD Ahmad Arabkoohsar
Department of Civil and Mechanical Engineering
Technical University of Denmark
Lyngby, Denmark

Development manager, PhD Aleksandr Šablinski
AS Utilitas Tallinn
Tallinn, Estonia

Defence of the thesis: 06/06/2024, 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 doctoral or equivalent academic degree.

Kertu Lepiksaar

----
signature

European Union
European Regional
Development Fund

Investing
in your future

ISSN 2585-6898 (publication)
ISBN 978-9916-80-142-0 (publication)
ISSN 2585-6901 (PDF)
ISBN 978-9916-80-143-7 (PDF)
DOI https://doi.org/10.23658/taltech.24/2024
Printed by Koopia Niini & Rauam

Lepiksaar, K. (2024). *Smart Energy System Efficiency Improvement Through Combined Heat and Power Production Flexibility* [TalTech Press]. https://doi.org/10.23658/taltech.24/2024

TALLINNA TEHNIKAÜLIKOOL
DOKTORITÖÖ
24/2024

Targa energiasüsteemi efektiivsuse parendamine läbi koostootmise paindlikkuse tõstmise

KERTU LEPIKSAAR

TAL
TECH
KIRJASTUS

Contents

List of Publications

The list of author's publications, on the basis of which the thesis has been prepared:

I Lepiksaar, K., Mašatin, V., Latõšov, E., Siirde, A., & Volkova, A. (2021). Improving CHP flexibility by integrating thermal energy storage and power-to-heat technologies into the energy system. *Smart Energy*, *2*, 100022. https://doi.org/10.1016/j.segy.2021.100022

II Lepiksaar, K., Mašatin, V., Krupenski, I., & Volkova, A. (2023). Effects of Coupling Combined Heat and Power Production with District Cooling. *Energies*, *16*(12). https://doi.org/10.3390/en16124552

III Lepiksaar K, Volkova A, Ruševljuk P, Siirde A. The effect of the District Heating Return Temperature Reduction on Flue Gas Condenser Efficiency. Environmental and Climate Technologies 2020;24:23–38. http://doi.org/10.2478/rtuect-2020-0083

IV Pieper H, Kirs T, Krupenski I, Ledvanov A, Lepiksaar K, Volkova A. Efficient use of heat from CHP distributed by district heating system in district cooling networks. *Energy Reports* 2021;7:47–54. http://doi.org/10.1016/j.egyr.2021.09.041

V Pieper, H., Lepiksaar, K., & Volkova, A. (2022). GIS-based approach to identifying potential heat sources for heat pumps and chillers providing district heating and cooling. *International Journal of Sustainable Energy Planning and Management*, *34*, 29–44. https://doi.org/10.54337/ijsepm.7021

VI Volkova A, Pakere I, Murauskaite L, Huang P, Lepiksaar K, Zhang X. 5th generation district heating and cooling (5GDHC) implementation potential in urban areas with existing district heating systems. Energy Reports 2022;8:10037–47. https://doi.org/10.1016/j.egyr.2022.07.162

VII Lepiksaar, K., Kalme, K., Siirde, A., & Volkova, A. (2021). Heat Pump Use in Rural District Heating Networks in Estonia. Environmental and Climate Technologies, 25(1), 786–802. https://doi.org/10.2478/rtuect-2021-0059

Approbation of the results

The results of this Doctoral Thesis were presented at the following scientific conferences:

1. Kertu Lepiksaar, Anna Volkova, Andres Siirde. The effect of the district heating return temperature reduction on flue gas condenser efficiency. XIII International Scientific Conference of Environmental and Climate Technologies CONECT 2020, May 13-15, 2020, held online

2. Kertu Lepiksaar, Anna Volkova. Increasing CHP flexibility to improve energy system efficiency. 6th International Conference on Smart Energy Systems. 4th Generation District Heating, Electrification, Electrofuels and Energy Efficiency, October 6-7, 2020, Aalborg, Denmark (online presentation)

3. Kertu Lepiksaar, Kiur Kalme, Anna Volkova, Andres Siirde. Heat pump usage in Estonian rural district heating networks. XIV International Scientific Conference of Environmental and Climate Technologies CONECT 2021, May 12-14, 2021, Riga, Latvia

4. Pei Huang, Kertu Lepiksaar. 5th generation district heating and cooling implementation potential in urban areas with existing district heating systems. 7th International Conference on Smart Energy Systems. 4th Generation District Heating, Electrification, Electrofuels and Energy Efficiency, September 21-22, 2021, Copenhagen, Denmark (online presentation)

5. Henrik Pieper, Kertu Lepiksaar. A GIS-based Approach to Identify Potential Heat Sources for Heat Pumps and Chillers Supplying District Heating and Cooling. 16th Conference on Sustainable Development of Energy, Water and Environment Systems (SDEWES), October 10-15, 2021, Dubrovnik, Croatia

6. Kertu Lepiksaar, Anna Volkova. Effects of Coupling Combined Heat and Power Production with District Cooling. 17th Conference on Sustainable Development of Energy, Water and Environment Systems (SDEWES), November 6-10, 2022, Paphos, Cyprus

Author’s Contribution to the Publications

Contribution to the papers in this thesis are:

I Improving CHP flexibility by integrating thermal energy storage and power-to-heat technologies into the energy system

Lepiksaar is the main author of the paper and developed the model, carried out the calculations and analysed the results. Mašatin gathered and provided data. Mašatin, Siirde and Volkova provided advice in technical field and helped to analyse the results. Latõšov and Volkova advised, reviewed and edited the paper.

II Effects of Coupling Combined Heat and Power Production with District Cooling

Lepiksaar is the main author of the paper and developed the model, carried out the calculations and analysed the results. Mašatin provided and processed data about turbine load and technical parameters, technical consultations regarding combined heat and power plants and mostly used absorption chillers technical data. Krupenski provided knowledge about business models and different technologies used for cooling production and advised the technical parts. Volkova provided data regarding Mustamäe district cooling demand and gave advice, reviewed and edited the paper.

III The effect of the District Heating Return Temperature Reduction on Flue Gas Condenser Efficiency

Lepiksaar is the main author of the paper and developed the model, carried out the calculations and analysed the results. Ruševljuk and Siirde provided technical consultations regarding flue gas condensers and heat and mass transfer processes. Volkova provided advice, comments and suggestions with structuring and editing the paper.

IV Efficient use of heat from CHP distributed by district heating system in district cooling networks

Pieper is the main author of the paper and did the conceptualisation of the research. Kirs and Krupenski provided data regarding district heating load, combined heat and power plant’s technical data and district heating, combined heat and power and cooling generation related consultation. Volkova developed the methodology of calculations and analysed the results. Krupenski provided consultation regarding business model in district cooling and district cooling networks planning. Lepiksaar conducted literature review, data management and contributed in methodology evaluation and calculations. Lepiksaar and Volkova edited the paper.

V GIS-based approach to identifying potential heat sources for heat pumps and chillers providing district heating and cooling

Pieper is the main author of this paper and did the conceptualisation of the research. Pieper conducted the analysis and together with Volkova finalized the research results. Lepiksaar gathered, arranged and prepared the data for the research and assisted with literature review. Volkova provided advice, comments and suggestions with structuring and editing the paper.

VI 5th generation district heating and cooling (5GDHC) implementation potential in urban areas with existing district heating systems

Volkova is the main author of the paper. The conceptualisation was developed by Volkova, Pakere and Murauskaite together and they concluded the main analysis of the research. Huang and Zhang conducted the calculations provided the results that the research is based on. Lepiksaar gathered, arranged and prepared the data for the research and assisted with literature review, methodology evaluation and analysing the results.

VII Heat Pump Use in Rural District Heating Networks in Estonia

Lepiksaar is the main author of the paper and did the conceptualisation of the research. Kalme gathered and arranged the data. Lepiksaar and Kalme developed the model for the calculations and analysed the results. Volkova provided advice, comments and suggestions with structuring and editing the paper.

Abbreviations

4GDH	4th generation district heating
5GDHC	5th generation district heating and cooling
AHP	Analytic hierarchy process
CCHP	Combined cooling, heating, and power
CHP	Combined heat and power
COP	Coefficient of performance
CPVT	Concentrating photo voltaic thermal
DC	District cooling
DH	District heating
EER	Energy efficiency ratio
EU	European Union
FGC	Flue gas condenser
GIS	Geographic information system
HP	Heat pump
LTDH	Low-temperature district heating
ORC	Organic Rankine cycle
PEC	Primary energy consumption
PV	Photo voltaic
RES	Renewable energy sources
RQ	Research question
TES	Thermal energy storage
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution

1 Introduction

1.1 Motivation

The European Union (EU) has set a very ambitious goal: to become climate neutral by 2050, which means developing an economy with net-zero greenhouse gas emissions. To achieve this, the EU has made it a priority to become the leader in the transition to clean energy by reducing CO_2 emissions by at least 40%, increasing the share of renewable energy by at least 32%, and improving energy efficiency by at least 32.5% by 2030, compared to the 1990 data [1].

The transition from fossil fuel to the integration of an increasing number of renewable energy sources (RES) requires the revision and redesign of the energy system in terms of both generation and consumption. To this end, the future sustainable energy system will have multiple infrastructures for various sectors, such as electrical grids, district heating (DH) networks, and district cooling (DC) networks. Although, throughout the last decades RES gone through remarkable development, they can also become problematic for balancing generation and consumption because of their unpredictable nature.

The number of combined heat and power (CHP) plants in the EU, including Estonia, has been growing over the past two decades. In the light of RES development in the energy sector, the necessity and role of CHP plants becomes questionable. One of the key challenges in the energy sector is the creation of flexible energy supply with an increased number of fluctuating RES. When the proportion of RES is high, CHPs are crucial for power grid stabilisation, that is, ensuring and maintaining the frequency and voltage in the power supply.

Cogeneration is a process in which both electricity and heat are produced simultaneously. Turbine is one of the most important components for most larger thermal power and CHP plants, because it converts the thermal energy of the steam into useful work that is then turned into electricity by the generator. It is crucial for turbines to be able to dissipate excess heat. In conventional thermal power plants, chillers and cooling towers are utilized for this purpose. In the case of a cogeneration plant, the main difference from a power plant is that, instead of leading the excess heat to cooling towers or chillers, the heat is used for DH. Typically, the efficiency of a thermal power plant is around 33%, but while working in condensation mode, all the remaining excess heat is lost. In the case of cogeneration, the electrical efficiency may be slightly lower, ranging between 30 and 33%. This is determined by the DH supply temperature. Greater DH supply temperatures result in lower CHP electrical efficiency. Cogeneration plants usually have a thermal efficiency between 55 and 60% [2].

Since it is crucial for the turbines to be able to dissipate excess heat, a constant heat load is crucial for CHP plants to work. Without a sufficient heat load, the CHP plant must either install coolers, which significantly reduces the efficiency of primary energy use, or stop operating until the heat load is sufficient again. CHP plants are not particularly flexible when it comes to working at partial load either. Depending on the type of turbine, some cogeneration plants can reduce the load and operate at partial load even when the heat load is lower. As a result, the operation of the cogeneration plant directly depends on the heat load, or the lack of it, when no cooling towers, thermal energy storages (TES) or other heat utilization technologies are used.

The existing heat load is the most important parameter when planning the capacity of a cogeneration plant; it must be considered that the cogeneration plant can operate at maximum capacity for an even longer period of time during the year. Winter heat load is usually 5–7 times higher than summer heat load; spring-autumn heat load is 3–4 times higher [3]. This is because the heat load in summer only involves domestic hot water, while in the heating season the heat used for space heating depends on the thermal insulation of the buildings and the outdoor temperature.

The DH sector and CHP plants have a strong connection, as excess heat generated in the cogeneration process is normally used to cover DH demand. On the one hand, it is important for efficient energy use, on the other hand, heat production is part of the CHP plant economic model. DH is important for CHP plants' feasibility and resource efficiency. CHP excess heat cannot be utilised without a centralised DH network. DH systems serve multiple buildings or homes within a localised area, allowing for the centralisation of heat production. This centralised approach benefits from economies of scale, as larger, more efficient heating facilities can be used to generate heat rather than individual heating systems for each building. In addition to CHP plants' excess heat, centralised DH plants can utilise various energy sources, including renewable and low-carbon options like biomass, geothermal, or waste heat from industrial processes. These sources can be harnessed much more efficiently on a larger scale compared to individual heating systems, which may not have access to such diverse or efficient sources. Compared to local heating systems, DH systems can be optimised for load balancing and demand management, ensuring that the right amount of heat is delivered to each building based on its specific needs. This optimisation helps to minimise waste and ensures a more efficient utilisation of energy resources. Overall, DH systems capitalise on centralised production, efficient technologies, and diverse energy sources to achieve higher energy efficiency compared to local heating systems.

In essence, the integration of CHP production into DH systems presents a more efficient, cost-effective, and environmentally friendly approach to providing heat and electricity to communities compared to conventional methods.

Besides heat and electricity, there is also the cooling sector, which is a small but rapidly growing and important part of today's energy system. Final energy consumption for cooling purposes has been increasing in recent years. In the EU, it was 2.7% for commercial buildings in 2019. The cooling demand is expected to increase to 45% by 2050 compared to 2016 [4].

DC has several advantages over local cooling. First, DC is more environmentally friendly than local cooling because DC can often use a variety of RES to produce cooling energy. There are several technologies that can be used to generate cooling energy in DC systems. The most common technologies include absorption chillers, free cooling, heat pumps (HP), and cooling towers. Industrial waste heat and excess heat from CHP plants can also be used with absorption chillers for cooling generation [5]–[7].

Smart energy system, that is in the center of this thesis can be defined as an energy system that integrates all our energy solutions into one united system. This means that neither electricity, DH nor cooling are considered as isolated systems, but as connected and integrated unity. The integration of different energy technologies, such as cogeneration of heat and power, boiler houses, heat pumps, renewable electricity production units and cooling technologies must be integrated wisely to ensure the expected RES integration, energy efficiency increase and primary energy savings. The motivation of this thesis is to investigate how to integrate different energy technologies into united energy system, also considering the nature of existing, CHP production-based energy system. This means that for wise integration of different technologies to today's energy system, CHP production characteristic features must also be considered. As was explained above, lack flexibility of CHP production is one of the main problems that prevents effective use primary energy. This problem can be mitigated through increasing the flexibility by integrating different technologies and energy sectors and thus creating a smart energy system.

The European Commission's Strategy for Energy System Integration states that sector coupling will significantly increase electricity consumption, which, in turn, will increase renewable energy production and spread the use of RES technologies [8]. HPs, as power-to-heat solutions, play a major role in the sectoral coupling of RES and the heating sector, and the amount of heat extracted from RES strongly depends on the type of strategy; the most RES can be integrated into a system using a strategy based on wind power generation. When the electricity and heat sectors are combined, residential heat load has the potential to enhance the usage of wind power while reducing carbon emissions significantly. The operation of existing thermal power plants in cogeneration mode, together with DH networks and thermal storage units, can still contribute to the decarbonisation of the European heating sector.

Overall, the motivation for writing this thesis is to find and investigate the most suitable solutions for district energy production in heating and cooling sectors and how to integrate them into one, united and energy efficient smart energy system to move towards climate neutrality.

1.2 Background

This thesis mostly relies on studies that investigate the possibilities of increasing flexibility, energy efficiency and use of RES in local level, therefore in the following paragraph an overview of energy sectors in Estonia and in the Baltics is given.

Oil shale serves as the primary energy source in Estonia and is a crucial component of its energy mix. While relying on oil shale ensures a significant degree of energy security, it is an inherently carbon-intensive fuel. Consequently, energy production from oil shale contributes substantially to greenhouse gas emissions, exacerbating climate concerns. As a result, the Estonian economy exhibits double the amount of carbon dioxide (CO_2) emissions compared to the EU average. However, Estonia is swiftly addressing this issue by phasing out old energy plants and implementing innovations aimed at reducing CO_2 emissions and mitigating their adverse effects. Despite efforts, Estonia's power generation falls short of meeting domestic demand, leading to daily electricity imports. In 2023, Estonia generated 4.91 TWh of power, whereas demand stood at 8.07 TWh. These figures contrast with 2022, where generation and demand were 7.34 TWh and 8.18 TWh, respectively [9]. Notably, over half of Estonia's electricity was generated using oil shale (56%), biomass (17%), wind (9%), and sustainable waste (1%) power plants. A substantial portion of this electricity (2.704 TWh; 76% to Latvia and 24% to Finland) was exported [9]. All three Baltic states are attempting to separate from the Russian power grid and join the Western European grid, which is expected to be completed by 2025 [10].

Another critical objective for Estonia is achieving climate neutrality by 2050, necessitating an increase in renewable energy capacity [11]. Wind energy constitutes the largest renewable energy source (RES) in Estonia, with the Aulepa 48 MW wind power plant being the largest in the Baltics. Wind farms, totalling 373 MW, are predominantly located inland in Estonia's northeast, northwest, and west regions [12]. Despite this, offshore wind parks have yet to be developed. Tallinn hosts the largest CHP plants, with four operational facilities boasting a total capacity of 240 MWth and 73.4 MW_{el}. Additionally, there are sizable biomass CHP plants in Tartu and Pärnu, each with a capacity of 25 MW. Estonia also has biomass (102 MW), waste (17 MW), and biogas-powered (11 MW) plants integrated into its power network [10]. In Estonia, it is common to reject excess cogeneration heat when there is no demand. This type of approach is only feasible if subsidies for electricity production are available. In the case of Estonia, this refers to biomass CHP plants under 12 years old [13]. These types of CHP plants receive 53.7 EUR/MWh_{el}, making heat rejection feasible. Tallinn has three CHP plants with rooftop coolers [14].

There are 210 DH networks in Estonia, with about 160 of them using wood chips or other wood-based fuels. However, natural gas or shale oil-fired boilers still cover peak loads, serving as reserve boilers in many instances. Eleven networks rely on peat due to its local availability and price stability. Most biomass boilers were installed after 2014 with support from the European Cohesion Fund [15]. As the EU aims for climate neutrality by 2050 [16], all fossil fuel-fired boilers must be replaced with RES, necessitating the development of a sustainable alternative to cover peak loads. Replacing old biomass boilers with HPs is one alternative that should be considered. Centralised HPs, which are used in three DH networks, can also be regarded as a sustainable and environmentally friendly heating solution [17].

Tallinn has a single large-scale heating network created by combining smaller DH networks. A connecting pipeline established in 2010 allows heat transmission between Tallinn’s western and eastern regions, facilitating heating distribution to the city centre, Maardu, and Lasnamäe [18].

Cogeneration plants, including Tallinn CHP1 (Väo I), the Iru waste incineration plant, Tallinn CHP 2 (Väo II), and Mustamäe CHP cover Tallinn's base heat load. Except for Iru, all of the cogeneration plants mentioned above run on wood chips. The Kristiine and Ülemiste boiler houses are two of the major boiler houses connected to the network [18].

In Tallinn’s DH network, used as a case study in papers I-IV, summer heat loads can be covered by excess heat from a single CHP plant. The remaining cogeneration plants are left with a choice: either to cool down the excess heat via chillers to continue producing electricity to receive subsidies for RES electricity production, or to stop working. In the winter, the situation is reversed: even if all Tallinn cogeneration plants operate at full capacity at the same time, there is insufficient to cover the heat load of the entire Tallinn DH network, therefore the remaining heat load is covered by boiler houses. Peak loads are currently covered by natural gas boiler buildings in Tallinn and elsewhere in Estonia, which have been temporarily replaced with shale oil due to gas supply issues in 2022. While shale oil is a local alternative, it remains a fossil fuel and does not align with national climate targets. Thus, sustainable alternatives to natural gas or shale oil boilers are imperative.

Improvements in DH infrastructure promise enhanced energy efficiency, aligning with the EU’s energy policy promoting DH and CHP generation. According to Directive 2012/27/EU, energy-efficient DH systems utilise at least 50% renewable energy, 50% waste heat, 75% cogenerated heat, or a combination thereof [19].

Tallinn started developing the DC distribution network and production in 2019. By the end of 2023, the installed cooling capacity was approximately 6 MW. In the long term, the goal is to build a large DC network that has a base-load DC plant and two peak-load DC plants. As a coastal city, has potential for seawater-based free cooling, supplemented by electrical chillers, or HPs, during periods when seawater temperatures are inadequate to meet DC demand [20].

1.3 Research problem

Conventional power plants and CHP plants continue to play an important role in the modern energy system. They are crucial for covering the base load of electricity and heat demand and maintaining stability and frequency in the power grid. However, with the rapid development of renewable energy sources (RES) and their increasing controllability in both the heating and electricity sectors, the future role of conventional power plants and CHP plants is being questioned, given the availability of more environmentally friendly methods of heat and power production.

It is evident that CHP plants will play an important role in the energy system in the near future. However, there is a pressing need for them to enhance operational flexibility to maintain competitiveness and resource efficiency, thereby securing their position in the energy sector.

Due to the technical processes involved in both heat-only and CHP production, flexible energy production is essential for both the heat and power sectors. RES in these sectors are challenging to control and heavily reliant on weather conditions such as wind and sunshine. The volatility of RES generation can be reduced by introducing storage options into the system. Various types of energy storage exist, each with unique strategies for utilisation. To optimise investments in storage technology, thorough calculations and analyses are necessary. While electric energy storage units are more expensive and have capacity limitations, thermal energy storage (TES) is technically simpler, resulting in lower installation and operation costs. TES offers a wide range of capacities suitable for both seasonal and short-term energy storage, thereby enhancing flexibility in heating production and reducing CO_2 emissions by decreasing the need for peak boilers.

Flexibility in power production is also a challenge for CHP plants, particularly when there is a surplus of RES in the electricity grid. This poses a problem for CHP plants since they cannot pause operations. Demand-side management solutions, such as power-to-heat technologies, can alleviate this issue.

In the district cooling (DC) sector, flexibility is less of a concern compared to the heating and power sectors due to differences in technologies. However, sustainability in the cooling sector remains crucial, with potential for improvement in energy efficiency through the use of heat pumps (HP) and absorption chillers.

Sector coupling is vital for flexibility and energy efficiency. Coupling heat, power, and cooling sectors through different technologies is explored in this thesis to enhance overall system performance.

The current research focuses on three main fields: CHP flexibility, district heating (DH) systems, and district cooling (DC) systems. Figure 1 illustrates the key fields and technologies investigated in this thesis.

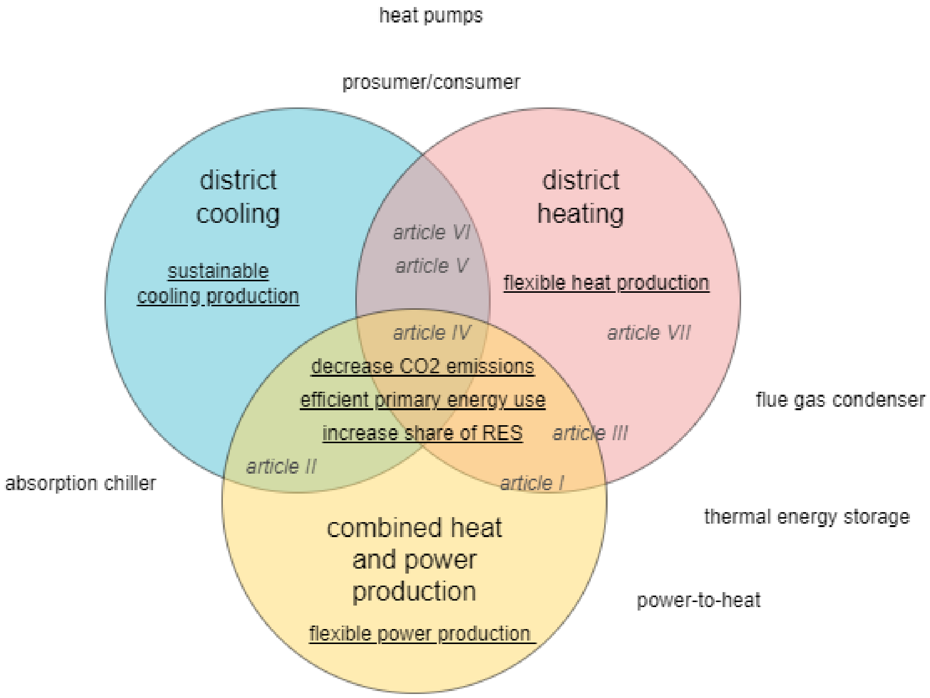


Figure 1. Fields and technologies investigated in this thesis

The goal for each sector is underlined in the circles. Text outside the circles indicates technologies that can be used to achieve the established goals. In cursive, articles included in the thesis that contribute to the goals and solutions within the sectors are marked.

By exploring and investigating these topics, the following research questions are being addressed:

Research Question 1 (RQ1): How can the operational flexibility of combined heat and power production be increased?

Research Question 2 (RQ2): How can primary energy usage efficiency in the energy system be increased through coupling different energy sectors?

The first research question seeks to identify solutions and technologies to enhance the operational flexibility of CHP plants and increase their feasibility. This study examines thermal energy storage, coupling with district cooling, power-to-heat solutions, and load shifting. The justification of the selected technologies is given in the literature review chapter.

The second research question investigates technologies for coupling heat, power, and cooling sectors to maximise primary energy usage efficiency. This study explores heating and cooling production, HPs, TES, and low-grade heat sources. Building upon RQ1, RQ2 analyses how flexibility in energy production can improve primary energy usage efficiency.

Through comprehensive discussion and analysis, the author aims to address the overarching question: What is the future position of CHP plants in the smart energy system, considering all the research findings and insights gained from addressing the research questions stated above?

1.4 Structure

This dissertation comprises seven research articles published in international peer-reviewed academic journals, along with a compilation section. The articles and their corresponding research questions are outlined in Table 1.

Table 1. Articles and their corresponding research questions

Article no.	Focus of the paper	Primary unit of analysis	Corresponds to research question no.
Article I	RES integration	CHP, DH	RQ1, RQ2
Article II	Coupling CHP with cooling production	CHP, DC	RQ1, RQ2
Article III	CHP efficiency	CHP, DH	RQ2
Article IV	Cooling generation	CHP, DC	RQ1, RQ2
Article V	Low-grade heat sources mapping	DH and DC sector	RQ1, RQ2
Article VI	5GDHC implementation	DH sector	RQ1, RQ2
Article VII	DH in rural areas	DH network and heat production	RQ2

The research conducted in this thesis addresses efficient energy use problems in energy systems on various levels, including the technology level, DH network level (based on Tallinn case studies), national level, and regional level (pertaining to the Baltic states). The articles and their corresponding research scales are provided in Table 2.

Table 2. Articles and their research scale

Research scale	Articles no.	Description of contribution
Technology level	II, III	Efficient use of energy
DH network	I, IV, VII	RES integration into the DH system, efficient use of energy
National	VII	Efficient use of energy
Regional	V, VI	RES integration into the energy system, efficient use of energy

At the technology level, the articles offer suggestions on implementing technologies such as flue gas condensers (FGC) and absorption chillers to achieve more efficient energy use. At the DH network level, different strategies and technical solutions within DH networks are investigated in order to integrate more RES into the system and utilise energy more efficiently. For regional contributions, the implementation of various technologies and strategies is studied on a larger scale, considering their influence on regional development.

1.5 Research methodology

The methodology used in this thesis facilitates the assessment of efficient energy use and primary energy reduction in district energy systems (DH, DC) and CHP plants through the integration of various technologies and technical solutions into the energy system. Multiple methods were utilised to achieve this objective, with the rationale behind method selection and a comprehensive description of each approach elucidated in the papers. Initially, a review of published articles was conducted to explore energy efficiency opportunities.

Four main research methods were employed in this thesis: mathematical simulations for energy system modelling and process modelling, geospatial analysis and multi-criteria analysis. Table 3 presents the research methodologies, designs, and descriptions.

Table 3. Research methods, designs and description of the articles

Article no.	Research method and design	Research description	Source of data
Article I	Comparison of simulation results from different scenarios, optimisation	DH system simulations with EnergyPRO simulation tool aimed to reduce of heat rejection and natural gas use in DH networks by adding TES and power-to-heat to CHP	Annual heat demand, data from CHP plants
Article II	Calculations based on simulation model's results, optimisation	Creation of mathematical calculation model for absorption chiller and turbine efficiency, DC system simulations with EnergyPRO tool to find most energy efficient DC solution	Data from CHP plant, Estonian Buildings Register
Article III	Calculations based on simulation model's results, regression analysis	Creation of mathematical calculation model for FGC efficiency	Data from CHP plant
Article IV	Comparison of simulation results from different scenarios	DH and DC systems simulations and heat loss calculations with different DH supply temperatures	Hourly cooling profile, data from CHP plant and DH company

Article no.	Research method and design	Research description	Source of data
Article V	Geospatial analysis	Creation of interactive GIS map for industrial and low-grade heat sources and DH and DC networks in the Baltic States	Annual heating and cooling demand in local DH and DC networks, Environmental Register, Estonian Weather Service
Article VI	Multi-criteria analysis	Qualitative comparison by discussing the barriers and drivers, quantitative comparison by assigning numerical values to each criterion	Electricity price, National Energy and Climate Plans, Building Register, national databases
Article VII	Comparison of simulation results from different scenarios	DH system simulations with EnergyPRO simulation tool	Annual heating demand of DH networks, ambient temperature, electricity price

1.5.1 Energy system modelling

Energy systems are complex systems influenced by various factors from both the supply and demand sides. Different scenarios must be modelled to see how the system behaves under the influence of various circumstances. For this, the examination of case studies is crucial.

In Articles I, II, IV and VII, heat demand profiles are analysed, and scenarios involving different heating or cooling production options are investigated to assess their impact on system performance.

In Article I, the Tallinn DH network serves as a case study, with the present situation acting as the reference scenario. Scenarios involving thermal energy storage (TES) and power-to-heat options are analysed to reduce heat rejection and natural gas consumption in the DH system. Heat demand profiles were modelled with EnergyPRO software, and data for annual heat demand were sourced from the Tallinn Heat Management Development Plan. Electricity prices were obtained from Nord Pool, and technical data regarding CHP parameters were acquired from CHP companies.

Article II focuses on the Mustamäe district and the Mustamäe CHP as a case study. For the study, a DC network in the Mustamäe district was proposed, with annual cooling demand estimated based on building capacity data from the Estonian Building Register. Using EnergyPRO software, a cooling demand profile was modelled, and various energy-efficient cooling production technologies were proposed.

In Article IV, the Tallinn DH network is once again used as a case study. For the study scenarios with different DH supply temperatures are examined. The study examines scenarios with different DH supply temperatures, with a particular focus on cooling production via absorption chillers. Since the DC plant is located seven kilometres from the CHP plant, the DH network is employed for heat transportation. The evaluation parameters used to compare and determine the optimal solution take into account the technical characteristics of both the cooling plant and the DH system. Heat loss, flow rate, pump electricity consumption, annual CHP energy efficiency, and overall system efficiency were calculated for the DH system.

In Article VII, data on annual consumption, network temperatures, heat production units, heat price, and consumers of Estonian rural DH networks were gathered from local municipalities' heat management development plans. Over 140 heat management development plans were examined. Rural DH networks were divided into seven groups based on annual heat consumption, and a reference scenario was created for each group. Reference scenarios illustrate each group's average heat demand profile and the current DH consumer price. Various scenarios with different HP solutions were examined for the analysis, and the DH consumer price for each scenario was calculated.

1.5.2 Process modelling

Various technical processes have an impact on heat, power, and cooling production. In-depth analysis of these technical processes often requires mathematical calculation models. To achieve this, these processes must be described through their parameters and formulas. By manipulating various parameters within these processes, the outcome and performance indicators also change, providing essential insights into how the system should be designed for optimal performance.

In Articles II and III, mathematical process models were created using data from CHP plants. Both models utilise Mustamäe CHP as a reference case, with the necessary data for model validation obtained directly from the CHP plant.

In Article II, a comprehensive model for absorption chiller and turbine efficiency was developed to investigate the effect of turbine outlet temperature on cooling and power generation. This model depicts the simultaneous heat and mass transfer processes within the absorption chiller, which are affected by the turbine outlet water temperature. The results obtained from this model were subsequently used in the energy system modelling discussed in the article.

In Article III, a detailed model for FGC performance was created. The performance of the FGC is influenced by the DH return temperature and has a significant effect on the thermal efficiency of the CHP plant. This model provides a detailed mathematical description of the simultaneous heat and mass transfer processes occurring within the FGC.

1.5.3 Geospatial analysis

Geospatial analysis is a powerful tool for visualising possibilities and identifying usable resources. It is instrumental in locating the most suitable sites for applying waste heat in DH systems. Such analysis yields valuable insights for a given geographic area, facilitating the formulation of future strategies and development plans.

In Article V, an extensive analysis of available industrial and low-grade heat sources was conducted, focusing particularly on their suitability for large-scale HPs or chillers. Through this analysis, the potential for implementing large-scale HPs and chillers within

DH and DC networks can be discerned, with barriers potentially lowered. This is achieved through the utilisation of geospatial analysis, leveraging advanced GIS (Geographic Information System) software to provide detailed information and an overview of suitable locations for heat sources and sinks near DH or DC regions. Such an approach adds value to GIS maps by concentrating on and incorporating heat sources that are particularly relevant for large-scale HPs, thus enabling the quantification of their potential usage.

1.5.4 Multi-criteria analysis

The Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) method of multi-criteria analysis is widely used to compare different environmental strategies for sustainable development, taking into account various perspectives. Its primary objective is to allow users to compare and choose from multiple alternatives.

In Article VI, the potential introduction of 5th Generation District Heating and Cooling (5GDHC) in the Baltic States was assessed using multi-criteria analysis. A qualitative comparison was conducted by examining the barriers and drivers unique to each country, while a quantitative comparison involved assigning numerical values to each criterion. The quantitative analysis utilised a multi-criteria decision-making method to compare various aspects of potential 5GDHC implementation, resulting in a ranking of countries for each aspect. The criterion values obtained were evaluated using both the TOPSIS and the Analytic Hierarchy Process (AHP) methods to determine the weight of each criterion.

2 Literature review

The literature review briefly outlines the role of CHP production within the current energy system. It addresses the challenges faced by CHP plants, as discussed in the literature, and presents potential future development paths. The second part of the literature review focuses on sector coupling and flexibility in energy production to enhance the efficient utilisation of primary energy. This section explores different approaches to sector coupling and highlights the advantages and disadvantages associated with them. Each subsection discusses a separate useable technology.

Furthermore, the literature review encompasses international studies that hold relevance not only globally but also within the context of Estonian conditions. Given the thesis's emphasis on Estonian District Heating (DH) systems and CHP production, these international perspectives provide valuable insights for contextualising the research within a broader framework.

2.1 Combined heat and power production in district heating and cooling systems

Over the past decades, the number of CHP plants in Europe and Estonia has increased, and there are currently over 20 CHP plants in Estonia, four of which are located in Tallinn [21]. Biomass-based CHPs are widely used in DH systems in Europe. As for Estonia, this type of RES is actively supported by the government, which has introduced a feed-in-premium policy instrument[22].

The utilization of biomass resources presents a practical solution to address energy supply shortages and reduce greenhouse gas emissions. Harnessing excess biomass for CHP production offers a promising avenue for clean energy generation. In [23], a comprehensive techno-economic analysis and life-cycle environmental assessment model were developed to investigate the feasibility of a CHP plant utilising biomass waste, with the findings highlighting the positive environmental impact of this approach. Sensitivity analysis conducted in the study underscored that reducing capital costs and increasing annual power generation could substantially improve project viability.

Effective energy management is essential for the design and implementation of CHP systems, particularly those incorporating Renewable Energy Sources (RES). Such management is critical for optimising energy utilisation and achieving cost-effectiveness, energy conservation, emission reduction, and component longevity. In [24], various energy management approaches employed in CHP systems that utilise RES were discussed.

One option for improving heat production efficiency is to install FGCs to recover waste heat from flue gases. In recent years, FGC has often been used to increase the efficiency of CHP or boiler plants, improving tboth heating and CHP plant efficiency by recovering latent and sensible heat from flue gases and water vapours. The proportion of heat recovery in the total supplied heat can reach up to 30%, increasing overall plant efficiency by up to 15% [25]. Major factors influencing the proportion of FGC heat recovery include fuel moisture content, condensing temperature, fuel composition, and flue gas temperature [25]. Additionally, other factors predominantly affecting heat and mass transfer in FGCs encompass flue gas flow velocity and regime (laminar or turbulent), as well as FGC construction. FGC efficiency has also been studied in [26] and [27]. The method proposed in [26] was specifically tailored for heat and mass transfer in tubular FGCs, while [27] examined different configurations for combined-cycle power plants to recover heat from flue gases. Furthermore, [28]] illustrates the retrofitting of an existing FGC with a heat exchanger system to increase heat recovery from flue gases. This study also highlights the significant influence of return water temperature on potential heat recovery. For the most optimal FGC design, comprehensive numerical analysis was conducted in [29] to maximise latent heat recovery. Moreover, FGC design was investigated in [30] to improve the capture of acid gases like SO_x and NO_x using vortex generators.

CHP plants also play a crucial role in power grid stabilisation, ensuring the maintenance of frequency and voltage in the power grid [31]. Amidst climate change concerns, when non-combustion heat sources are gaining prominence, the relevance of CHP plants in the energy system may be questioned. While there are various ways to generate electricity and/or heat from non-combustion sources such as solar, wind, and geothermal energy, among others, CHP plants offer distinct advantages over these technologies. They generate electricity and heat in a single operation, minimising energy loss and producing consistent energy. In addition, CHPs help to balance the energy system, especially when run on biomass, making the energy produced renewable [32].

The main operational challenges faced by CHP plants are related to fluctuating or low heat loads. During periods of low heat demand, the plant may either cease operation entirely or use coolers to dissipate excess heat. While heat rejection allows the CHP system to continue electricity production, it constitutes an inefficient use of energy since all heat energy is wasted.

Although subsidies and national support for CHP production may create the illusion of an economically profitable industry, there remain technical and non-technical issues that require attention. The primary obstacles to efficient CHP operation under current conditions include:

- Inefficiency during periods of reduced heat demand, particularly in warmer months;
- Infeasibility of electricity generation and sale through CHPs when market prices for electricity are low.

The first obstacle is well-known and extensively researched, with various technical solutions available. Typically, a CHP plant operates to supply heat during the cold months when heat demand is high. However, during periods of low heat demand, when there is limited capacity to utilise the generated heat, the CHP system must either operate at partial load or cease operation altogether. One potential solution, in cases where electricity generation can proceed without heat utilisation, involves installing additional auxiliary coolers to dissipate excess heat during periods of minimal heat demand, for example, in summer. This approach has been implemented at various facilities such as the Järvenpää Biomass CHP (Finland) [33], Klaipeda Waste Incineration CHP (Lithuania) [34], Tallinn CHP2, Mustamäe CHP [14], and Pärnu Biomass CHP (Estonia) [35]. However, it is crucial to note that this solution cannot be considered sustainable.

Addressing the other problem entails considering various approaches, as solutions hinge on external factors within the energy system. These factors encompass subsidies, investment support for storage options, fuel prices, availability in the heating sector, and other variables prone to rapid fluctuations. The unpredictable nature of these factors complicates decision-making, making it challenging for companies to determine the most feasible solution. The next chapter will explore various approaches to tackle the issue of unfeasible power production in CHP plants in more detail.

2.2 Sector coupling for increased flexibility and energy efficiency

Power systems reliant on various RES such as wind and solar power, require substantial flexibility in both power generation and demand. In [36] the concept of a residential area acting as a locally operated entity, akin to a virtual power plant, was proposed to provide power-balancing services to the national power grid. To explore this concept, a case study was conducted in Sweden, where a local entity comprising a CHP unit, HPs, a local heat distribution system, and a thermal storage unit was modelled. Energy balance simulations, coupled with storage size optimisation, demonstrated that all power surpluses in the system were efficiently absorbed by the HPs. Moreover, the CHP unit met 43% of the annual electricity load and 21% of the peak electricity load. In [36], the importance of inter-seasonal thermal storage systems in achieving the desired flexibility was emphasised.

The enhancement of flexible operation in thermal power plants has emerged as a significant research focus, given its pivotal role in maintaining a stable power grid amidst the integration of renewable energy on a large scale. In [37], an adaptive modelling approach combining mechanism analysis and data-driven fuzzy modelling was proposed to design controllers for rapid and precise load regulation during flexible operation. The study demonstrated that even with enhanced controllers, the efficiency and flexibility of a CHP plant could be improved further.

Esmaeili and Pourmoghadam [38] conducted a dynamic simulation of a combined cooling, heating, and power (CCHP) system using concentrated photo voltaic thermal (CPVT) collector. The proposed configuration included CPVT collectors, a phase change material storage tank, an organic Rankine cycle (ORC), an absorption chiller, and heat exchangers. To ensure continuous operation, even during low or no solar irradiation, an auxiliary heater was incorporated to provide thermal energy. The performance of the CCHP system was analysed from energy, exergy, and economic perspectives, particularly during the warmer months (May to September). The results indicated that increasing the CPVT area from 100 m^2 to 400 m^2 led to a remarkable 161% improvement in the solar fraction. However, it was observed that CPVT was a major contributor to exergy destruction, accounting for 49% of the total. These findings provide valuable insights into the optimisation of the CCHP system and highlight the significance of CPVT collectors in enhancing its performance both energetically and economically.

2.2.1 Combined heat and power production role in heating sector electrification

The European Commission's EU Strategy for Energy System Integration asserts that sector coupling will significantly boost electricity consumption, thereby increasing renewable energy production and promoting the use of RES technologies [39]. In [40] the pivotal role of HPs as power-to-heat solutions in sectoral coupling between RES and the heating sector was discussed, highlighting that the amount of heat extracted from RES is greatly dependent on the chosen strategy. The integration of wind power generation offers the highest potential for incorporating RES into a system. Moreover, [41] suggests that residential heat load presents significant potential for maximising wind power utilisation and minimising carbon emissions through the coupling of the electricity and heating sectors. Additionally, [42] notes that operating existing thermal power plants in cogeneration mode, alongside DH networks and thermal storage units, can still contribute to the decarbonisation of the European heating sector.

Coupling the CHP with TES helps mitigate the impact of fluctuations in consumer heat load on heat and electricity production. Typically, short-term TES utilises accumulator tanks. The feasibility of this technical solution was investigated in [22], [43], [44], with the main conclusion being that implementing accumulator tanks can prolong the period during which CHPs operate at full load and enhance their overall efficiency. Furthermore, as demonstrated in [45], seasonal TES emerges as a superior choice when solar energy is also utilised.

A fairly new problem faced by CHPs is associated with brief periods when electricity prices are very low, rendering electricity production and sale unviable. Various storage options can be used to deal with peak demands and integrate renewable energy into the system. Electrical storage is the best way to integrate solar, PV, and wind energy into the grid, although these solutions can often be expensive [46]. At the moment, large-scale electricity storage facilities are also limited and very expensive [47]–[49]. Other energy storage options, such as pumped hydro storage, are restricted by location and not widely available. Power-to-heat is a feasible option when heat is consumed via DH or stored in short-term heat storage facilities. If periods of low electricity prices coincide with the heating season (e.g., in Nord Pool, when electricity prices dropped to 0 EUR/MWh for a few hours on 9.02.19, with the average price for the day of 10.07 EUR/MWh), the heat produced from the CHP electricity can replace the heat produced from fossil fuels, reducing CO_2 emissions.

Andersen et al. have explored various ways to make energy systems more flexible and introduce more RES into the system, with a particular focus on tax incentives [50], government support schemes [51], and developing power plant operating strategies [52]. Using HPs for power-to-heat can be very beneficial, but because the investment in the installation is very high, an electricity tax system was proposed in [50] to help increase the capacity of HPs and TES units in order to create a basis for flexible operation and match the operation of HPs with the dynamic needs of the electric power system. The results showed that 100% of the spot electricity prices could stimulate investment in additional TES capacity but won't do as much for the capacity of DH HPs. In [51], it is argued that the support scheme must ensure the correct ratio between the production capacity and TES capacity. Before a country achieves intermittent renewable energy production at full volume, it is recommended that production-dependent support schemes be used to increase the displacement of production at condensing power plants running on fossil fuels. When a high level of intermittent renewable energy is achieved, this production covers the electricity demand for most hours, leaving only a few hours for CHP production. Investment support schemes can be considered at this stage as they require less assistance.

2.2.2 Heat sector electrification

There has been a growing interest in the utilisation of electrical solutions in the heating sector in recent years. The availability of diverse low-grade heat sources, along with advanced and highly efficient heat pump (HP) technology, has spurred widespread exploration of large-scale HPs in district heating (DH) systems. DH has emerged as an efficient means of supplying space heating and domestic hot water in densely populated areas [53], while also facilitating the seamless integration of various renewable energy sources (RES) into the energy system [54]–[56].

Power-to-heat technologies have been the subject of extensive research recently. One study [57] examined the impact of wind penetration in electricity markets on optimal power-to-heat capacities within local DH systems. Another study investigated the influence of power-to-heat on Germany's power system, concluding that the interaction between the heating and electricity sectors can enhance flexibility in both sectors to address short-term fluctuations in wind and solar power generation. In [59], it was noted that in systems where biomass resources are limited, employing power-to-heat solutions can aid in the integration of additional RES into the heating sector as the share of renewable energy increases. In [60], various methods for the optimal design of distributed energy systems were compared, with HPs considered as power-to-heat solutions. Risk assessment for integrated heat and electricity systems revealed that utilising power-to-heat solutions, such as HPs and electric boilers, can mitigate risks associated with integrating a higher proportion of RES into the system [61].

The impact of power-to-heat technologies on Germany's energy system was further explored in [59], highlighting the potential for enhancing flexibility in both the heating and electricity sectors to manage short-term fluctuations in wind and solar energy production. The study emphasised that when biomass resources are limited, integrating power-to-heat solutions into systems with a growing share of renewable energy can further augment RES incorporation into the heating sector. A comparison of various methods for the best design of distributed power systems was performed in [60], with HPs considered a viable power-to-heat solution.

Assessing the implications of adding a large number of electricity consumers, such as HPs, on the balance and functioning of the electricity grid is imperative for maintaining grid stability. One study [62] outlined electricity market options for HPs in rural DH networks in Austria, illustrating how HPs can serve as grid regulators to bolster grid stability and balance.

The use of HPs in DH also yields a positive effect on air quality, since HPs do not require combustion to generate heat and therefore no fine particles or acidic oxides (NO_x and SO_x) are emitted. While biomass boilers are extensively used due to their perceived CO_2-neutrality and the wide availability of biomass in Estonia, their usage can contribute to air pollution. The impact of biomass boilers on the atmosphere has been scrutinised in previous studies [63]–[65]. Emissions from biomass boilers vary depending on combustion methods. As indicated in [65], NO_x and SO_x emissions remain below environmentally harmful levels, with CO_2 emissions not surpassing the amount consumed by plant growth, rendering biomass a more environmentally friendly fuel option. Conversely, [63] suggests that emissions of fine particles from biomass combustion can pose health risks if flue gas cleaning equipment is not used. When considering HPs for space heating, it's important to note that their use, as opposed to combustion boilers, has an overall positive impact on the atmosphere only if the electricity powering HPs is generated in accordance with clean production principles and sourced from RES. Emissions of fine particles and acidic oxides during combustion can be mitigated by utilising air treatment equipment like FGCs, electric precipitators, and various kinds of filters. However, such equipment can be expensive and not all boiler houses have it installed. According to Directive 2015/2193 of the European Parliament and of the Council of 25 November 2015 on the limitation of emissions of certain pollutants into the air from medium combustion plants, the maximum amount of fine particles (dust, fly ash) for medium-sized biomass boilers is 20 mg/Nm^3 [66]. Emissions of fine particles are also regulated by Directive 2016/2284 of the European Parliament and of the Council of 14 December 2016 on the reduction of national emissions of certain air pollutants, which established an emission reduction strategy [67].

Large-scale HPs and chillers are viewed as highly efficient technologies for utilising RES, integrating the power and thermal energy sectors, and thereby aiding in balancing power generation in case of fluctuating RES. HPs allow the use of heat at ambient temperature from sources such as seawater, rivers, lakes, or sewage water for DH, which would reduce the proportion of fossil fuel-based heat [68], [69]. Similarly, these sources can be used by chillers as a heat sink to supply DC. Connolly et al. [70] demonstrated the significance of large-scale HPs for European DH systems, which are expected to produce 520TWh/a in the EU by 2050, accounting for 25% to 30% of the total DH production.

2.2.3 Coupling combined heat and power production with district cooling

DC technologies have evolved over the years, with numerous studies conducted to determine the most sustainable approaches. The most environmentally friendly solution is free cooling, where chilled water is sourced from nearby reservoirs, such as rivers, as is the case in Paris [71]. In the absence of natural bodies of water nearby, large-scale HPs, chillers, absorption chillers, or other innovative technologies like hybrid solar power can be utilised. An optimisation model developed in [72],], for large-scale HPs and cooling plants aimed to ascertain the most economical and/or sustainable production and storage capacities, heat sources, and demand profiles for both DH and DC supply. Modelling outcomes revealed that HPs, when combined with DC networks, can establish a sustainable symbiosis, with HPs utilising the DC network as a heat source, presenting significant potential for reducing CO_2 emissions. Additionally, as indicated in [73], the introduction of DC systems, cold TES, and cooling towers into the system can yield even greater energy savings when operated properly. Exergy assessment suggests that chillers perform best when integrated with cooling towers.

Absorption chillers play a crucial role in coupling DC with CHP plants, as they can utilise excess heat produced by CHP plants during periods when it is not required in the DH sector, particularly in summer. Various absorption designs are available, mainly single-stage and two-stage absorption chillers. Single-stage machines can be powered by hot water (90–115 °C) or low-pressure steam (1 bar) and are often paired with reciprocating engine CHP plants. In contrast, two-stage machines require higher-temperature hot water (e.g., 175 °C) or higher-pressure steam (e.g., 8 bar) and are often matched with combustion turbine CHP plants. Typically, the COP for a single-stage absorption chiller is about 0.75, whereas for a two-stage absorption chiller, the COP is 1.35 or higher [74].

When absorption chillers are used, special attention should be paid to their heat rejection systems. Generally, the heat rejection system capacity of an absorption chiller is about 2.35 times the cooling capacity of the chiller [75]. When TES units are integrated into the system and there is a demand for DH, the rejected heat from the cooling process can be repurposed for heating.

Comparative analysis of DC configurations, encompassing electric chillers coupled with CHPs, absorption chillers, TES, solar thermal plants, and HPs, revealed that the most viable option is to integrate CHP with TES and absorption chillers alongside electric chillers [76].

With cold TES, chilled water can be stored and matched to the cooling load during the hottest hours of the day to prevent excess loads on chillers. By adjusting the charge and discharge times of the cold TES, it is possible to maintain a more constant discharge temperature and avoid discharging water that is too warm for the cooling system [73]. As described in [77], solar energy can also be utilised in DC systems by harnessing the heat generated by solar collectors for absorption chillers. Furthermore, solar energy can power electric chillers in DC systems.

Another advantage of DC is cooling load diversification [78]. In [78], a techno-economic analysis of a DC system was conducted, integrating a cold storage unit into the system to smooth the load profile. This effect was similar to using TES in DH systems. It provided more flexibility for load switching, enhanced system reliability, and facilitated the integration of more RES into the system.

In [79], the use of surplus heat from waste incineration CHPs in DC was analysed. A 73 MW real-life CHP plant from Denmark was simulated, showing that 20 MW of DC could be supplied by absorption chillers and cold TES with a payback period of less than 5 years. Such a solution would be mutually beneficial for CHPs and cooling supply, as the CHP operator could earn revenue by providing heat for cooling instead of releasing it into the ambient air or allowing others to expend it at their cost. A DC power supply via absorption is more economical and sustainable than using individual electric chillers.

Similarly, the author of [76] conducted extensive research into establishing a DC network in Italy. In [76], various installations were evaluated alongside the absorption chiller, aiming to find an economically viable solution contributing to primary energy savings. The Italian study [76] compared four different scenarios, each with a different technical configuration involving electric chillers, boilers, CHP plants, absorption chillers, TES units, and HPs. It demonstrated that combining multiple technologies produces the best results in terms of energy and economic compromise.

More renewable energy can be introduced into the system using solar energy [80]. Solar DC systems also utilise absorption chillers for cooling generation, but unlike CHP plants, they use solar energy instead of excess heat to generate hot water to power the process. The main components of a typical solar absorption cooling system include a solar thermal collector, an absorption chiller, storage tanks, and an auxiliary boiler [80]. Additionally, hot flue gases can serve as a heat source for absorption chillers, as explored via a similar system in [81]. Like DH systems, solar-powered DC systems also require TES to operate optimally. It is argued that by using both cold and hot storage, the overall coefficient of performance (COP) of the system can be increased, and the cooling plant’s capacity can be lower than peak demand, thus reducing costs.

In [82], a comprehensive review and comparison of solar-enhanced heating and cooling systems were provided. The study revealed that although solar radiation intensity graphs and cooling consumption graphs exhibit similar profiles, absorption chillers require additional heat flow, which can be supplied by a natural gas boiler, as demonstrated in [82]. However, in terms of primary energy consumption and cost, they also recommend the use of HPs. To achieve even greater savings on primary energy, excess heat from CHP systems can be utilised. In [83], a novel concept involving a solar pond and an absorption chiller for cooling energy production was introduced. While using solar ponds can enhance the flexibility of utilising solar energy, it was also highlighted that sufficient solar radiation is essential as the hot water temperature significantly impacts the absorption chiller's Coefficient of Performance (COP), requiring careful pond design.

Similar to DH, DC systems can also be more beneficial if more consumers are connected to the network [84]. However, DC systems are typically smaller in scale than DH systems because DH consumers primarily consist of multi-family buildings and office buildings, whereas DC systems mainly serve office buildings and large consumers such as hospitals and supermarkets. Due to the smaller temperature difference between supply and return in DC systems compared to DH systems, the pipe diameter in a DC system is larger, necessitating greater investments in establishing the network [85].

DC network temperatures typically range from 6–16 °C on the supply side and 8–25 °C on the return side. In [8], the concept of high-temperature DC was discussed in the context of the Gothenburg DC system in Sweden. Proposed supply temperatures of 12–14 °C and return temperatures of 20–22 °C aim to enhance the use of free cooling and facilitate temperature reduction in DH systems. Consequently, introducing higher temperatures into the system can support its evolution towards a future smart energy system with increased efficiency and energy savings [86].

2.3 Summary of the literature review

The literature review described the key actors for CHP production efficiency and flexibility and sector coupling. The topics that were addressed include technologies aimed at improving energy efficiency and primary energy use in the power plant, e.g. FGC.

The first chapter of the literature review justified CHP plants as environmentally friendly energy producers, emphasising their importance in ensuring stability and frequency in the power grid. Additionally, it outlined the main obstacles hindering the efficient and flexible operation of CHP plants.

The subsequent chapter examined solutions to the obstacles identified earlier, suggesting that sector coupling could alleviate issues associated with fluctuating RES production and feasibility. Various sector coupling approaches were discussed, with a focus on the electrification of the heating sector to channel more RES into heating.

In conclusion, the reviewed literature indicated that the flexibility and efficiency of CHP plants could be significantly enhanced through the implementation of different sector coupling technologies, such as TES, power-to-heat technologies, and absorption chillers, as evidenced by numerous research articles. Moreover, optimal operation strategies and equipment capacities were deemed crucial, alongside discussions on financial models and tariff systems, which could substantially impact feasibility.

As heat sector electrification plays a pivotal role in the future evolution of the energy system and significantly influences CHP production, it was thoroughly examined in the literature review. The scope of the study extended beyond CHP plants, acknowledging the impact of heat production in small DH networks on power consumption. The review also provided insights into the Estonian electricity mix for comparison purposes. Electrifying the heat sector could either increase or decrease the share of RES, depending on the efficiency of the technologies utilised. Efficient waste heat recovery using RES electricity could bolster RES integration and energy efficiency, thereby mitigating issues associated with fluctuating RES production. Conversely, reliance on fossil-fuel-based electricity for heating could exacerbate environmental concerns.

Several articles suggested coupling CHP production excess heat with DC as an efficient solution. Various methods to maximise primary energy efficiency in cooling production, including the integration of solar energy facilities, HPs, and both cold and thermal energy storage systems, were explored in the literature review.

Overall, the literature review provided a rationale for integrating specific technologies into the existing energy system to establish an efficient, smart energy system. However, despite extensive studies, there remains a gap in understanding how to increase CHP production flexibility to enhance energy efficiency in a smart energy system, particularly in cold climate conditions. The studies conducted in this thesis aim to address this research gap and contribute to enhancing smart energy system energy efficiency by integrating different technologies to increase CHP production flexibility.

3 Summaries of the articles

In this section, the individual research articles are summarised. The purpose, methodology, findings and contribution to the thesis are described for each article, and the findings in relation to the research questions of the dissertation are described.

3.1 Article I: Improving CHP flexibility by integrating thermal energy storage and power-to-heat technologies into the energy system

This article studies the possibilities to increase CHP production primary energy use efficiency. The goal of the study is to find ways to decrease heat rejection and natural gas consumption and also increase energy system flexibility by integrating power-to-heat technologies and TES to the system.

The proposed technical composition therefore consists of electric boiler as power-to-heat option and TES and Tallinn DH network, where are four CHP plants for covering heat demand base load and natural gas boilers for covering the remaining peak load. The technical composition described in the paper is also depicted in Figure 2.

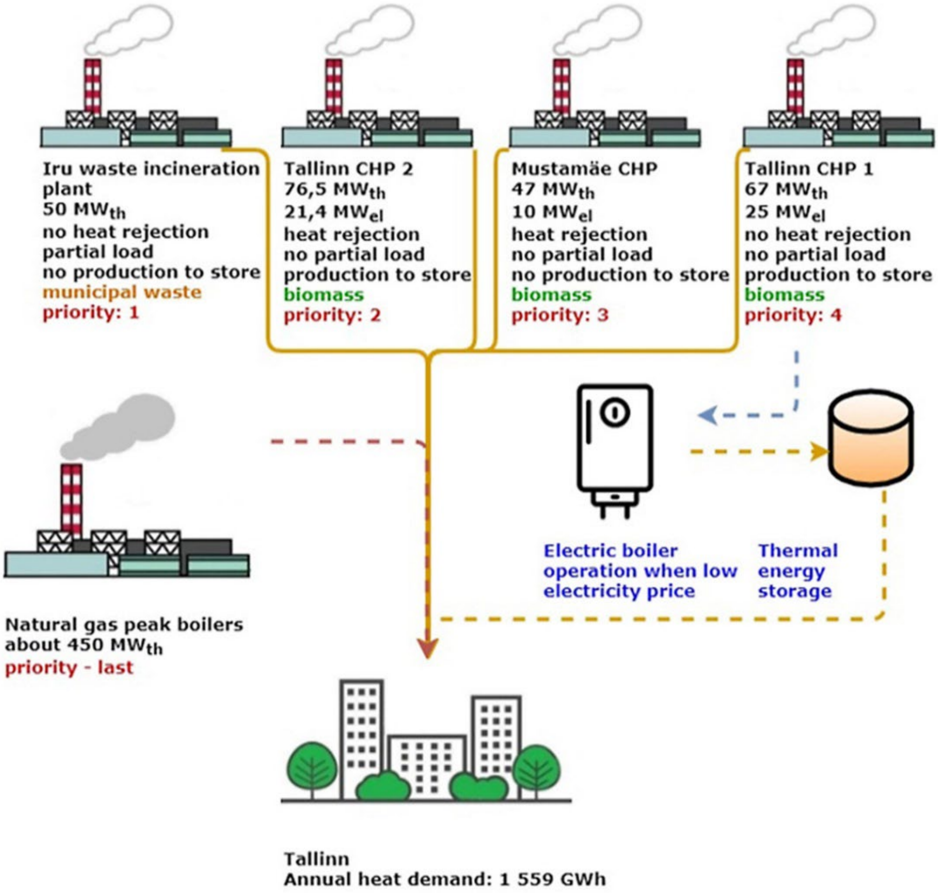


Figure 2. The proposed technical solution within Tallinn DH network [87]

As is seen on the Figure 2 not all CHP plants have the possibility to reduce their load or use heat rejection. There is one CHP plant that has neither of these possibilities, Tallinn CHP 1. For this CHP plant, the only possibility in case of too low heat load is to stop working. Iru waste incineration plant is capable of working part load, but there is no heat rejection possibility. This means that in case of low heat load, the power production is also reduced. There are also two CHP plants in Tallinn, Mustamäe CHP and Tallinn CHP 2, that are capable of rejecting excess heat because of installed chillers, but these plants cannot work part load. This means that these CHP plant have to reject excess heat when there is not enough heat load.

This leads to the problem where in times of low heat demand heat is rejected which is inefficient use of primary energy and power generation is reduced because of reduced CHP production load. When the heat produced by CHP plants is not enough to cover heat demand, natural gas boilers are used. All heat production units and their relevant parameters are given in Table 4. Annual heat consumption in Tallinn DH network is approximately 1 700 GWh. It is also considered that there is a two-week restriction period during summer for each CHP plant when they stop working for maintenance.

Table 4. Heating units in Tallinn DH system [87]

Heating unit	Thermal power, MW	Fuel	Place on priority list (since 2021)	Heat rejection
Iru waste incineration	50	Municipal waste	1	No
Tallinn CHP 2	76	Biomass	2	Yes
Mustamäe CHP	48	Biomass	3	Yes
Tallinn CHP 1	67	Biomass	4	No
Natural gas boilers	827	Natural gas	5	No

In the study it is proposed to add the system TES and electric boiler and the research is determined to investigate their influence to the system. The influence of the TES and electric boiler also depends on their capacity which is also studied in the paper.

In the paper there are studied different sized TES's and also the capacity of electric boiler is investigated. As electric boiler is used for converting electric energy to thermal energy, then threshold electricity price which decides whether electricity is used for heat generation, or it is given to the grid.

In the study is focused on the following scenarios:

- Tallinn DH system without TES and power-to-heat – reference scenario
- Tallinn DH system with TES
  - 3000 m^3
  - 7000 m^3
  - 100 000 m^3
  - 150 000 m^3
- Tallinn DH system with enhanced electric boiler
  - 20–80 MW
- Tallinn DH system with TES (3000–150 000 m^3) and electric boiler (40 MW)

All these scenarios were also considered in case of LTDH, where annual heat production is reduced 14% due to smaller heat consumption and reduced heat losses.

For power-to-heat calculations the threshold electricity price is considered to be 30 EUR/MWh, but there are also included sensitivity analysis with threshold price range 20–40 EUR/MWh.

The results show that natural gas consumption is slightly lower when an electric boiler is also integrated into the system. The effect is less noticeable with a lower heat demand, as in the case of LTDH. An electric boiler is more effective without TES or with smaller TES, although natural gas consumption is lower when both an electric boiler and TES are used (Figure 3).

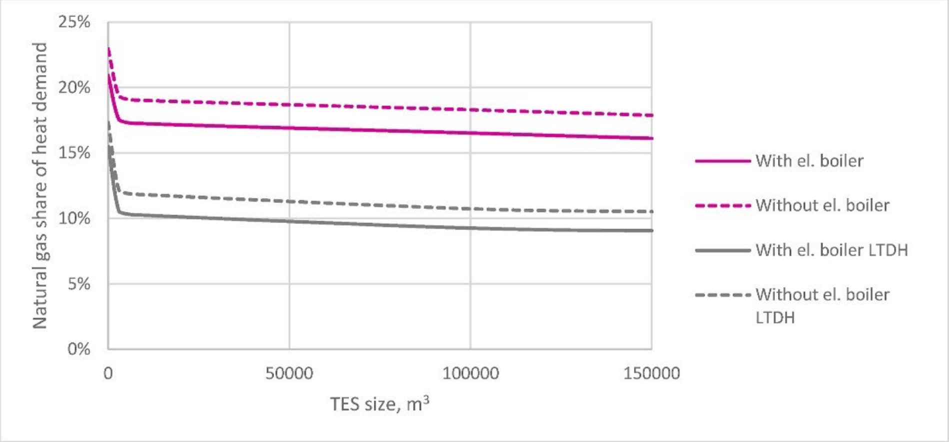


Figure 3. Natural gas consumption with and without el. boiler for various TES sizes [87]

When only TES is used, then natural gas consumption can be reduced up to 19% (for LTDH up to 34%). When also electric boiler is integrated to the system, natural gas consumption can be reduced up to 36% (for LTDH up to 52%). The results are shown in Table 5.

Table 5. Average decrease in natural gas consumption in the existing DH system and LTDH [87]

Scenario	Without TES	With 3000 m^3 TES	With 7000 m^3 TES	With 100 000 m^3 TES	With 150 000 m^3 TES
Without el. Boiler	0%	13%	14%	18%	19%
With 40 MW el. Boiler	9%	30%	31%	35%	36%
Without el. Boiler LTDH	0%	25%	27%	33%	34%
With 40 MW el. Boiler LTDH	12%	45%	46%	51%	52%

Using electric boiler and TES can also help to reduce heat rejection and therefore increase primary energy use efficiency. In Table 6 is given average heat rejection decrease for the examined scenarios.

Table 6. Average decrease in heat rejection [87]

Scenario	Without TES	With 3000 m^3 TES	With 7000 m^3 TES	With 100 000 m^3 TES	With 150 000 m^3 TES
Without el. Boiler	0%	13%	14%	23%	26%
With 40 MW el. Boiler	5%	30%	31%	37%	40%
Without el. Boiler LTDH	0%	11%	12%	19%	30%
With 40 MW el. Boiler LTDH	4%	27%	27%	34%	44%

Heat rejection reduction effect becomes more pronounced when using a combination of TES and an electric boiler. As is seen on Table 6, heat rejection can be reduced up to 26% (for LTDH 30%) without electric boiler and with electric boiler up to 40% (for LTDH 44%).

The relation between the electricity price threshold and the share of the total heat demand produced by electric and natural gas boilers is shown in Figure 4 as an average value for 2017–2019. The analysis presented in Figure 4 was conducted for a 40 MW electric boiler and a 7000 m^3 TES for the existing DH system and LTDH.

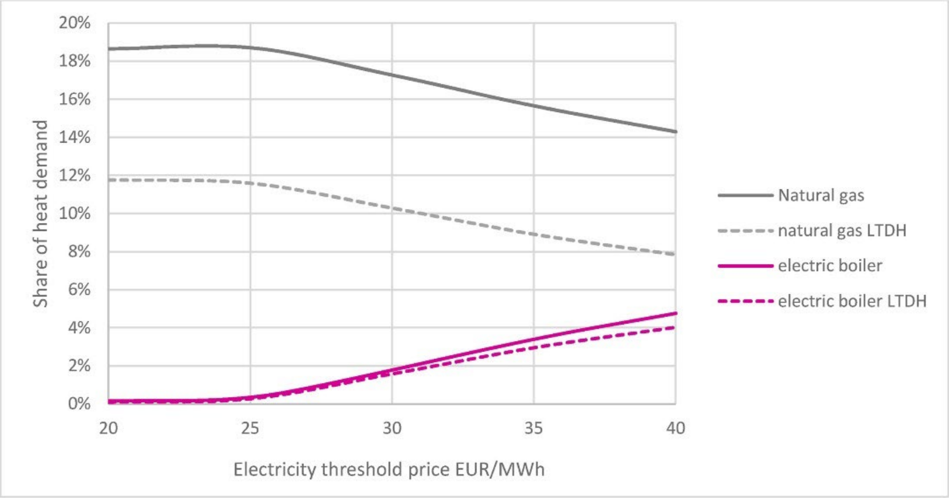


Figure 4. Share of heat demand covered by electric and natural gas boilers at different threshold prices in the case of a 40 MW electric boiler and 7000 m^3 TES [87]

As can be seen in Figure 4, the threshold price should be more than 25 EUR/MWh, otherwise the integration of power-to-heat technologies into the system would have practically no effect since the electric boiler will only be used for a few hours. The threshold also cannot be too high, because otherwise it would not be economically feasible, since heat generation from natural gas costs about 35 EUR/MWh, and when the electricity price threshold is higher than this, it is more economically feasible to produce heat from natural gas.

Electric boiler capacity also affects the system, as a bigger electric boiler allows more heat to be produced. Still, the limiting factor here is heat demand. If the demand is not enough, there is no point in installing a larger boiler, and the amount of energy supplied to the system will not be greater when there is just not enough demand.

The greater the share of the electric boiler, the lower the consumption of natural gas. The share of heat supplied to the system by an electric boiler and natural gas for various electric boiler capacities is shown in Figure 5 as an average value for the existing DH system and for low-temperature district heating (LTDH).

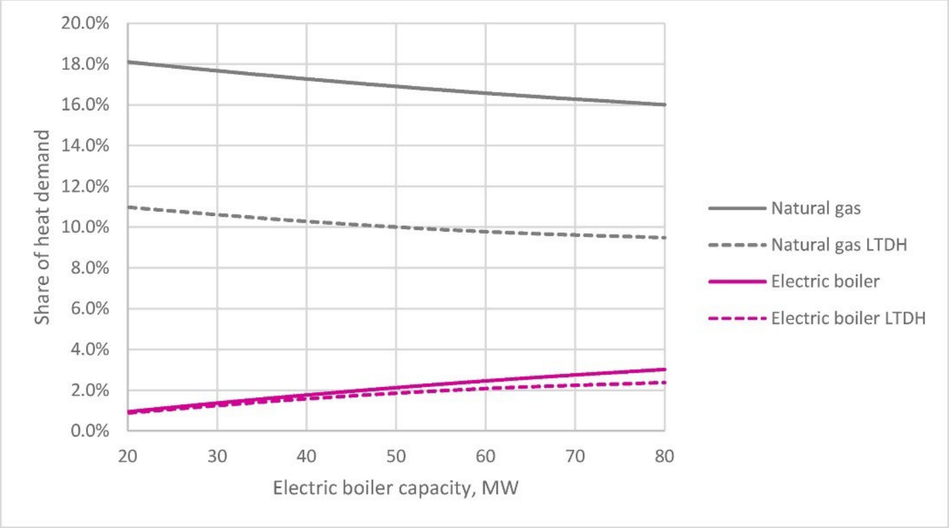


Figure 5. Share of heat supplied to the system by an electric boiler and natural gas for various electric boiler capacities (2017–2019 average) at 30 EUR/MWh electricity threshold price and 7000 m^3 *TES* [87]

According to this study, using power-to-heat together with TES will help improve CHP flexibility, since then the system will not depend as much on the heat demand. Even using a small electric boiler will increase the flexibility because it will provide additional heat to the system that can be stored and used later. In the case of Tallinn, the best power-to-heat solution is about 40 MW$_{th}$.

CHPs with no base load that have no heat rejection can operate more efficiently and produce more heat when they have the ability to produce heat for storage, but the use of an electric boiler will have a negative effect on the heat production of CHPs of the lowest priority.

As a result, using these technologies together will have a greater impact than using these technologies separately. Using power-to-heat together with TES is a good technical solution for heat demand peak shaving and scientifically reducing natural gas consumption. It can also help stabilise the system when power consumption is too low.

3.2 Article II: Effects of Coupling Combined Heat and Power Production with District Cooling

This article studies how to use CHP excess heat sufficiently for cooling production using Mustamäe CHP and Mustamäe district as a case study. The examined system and its boundaries are depicted in Figure 6.

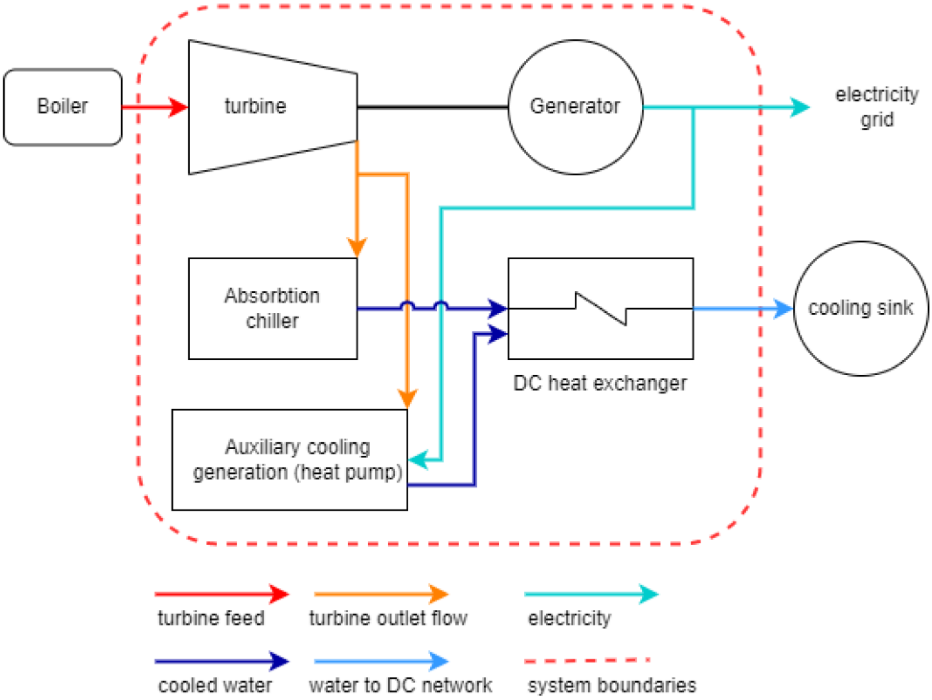


Figure 6. System boundaries [88]

As can be seen on Figure 6, the study concentrates on the generation of cooling by the absorption chiller and auxiliary cooling generation, which could be achieved, for example, by a HP, and the devices that either have effect on cooling generation or are affected by it. Within these boundaries are also the turbine that effects the absorption chiller and drives the generator. Within the boundaries there is also DC heat exchanger, which is connected to cooling sink, that is the DC network.

In this study, the effects of coupling DC with CHP plants on electricity production are examined via the technical processes that take place in absorption chillers. Absorption chillers require a heat flow to initiate processes that ultimately create a cooling effect. When DC and a CHP system are connected, this heat flow comes from the CHP turbine condenser. The heat flow is necessary for the desorption process to separate the strong lithium–bromide (LiBr) solution from the water prior to the absorption process that creates the cooling effect.

For the study a calculation model for cooling generation capacity and driving hot water (turbine outlet) relation was constructed. According to the results, the higher the specific enthalpy and temperature of the flow is, the more intense the cooling production process is (Figure 7).

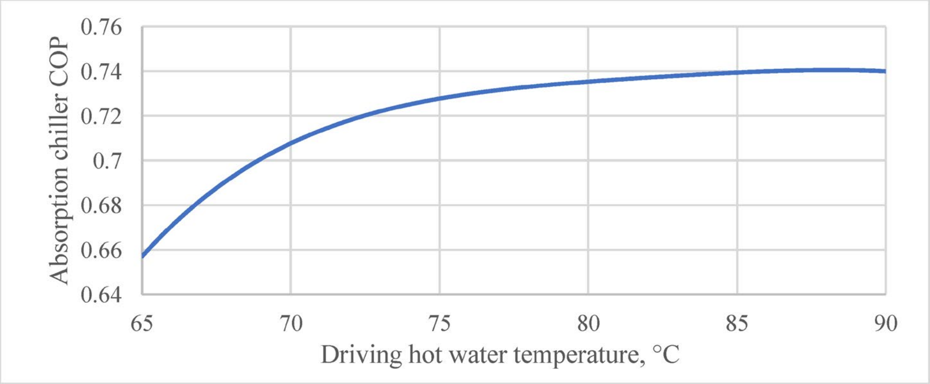


Figure 7. Absorption chiller COP at driving hot water temperatures ranging between 65 and 90 °C [88]

On the other hand, turbine outlet flow is also relevant for power generation. When turbine outlet temperature is higher, then less electricity can be generated. This means that if absorption chiller is used for cooling generation, then power production will be used. If turbine outlet will be low, then cooling generation will not be efficient.

To investigate the influence of DC on power generation Mustamäe DC demand and Mustamäe CHP were used as a case study. Potential consumers in the area were selected and the approximate cooling demand was estimated to be 5700 MWh with the highest load for 12.4 MW.

According to Mustamäe CHP parameters, the capacity of the absorption chiller can be about 0.8 MW. This means that when absorption chiller is used, then it should work full-load throughout the cooling season. On Figure 8 is shown Mustamäe DC demand and the load that can be covered by absorption chiller.

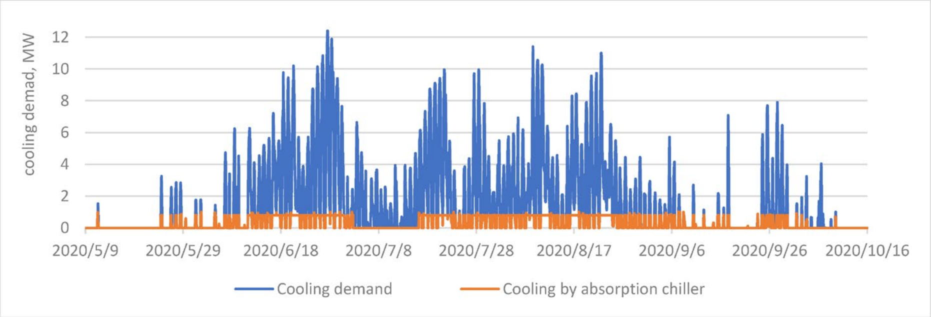


Figure 8. Tallinn University of Technology and Tehnopol Science Park cooling needs, and the cooling produced by the absorption chiller [88]

Figure 8 show that the system definitely needs auxiliary cooling generation units. In the article the following technology combinations for cooling production are proposed:

1. 12.4 MW HPs
2. 11.6 MW HPs and 0.8 MW absorption chiller

There are also discussed combinations with cooling towers but because of higher annual costs these solutions were neglected.

According to the Mustamäe DC demand, the absorption chiller would operate for 1530 hours per year and for about 1260 hours it would operate at full load. The calculations show that the absorption chiller could provide 1104 MWh of cooling which is 19.3% of total cooling demand.

According to the absorption chiller processes and the proposed absorption chiller capacity, the power produced and the cooling capacity for the driving hot water temperatures between 63 and 98 °C are shown in Figure 9.

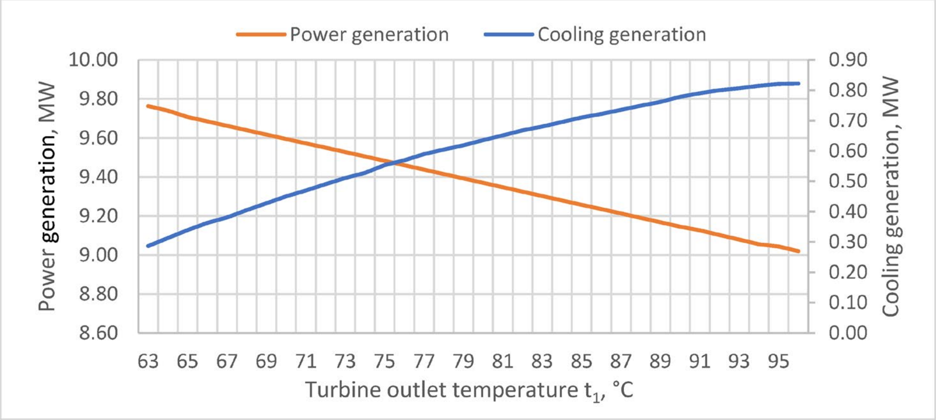


Figure 9. Mustamäe CHP plant power generation and absorption chiller cooling generation at driving hot water temperatures ranging between 63 and 98°C [88]

As shown in Figure 9, when the absorption chiller is operating at full load, i.e., 0.8 MW, then the turbine's electrical power will be 9.14 MW, which means that using the absorption chiller at full load will reduce the turbine's power generation by 6.3%. If the turbine is operated at maximum load and the chiller is using 70 °C driving hot water, then the absorption chiller will only be able to operate at a capacity of 0.45 MW, with a 45% reduction in capacity.

To select the most efficient cooling production for the district primary energy factors (PEF) were used for calculations. For absorption chiller the PEF would be 0.7, for local coolers and HPs, their PEF can be derived from PEF of electricity and their COP.

For local coolers COP is assumed to be 3 and for HPs it is estimated to be 4. For electricity PEF is 2. Accordingly the primary energy consumption (PEC) was calculated and results for annual PEC are given in Table 7 for each technical combination.

Table 7. Primary energy consumption (PEC) for technical solutions proposed [88]

Technical solution	Primary energy consumption, MWh
12.4 MW local cooling (air conditioners)	3808
12.4 MW HPs	2857
0.8 MW absorption chiller and 11.6 MW HPs	3077

If all cooling demands were covered by HPs, the annual PEC would then be 2857 MWh, which would be even lower than using an absorption chiller with HPs; this would be a PEC of 25% less than local cooling and a PEC of 7% less than using an absorption chiller with HP.

As a conclusion it can be said that for cooling generation for a DC network, HPs would result with the best PEC, as is shown in Table 7. Nevertheless, HPs can be used only in a district where are also low-grade energy sources or industrial heat sources available, which, in case of this study, is a CHP plant. The aim of this study was to find a good solution for cooling generation for a DC network that is located near a CHP plant. Another aim of the study was to find a good way to utilise the CHP plant's excess heat that is normally rejected by chillers, which is not an efficient use of energy. As an option that could do both – produce cooling and utilise excess heat – an absorption chiller is examined. In this study, the operation of an absorption chiller is thoroughly analysed, and the results show that when absorption chillers are used, power generation would decrease by 6.3%. As absorption chillers cannot cover the whole cooling load of the district, HPs should also be used. HPs could be used for cooling generation without absorption chiller; however, in this case, the excess heat of the CHP plant would not be completely utilised. Both proposed solutions would result in a smaller PEC than local cooling and would have approximately the same installation and operation and maintenance costs.

3.3 Article III: The effect of the District Heating Return Temperature Reduction on Flue Gas Condenser Efficiency

This article studies the effect of DH return temperature to FGC efficiency. FGC is a widely used device in most boiler houses and CHP plants that use woodchips for fuel, in some cases it is also used in natural gas boiler houses.

Transition to 4th generation district heating (4GDH) and LTDH is a long process and it requires that both building stock and DH network would meet the high energy efficiency standards, which means extensional refurbishment of the buildings, installing new pre-insulated DH pipes and optimising the heating substations. As a result, the temperature level in DH network can be lowered which would lead to lower heat losses and possibility to use large variety of low temperature renewable heat sources. Lowering the DH temperature level has also good effect on heat production efficiency through FGC that uses DH return water to recover heat from flue gases.

The article is focused on the heat and mass transfer processes in the FGC to demonstrate and explain the DH return temperature effect on the FCG and overall boiler efficiency.

Heat recovery from in the FGC comes from latent heat, that comes from condensation of the moisture in the flue gases, and sensible heat, that comes from cooling of non-condensing gases. Major effect of heat recovery is caused by latent heat which is more effected by the return temperature.

The amount of latent heat depends on flue gas moisture content and environment temperature, which in case of FGC is DH return temperature. The more moisture there is in the flue gases, the more moisture can be condensed, the more moisture is condensed in the FGC, the bigger the heat recovery is. The amount of condensed moisture is determined by the dew point of the environment. Dew point shows the maximum amount of water that can be in gaseous state in gas mix, when temperature is higher, more moisture is in gaseous state and will not be condensed. Lowering DH return temperature will also lower temperature in FGC and also the dew point which will allow more moisture to be condensed and therefore recover more heat.

The amount of sensible heat that comes from cooling of non-condensing gases in gas mix, such as oxygen, nitrogen, carbon dioxide and noble gases. The lower the temperature in FGC is, the more non-condensing gases can be cooled and the more heat can be recovered. Normally, the amount of heat recovery from sensible heat is about 30% of total heat recovery from flue gases.

To validate the model, the results were compared with real measurements obtained at the Mustamäe CHP Plant. The following indicators were calculated: heat recovery, FGC efficiency and primary energy savings. To compare the results obtained using the developed methodology and operational data, the following parameters were also measured: heat recovery, flue gas supply and return temperature, fuel moisture content, overall thermal power of the plant and DH return temperature. The average relative difference between the measured and calculated results is 4.3%.

The FGC recovered heat is used to pre-heat water, therefore it is added to the boiler heat output to determine the plant’s overall thermal power. Since the FGC recovered heat depends on the return temperature, the overall thermal efficiency of the plant is also related to the DH return temperature. The DH return temperature also affects efficiency of the FGC. This can be explained by the FGC’s heat exchanger properties: like a heat exchanger, FGC also has a certain heat capacity which is determined by heat transfer area and other constructional properties (flat or cylinder surfaces, surface thickness, materials, etc.). This leads to the conclusion that when the condensation heat reaches the FGC’s design capacity, lowering the DH return temperature will not increase the amount of recovered heat. The correlation between the FGC efficiency and the DH return temperature is illustrated in Figure 10.

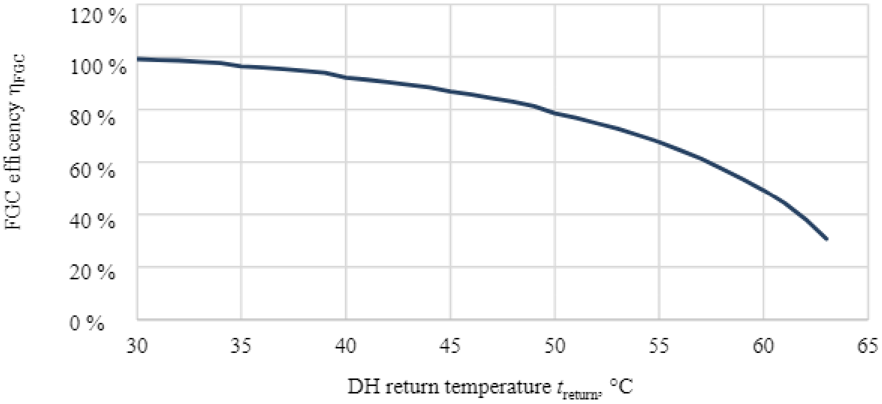


Figure 10. FGC efficiency at different DH return temperatures [89]

As a result of the study can be said that DH producers will benefit directly from an increase in the FGC efficiency, when DH return temperature is lower. Since fuel costs can be reduced as a result, this can have a positive effect on the price of DH, since lowering the return temperature affects the amount of FGC-recovered heat.

3.4 Article IV: Efficient use of heat from CHP distributed by district heating system in district cooling networks

This study investigates an applied approach to DC development in Tallinn's Ülemiste City. The parameters of the cooling medium in all Estonian networks are currently the same for the supply/return pipeline: 6/16 °C, pressure 16/10 bar. In the future, it is planned to increase the temperature of the cooling medium to improve the efficiency of the entire system and reduce harmful emissions. The main source of cooling for the DC network is an absorption chiller that uses rejected heat from a CHP 7 kilometres away from the DC plant.

The current DH supply temperature in Tallinn during the non-heating season is 70 °C. To determine the optimal technical solution for an effective energy efficiency ratio (EER) of the absorption chiller and heat transmission in the DH network, various scenarios were evaluated where the DH supply temperature was 70 °C, 80 °C, and 90 °C. The aim of this study is to evaluate DC supply options that take advantage of the excess heat generated by biomass CHPs during the summer and transfer the heat to an absorption chiller via the DH network. The main objective of this study is to find the optimal technical solution for the EER of the absorption chiller and heat transfer loss in the DH network by comparing scenarios with different average DH supply temperatures. The DC supply options were also compared with a power-based central cooling solution with free cooling and electric chillers.

Three scenarios were compared, each using an absorption chiller that is supplied with rejected heat from a CHP located 7 kilometres away from the DC plant. The current DH supply temperature in Tallinn during the non-heating season is 70 °C. It was investigated what effect an increase in the DH supply temperature during this period had on the EER of the absorption chiller and how such an increase in temperature affected the DH network losses and CHP efficiency. Thus, three scenarios were evaluated to determine the optimal technical solution for an effective EER of the absorption chiller and heat transmission in the DH network for DH supply temperatures of 70 °C, 80 °C, and 90 °C. The three scenarios were then compared with a reference scenario based only on electric cooling plants supplying DC using free cooling and electric chillers. The average annual cooling load is 1.85 MW, and the average cooling load in summer is 4.35 MW. Figure 11 depicts Ülemiste City cooling demand throughout the year.

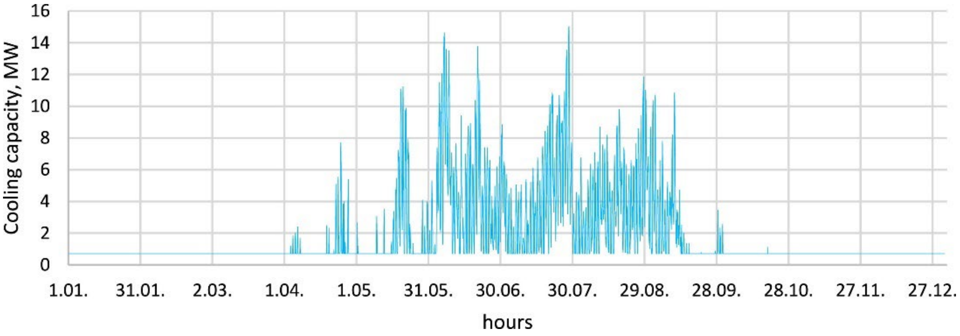


Figure 11. Ülemiste City cooling load profile [90]

The full capacity of free cooling is 0.71 MW and it can be used when outside temperature is below 5 °C. Also, it is not possible to use free cooler when outside temperature is above 15 °C. The capacity of the free cooler decreases linearly based on the outside temperature when the outside temperature is between 5–15 °C, while 100% capacity is at 5 °C and 0% is at 15 °C.

When free cooling cannot be used, then absorption chillers are used with rejected heat from CHPs as input heat. This helps to achieve a higher EER and utilise excess heat generated by biomass CHPs. Absorption chillers are used for base and intermediate loads in summer, while electric chillers are used for peak loads. An additional option would be to install a HP that will utilise excess heat from cooling and supply heat to the DH network in spring and autumn when the DH heat demand is sufficient. But this option was not considered in this study.

One of the options for absorption chillers is to use surplus heat from CHPs to supply cooling, which will also increase the overall efficiency of the CHP. In our case, the excess heat is from the biomass-based Tallinn CHP 2. This CHP plant was introduced to cover the semi-base load and provide heat mainly in winter, spring, and autumn.

Absorption chillers require a hot water inlet temperature of 90 °C, but the DH supply temperature in summer is usually only 70 °C. A supply temperature of 90 °C and a return temperature of 68 °C ensure maximum chiller capacity. At maximum temperature, its cooling capacity is 2863 kW, and at an inlet temperature of 70 °C from the DH network, it has a cooling capacity of 1500 kW. This is a 48% loss in cooling capacity.

The excess heat will be transferred to the cooling plant from the biomass CHP via Tallinn’s DH network. Since this CHP is the only one operating in summer and there are no heat exchangers between sections of the DH network, an increase in the DH supply temperature for DC will lead to an increase in the DH supply temperature in the entire DH network. Therefore, additional heat loss must be assessed in the technical analysis.

It is not possible to increase the DH supply temperature for only one section of the DH network. The temperature will increase in the entire system, resulting in a significant increase in heat loss. However, this additional heat would anyway be rejected into the atmosphere due to the specific structure of tariff support for biomass CHPs. In this case, no additional fuel will be consumed regardless of the supply temperature. As explained earlier, using heat to generate cooling will increase system performance efficiency. Without cooling integration, the energy efficiency will be 33.29%. When absorption chillers would be used, then heat loss would be 37.5, 42.2 or 46.8 MWh, regarding the driving hot water temperature, which would be 70, 80 or 90 °C, respectively. This means that increasing driving hot water temperature to 90 °C would increase heat loss 9269 MWh. That would decrease flow rate in the DH network and therefore also decrease electricity use for pumping.

The seasonal EER increases at higher DH supply temperatures and compared to the electricity-only DC supply, it has a better EER for higher hot water inlet temperatures to the absorption chiller, and the EER of the absorption chiller in summer is higher than the EER of the electric chiller at high outside air temperatures. The proportion of cooling provided by the absorption chiller is higher in the case of an increased DH supply temperature due to the higher capacity of the absorption chiller. The proportion of the cooling supplied by the electrical chiller decreases accordingly (Table 8).

Table 8. Technical DC parameters for three temperature scenarios and DC supply via electric chiller and free cooling [90]

Parameter	Chiller + free cooling	70 °C scenario	80 °C scenario	90 °C scenario
Electricity consumption, MWh	1869	1831	1653	1365
CO_2 from electricity, tonnes CO_2	1665	1631	1473	1216
Seasonal EER of cooling	8.48	8.55	9.48	11.47
Share of free cooling, %	24.7	24.7	24.7	24.7
Share of cooling via absorption chiller, %	-	26.8	32.8	43.0
Share of cooling via electric chiller, %	75.3	48.5	42.4	32.3

Using excess heat to supply DC via absorption chillers is a promising option because the demand for cooling is high in summer and the demand for heat is low. Due to the current legislation, large amounts of surplus heat are not used in Estonia. If the CHP is located within long distance from the DC plant and there is no separate direct line between the CHP and the cooling plant, additional heat loss must be considered for the entire DH network. On the other hand, this heat is currently rejected to the ambient air, so no additional fuel is used to generate it.

Absorption chillers perform better when the temperature of the heating carrier is 90 °C compared to lower temperature scenarios. In this case, the EER as well as the cooling capacity of the absorption chiller are higher. The use of absorption chillers results in lower electricity consumption. The higher the DH supply temperature, the larger the share of cooling supplied by the absorption chiller. Reducing electricity consumption is particularly important from an environmental point of view in Estonia, as the current CO_2 emissions from electricity generation are very high.

3.5 Article V: GIS-based approach to identifying potential heat sources for heat pumps and chillers providing district heating and cooling

This article focuses on mapping possible industrial and natural heat sources and their characteristics using geographical information system (GIS). The aim of the study was to perform a geospatial analysis and to develop a GIS map with the focus on providing detailed information about available sources that can be used particularly for large-scale HPs or chillers. Thereby, the potential of implementing large-scale HPs and chillers for DH and DC can be identified and barriers be lowered, if geospatial analysis based on advanced GIS software is used to provide detailed information and an overview of suitable locations of heat sources and sinks near DH and DC regions.

The methodology of the study was to locate the possible high- and low-temperature heat sources for large-scale HP and chillers in the Baltics states and visualise DH areas. Heat source potential was calculated based on the data gathered and the proximity to established DH areas. Industrial excess heat and flue gas from heat generation plants can be used as high-temperature heat sources to supply DH via HPs. Industrial excess heat is heat discharged into the atmosphere as a result of an industrial process. The exhaust gas that is discharged into the atmosphere because of the combustion process (e.g., at a DH plant) is flue gas. A heat exchanger and extra pipes can be used to deliver excess heat beyond the supply temperature of DH (for example, 90 °C) straight into the DH network. Excess heat below the DH supply temperature necessitates the use of an electric boiler or HP in order to get the excess heat temperature up to the DH supply temperature. In the study was considered the following high-temperature heat sources: boilers, CHP plants (flue gas), and industrial processes like wood, dairy, cement, and food processing (industrial excess heat).

Low-temperature heat sources were only considered in the case of utilising HPs to provide DH when the temperature of the heat source is near the ambient temperature. These sources are mostly based on natural sources. Seawater, lake and river water, and treated sewage water from cleaning facilities were among the considered low-temperature heat sources. The low-temperature heat sources mentioned above can also be utilised as heat sinks to discharge excess heat from DC consumers.

Data for the map about DH regions was obtained from national and regional heat development management plans and other local and national documents, for heat demand density information, also data from Hotmaps project was used. Data about heat sources was collected from various sources, both public national and private sources.

As a result, an interactive GIS map including data about Estonia, Latvia and Lithuania was created and published (Figure 12).

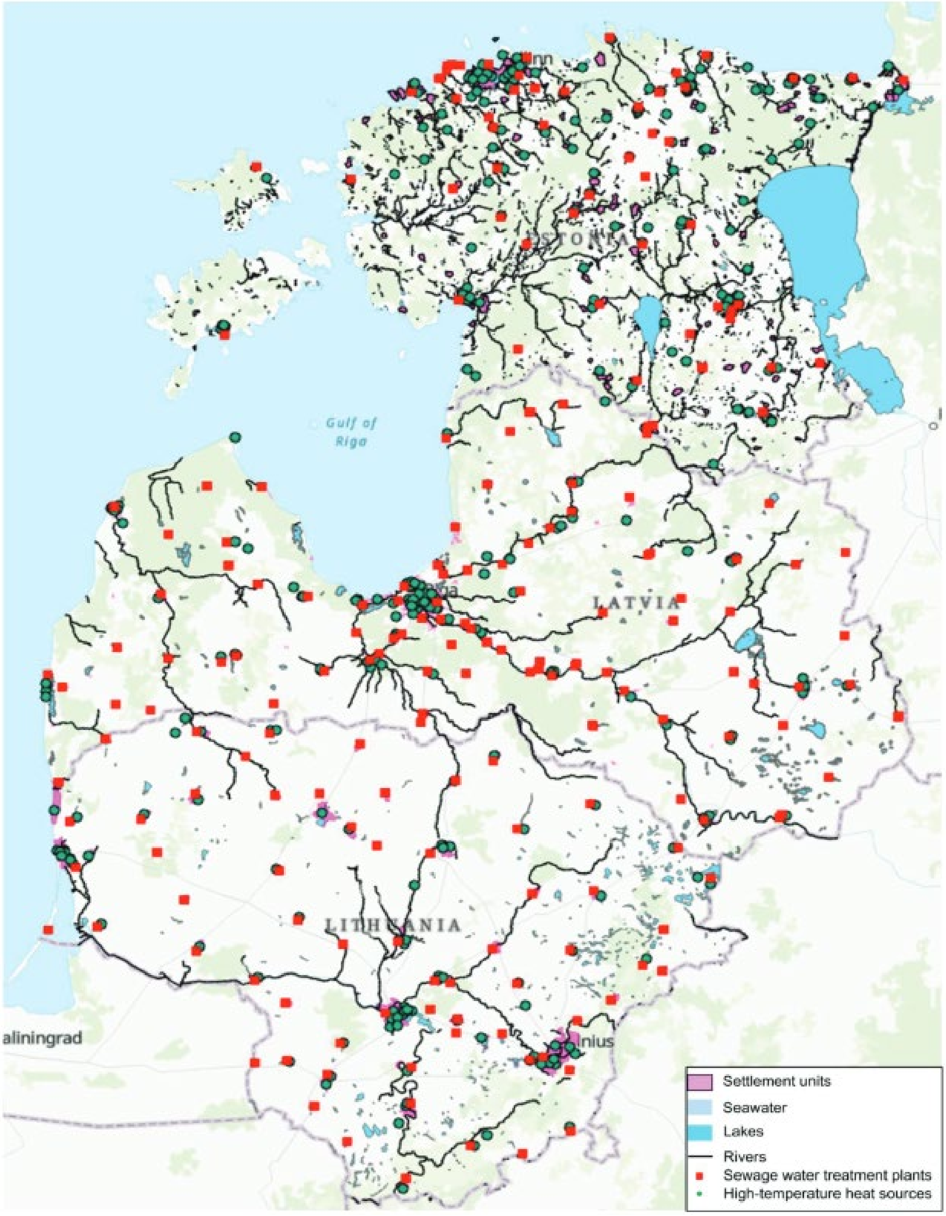


Figure 12. Interactive GIS-map about potential waste heat sources in Estonia, Latvia and Lithuania [91]

Many of the high-temperature heat sources are localised inside or near DH regions. Sewage water treatment plants are spread all over the Baltics. Most cities are situated near rivers, and a few are by the sea, especially in Estonia.

As can be seen, the DH regions have many industrial excess heat sources within their boundaries. However, a considerable portion, is concentrated in rural areas. The majority of boilers and CHPs are found in DH areas, which makes sense given that they supply DH. A separate evaluation should be carried out if any heat sources are further considered. Practical excess heat potential in the Baltic States is given in Table 9.

Table 9. Practical excess heat potential of each country [91]

Practical excess heat potential	Distance (km)	Estonia		Latvia		Lithuania	
		Number of sources	GWh	Number of sources	GWh	Number of sources	GWh
Industrial excess heat (direct supply and HPs)	0	44	2601	21	394	21	436
	<1	18	322	4	110	1	1730
CHPs and boilers (flue gas HPs)	0	46	445	54	901	63	413
	<1	1	66	1	5	1	0

For low-temperature heat sources, temperature level is an important criterion. Sewage water retains higher temperatures throughout the colder months when the heat demand is typically higher. Lake, river, and seawater temperatures are close to the freezing point in January and February. As a result, extracting extra heat from these sources during times of high demand of heat can be particularly difficult. Lakes, rivers, and the sea should be accessed from below the surface (≈10m), if possible, to prevent freezing. Other relevant criteria include distance to DH, available capacity, special equipment and investments, which may differ from heat source to heat source. Table 10 provides an overview on which DH regions contain low-temperature heat sources or are within 1 km of them. As can be seen, most DH regions with access to seawater are in Estonia, followed by nine in Latvia, and the city of Klaipėda, Klaipėda county, and the town of Palanga in Lithuania. Sewage water treatment plants are typically found in all major cities, although they are sometimes located outside of city limits. As a result, many DH regions have a sewage water treatment plant in the region or within 1 km. Many DH regions with river access are in Estonia and Latvia, along with quite a few in Lithuania. Most DH regions with access to large lakes are in Lithuania, while a few are in Estonia and Latvia.

Table 10. Potential of low-temperature heat sources in the Baltic States [91]

Heat source potential	Distance (km)	Number of sources in Estonia	Number of sources in Latvia	Number of sources in Lithuania
DH areas with access to seawater	0	18	9	3
	<1	4	0	0
DH areas with access to sewage water treatment plants	0	33	41	23
	<1	11	28	10
DH areas with access to large rivers	0	79	40	18
	<1	25	17	3
DH areas with access to large lakes	0	11	11	16
	<1	8	10	7

As shown, existing GIS datasets can be used for a variety of purposes, including DH area visualisation. The limitations and uncertainties in describing the desired regions should be considered for future analysis. It has been shown that settlement units can represent densely populated areas; however, the unit itself is often a very large region in a rural area. To limit the biomass use and competition with other sectors for this resource, HPs, wind, hydropower and solar (PV, thermal) could be used more in the future to balance the sustainable usage of resources.

Over 350 high-temperature heat sources have been identified and their excess heat potential has been quantified. It was found that the industrial excess heat potential is 3370 GWh in Estonia, 1199 GWh in Latvia and 2490 GWh in Lithuania. From these quantities, 2601 GWh, 394 GWh and 436 GWh are located within existing DH areas in Estonia, Latvia and Lithuania, respectively. In addition, seawater, rivers, lakes, and sewage water treatment plants were considered as potential heat sources and sinks. It was found that sewage water treatment plants are located in the most major cities and that most cities, in particular in Estonia and Latvia, have access to either seawater or rivers, which all can serve as a suitable heat source for large-scale HPs.

3.6 Article VI: 5th generation district heating and cooling (5GDHC) implementation potential in urban areas with existing district heating systems

In this paper 5GDHC implementation in urban areas with existing DH systems is investigated. 5GDHC as a concept is rather new and its implementation needs further discussion and analysis before actual projects and realisations.

The 5GDHC network is the latest DH and cooling concept, which is characterised by low temperature supply, bi-directional operation, which means that it can provide heating and cooling simultaneously, decentralised energy flows that allow multiple heat sources and heat sinks in the network, and heat sharing, which means that it can recover waste heat and share it with different users. Unlike the 4GDH technology, the 5GDHC technology is geared towards the consumer/prosumer. It only needs one thermal grid, but it serves multiple purposes for both heating and cooling distribution, including heat and cold storage, and thus provides flexibility in adopting local renewable energy and waste heat resources. By integrating the low-grade heat with photo voltaic arrays, batteries, and vehicle-to-grid applications, 5GDHC systems also support the electrification of both the building and transportation sectors towards the broader concept of ’fifth generation smart energy networks’.

This paper is mainly focused on implementation of 5GDHC in the Baltic States and therefore there are identified the main barriers and drivers regarding the situation in the Baltic States. The current situation was assessed and the main barriers to implementation were identified. Based on the 5GDHC definition, the following factors were analysed: stakeholders (DH operators and producers), regulatory mechanisms and DH tariffs, existing DH infrastructure, building stock, pilots, energy policy, and strategic DH energy goals. The main difference between DH stakeholders is ownership. In Estonia, DH operators are mostly private companies, while in Latvia DH operators are mostly municipalities, but private companies also own some systems. There are both private and public DH operators in Lithuania. Both private and municipal ownership are viable options for 5GDHC. Existing case studies show that private companies are more interested in developing the 5GDHC technology in parallel with 4GDH.

All Baltic countries have DH price regulators. The main difference between the three countries is the market situation. In Estonia and Latvia, the DH monopoly exists, while heat production in Lithuania is based on heat producers competition. For 5GDHC, strict regulation of DH may be a major disadvantage due to the inability to make a profit and pay banks for the investment necessary for a new low-temperature network.

The DH infrastructure in the Baltic states is well-developed and widespread in many cities and towns. High-temperature DH is currently just in its third generation, but the heat generation sources are mostly renewable. The main barrier to 5GDHC is the existing well-developed and widespread 3rd generation DH infrastructure in all three Baltic countries. As a result, 5GDHC development can be carried out primarily in newly built areas, in addition to the existing DH network. 5GDHC ultra-low temperature regime requires high energy efficiency in buildings. A large proportion of old buildings that consume large amounts of thermal energy are not suitable for 5GDHC implementation, which also refers to the fact that at the moment 5GDHC can be implemented only in newly built and developed areas.

The strategic DH goals of the Baltic states are ambitious in terms of the use of RES. 5GDHC is not mentioned in any of the Baltic countries’ strategic documents. In the DH sector, development is focused on renewable energy, primarily biomass. However, 5GDHC may have important infrastructure that can integrate different types of renewable energy technologies, especially in areas with new high-energy-efficiency buildings. The main aspect that distinguishes 5GDHC from 4GDH is the dependence on the electricity system. A new pipe system for the ultra-low temperature DH system, as well as a dedicated new infrastructure that incorporates both heating and cooling and RES, demand substantial initial expenses. The country's ambitious energy and climate change targets can be major drivers. Other drivers include the possibility of recycling low-temperature waste heat not only from industry but also from other local sources, as well as the development of local economic value and the creation of jobs.

The possibility for 5GDHC introduction in the Baltic states was assessed using a multi-criteria analysis. A qualitative comparison was made by discussing the barriers and drivers that each country faces, and a quantitative comparison was made by assigning numerical values to each criterion. The quantitative analysis was performed using a multi-criteria decision method to compare various aspects of a potential 5GDHC implementation. The result of the quantitative analysis is the ranking of the country for each aspect. The obtained criteria values were evaluated using the method of multi-criteria analysis called the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) and the Analytic Hierarchy Process (AHP) method to determine the weight of each criterion. The overview of the criteria and their weights is given in Table 11, where are also given the summary of criteria results for the Baltic States.

Table 11. Overview of the used criteria and their weights and summary of criteria results for Estonia, Latvia and Lithuania [92]

Criterion	Unit	Criterion weight	Estonia	Latvia	Lithuania
Average final price of electricity	EUR/MWh	0.10	0.12	0.14	0.14
Share of RES energy	%	0.082	22.0	53.42	18.79
Share of heat supplied via HPs	Unit per 1000 households	0.038	29.30	1.0	9.0
CO_2 emission factor for electricity	t CO_2/MWh	0.082	0.89	0.12	0.02
Future CO_2 emission factor for electricity	t CO_2/MWh	0.082	0.22	0.08	0.06
Maximum heat tariff	EUR/MWh	0.023	86.96	69.98	79.63
Minimum heat tariff	EUR/MWh	0.023	35.33	35.45	32.57
DH tax rates	%	0.018	20	21	9
Available support measures for possible 5GDHC implementation	Evaluation scale	0.126	1	2	2
Possibility to implement innovative business models	Evaluation scale	0.132	1	1	2
Specific building heat consumption	kWh/m2	0.032	142.8	159.7	131.3
Share of new buildings	%	0.056	2	5	6
Excess heat source potential from shopping malls	MWh	0.071	16%	10%	13%
Excess heat source potential transformers	MWh	0.071	1%	3%	1%
Excess heat source potential from data centres	MWh	0.065	2%	1%	0%

The final comparison between the Baltic countries was performed by multiplying the weight of the criterion by the corresponding normalised criterion value. The relative proximity of the alternative to the ideal solution is calculated by determining which country has the most potential to introduce 5GDHC systems.

The values of the identified criteria from Table 11 were normalised and weighted to determine the proximity to the ideal solution for each country. The results in Figure 13 show different values for similar and prioritised criteria values. When the identified criteria are prioritised by assigning higher weight values for the possibility of introducing an innovative business model and available support for technology implementation, followed by criteria describing the existing situation in each country's energy sector, Lithuania has the highest score due to support availability and open heating market conditions. However, when equal criteria weights are assigned, the highest evaluation rank belongs to Estonia due to the wider use of HPs and higher excess heat potential.

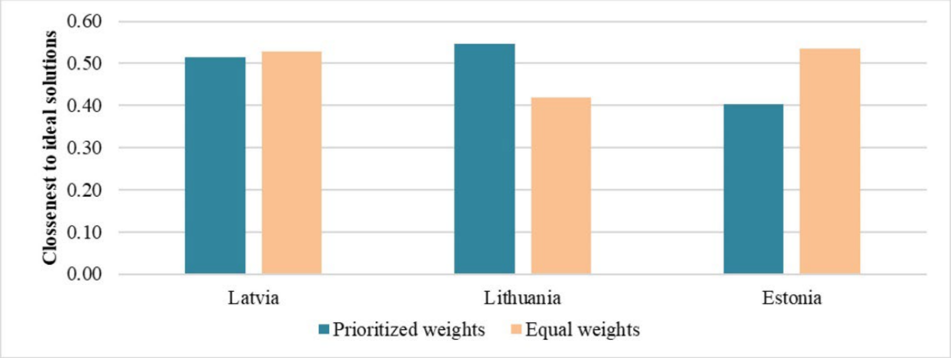


Figure 13. Results of multi-criteria assessment with prioritised criteria weights and equal criteria weights [92]

As a result of the study can be concluded that the main barrier to the development of 5GDHC in the Baltic countries is the well-maintained and widespread 3rd generation DH in all three countries. Another major hurdle is the high initial costs of the new 5GDHC pipeline system for ultra-low heating and cooling temperatures and RES. The main drivers for the development of 5GDHC in the Baltic countries are the countries' ambitious energy and climate change goals. Furthermore, the possibility of recycling low-temperature waste heat not only from industry but also from other local sources, as well as the development of local economic value and jobs are among the drivers. Although Latvia, Lithuania, and Estonia have similar conditions, there are some differences. For example, different fuel mixes are used for power generation; stricter heating market regulations exist in Latvia and Estonia; and Estonia has more experience with HPs use, while there are almost no installed HPs in Latvia. The highest score in the multi-criteria assessment was achieved by Lithuania due to support availability and open heating market conditions. When all applied criteria are weighted equally, Estonia has the most favourable conditions for 5GDHC systems due to widespread use of HPs and greater excess heat potential.

It should be emphasised that 5GDHC is a niche solution and, according to experts, will not replace 4GDH in the future, but in certain cases it may become the most effective technical solution for heat supply. Theoretical excess heat potential from 5GDHC agents was calculated, and the results indicated that the proportion of excess heat obtained would only make up a small portion of the DH supply (15% for Latvia, 14% for Lithuania, and 19% for Estonia). Even though the actual potential for excess heat from 5GDHC agents is even lower, this technical solution may be implemented in certain areas in the future.

3.7 Article VII: Heat Pump Use in Rural District Heating Networks in Estonia

This article is focused on studying the possibilities and effects of using HPs in Estonian rural areas to supply heat to DH network.

This study was designed to assess the impact of HP use in rural DH networks in Estonia on DH consumer prices. HPs can be a good solution for rural areas, as there is usually plenty of land available for HP facilities. In addition, HPs require low-grade heat sources such as ambient air, groundwater, lakes, rivers, sea, sewage water, and industrial waste heat.

There are some positive examples in Estonia where HPs are used successfully in DH. The use of HPs in DH also has a positive effect on air quality since HPs do not require combustion to generate heat and therefore no fine particles or acid-oxides (NO_x and SO_x) are emitted. Biomass boilers are widely used because they are considered CO_2-neutral and because biomass is widely available in Estonia. However, the downside to using biomass is that it can be a source of air pollution.

There are about 230 DH networks in Estonia, and 95% of them use woodchips as their primary fuel, while shale oil or natural gas is used to cover peak loads. In other DH networks, the main fuel is natural gas or shale oil. Most biomass boilers were installed after 2014 with the support of the European Cohesion Fund. As the EU’s goal is to become climate neutral by 2050, all fossil fuel-fired boilers must be replaced with RES, which means that it is necessary to find a sustainable solution to cover peak loads. Replacing old biomass boilers with HPs is a solution that should be discussed.

As price is the most important factor for the consumers, then in this article consumer price is one of the factors that is investigated when considering different HP DH scenarios. When DH is produced using HPs, the price of heat is directly related to the price of electricity. This study provides a thorough analysis of how the use of HPs in rural DH networks will affect the consumer price of DH and, as a result, it will determine the areas where the use of HPs for DH can be cost-effective and have a positive impact on the DH consumer price. At the same time, suitable HP capacities are estimated for DH networks of different sizes, resulting in two types of solutions: those that use HPs for covering only peaks and troughs and fully HP-based solutions.

Since this study is focused on rural areas, only DH networks with an annual consumption of less than 16 GWh are considered. There are about 140 DH networks in Estonia that meet this criterion. This limit was chosen because all DH regions with an annual heat consumption below it can be considered a rural area in Estonia. The average population in these areas is anywhere from 165 to 5000 residents, and the number of DH consumers ranges from 3 to 70. In this study, all these networks are divided into seven groups according to annual consumption. The criterion for division was to maintain minimum fluctuations in annual heat consumption within a group. The main characteristics of these groups are presented in Table 12. Annual consumption figures are given for a ‘normalised’ year. The input data in Table 12 is taken from the heat management and development plans of the DH networks considered.

Table 12. Main characters of DH groups [93]

Group no.	Average annual heat consumption, MWh/year	Average number of consumers in the DH network	Average DH price, EUR/MWh	Average DH supply temperature, °C	Number of such DH networks in Estonia
1	681	3	70.3	80	23
2	1914	6	67.4	80	58
3	3956	15	64.5	80	24
4	6235	25	61.7	85	8
5	7812	37	56.7	90	8
6	10 393	52	64.4	100	9
7	14 192	70	57.1	110	5

For all network groups, annual heat demand profiles have been generated using EnergyPro software, based on the annual heat demand, DH network temperatures and ambient temperatures. Base and peak loads that are important for estimating the required HP thermal capacity were determined using the generated heat demand profiles. Since the average ambient temperature for continental Estonia has been chosen (islands are excluded due to the milder climate), the shape of the heat demand profile is thus the same for all groups, and the groups with higher annual consumption lead to higher base and peak loads. Heat demand profiles for all groups are shown in Figure 14.

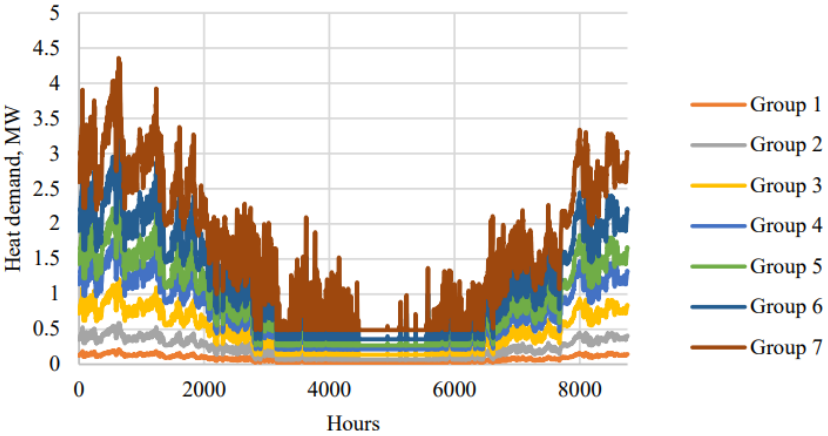


Figure 14. Heat demand profiles for each group [93]

In this study, the COP for each possible heat source is estimated considering the temperature levels of possible local low-temperature heat sources and the temperature levels in rural DH networks. Possible heat sources discussed in this study are ground, seawater, lakes and rivers, and sewage water.

To estimate the necessary electric capacity of HPs for each group for both options, the minimum COP value is used. This ensures the necessary electric capacity under all conditions. The required electric capacities for option 1 (HP and biomass boiler) and option 2 (HP only) for each group and for different heat sources are shown in Table 13.

Table 13. Required HP capacities for each group [93]

Group no.	Option 1 – HP electric capacity, MWel			Option 2 – HP electric capacity, MWel		
	Ground source	Surface water	Sewage water	Ground source	Surface water	Sewage water
1	0.033	0.033	0.031	0.088	0.093	0.084
2	0.081	0.085	0.077	0.247	0.26	0.234
3	0.164	0.164	0.155	0.509	0.509	0.482
4	0.273	0.287	0.259	0.845	0.888	0.803
5	0.357	0.375	0.319	1.11	1.164	0.992
6	0.511	0.534	0.490	1.608	1.608	1.541
7	0.755	0.784	0.726	2.366	2.459	2.277

The main assumptions used in this study are listed below:

- The base load boiler was selected based on the maximum number of hours of use at full load;
- HP COP was estimated using the Carnot equation for HP efficiency;
- To estimate HP COP, the annual heat source temperature graphs and DH supply temperature were used;
- The minimum COP value was used for the required HP electric capacity;
- For DH consumer prices, the Estonian Competition Authorities Method was used;
- To estimate fuel costs, 2020 prices (electricity and woodchips) were used;
- Flue gas treatment equipment was not considered;
- Water and sewerage services are the same for both options.

The results also showed that the maximum share of the total heat that can be delivered by base load boilers is 78 %, and peak boilers or HPs can cover the rest, i.e., 22%. In addition, the existing base load boiler capacities are significantly higher than those proposed in this study. For smaller DH networks (groups 1, 2 and 3), this may be associated with high losses in the network caused by the low heat demand density.

Since HPs are also electricity consumers, when they are used for heat production in DH, they can significantly increase the demand for electricity in the power grid. Within the study, the total additional electricity consumption of the HPs is also calculated and the results show that applying Option 1 to all rural DH networks will result in an additional consumption of around 50 MW in the electric grid. If all considered rural DH networks choose to cover the heat demand using HPs, the additional consumption will amount to 160 MW. The peak consumption in the Estonian electric grid is usually around 1500–1600 MW, therefore, the consumption of HPs in rural areas will amount to a maximum of about 10% extra consumption.

In the study weighted average cost of capital, capital costs, operation and maintenance costs, water and sewage costs, environmental fees and fuel costs are estimated for each group and for both solutions to estimate the presumable consumer price. The results of these calculations are shown on Figure 15.

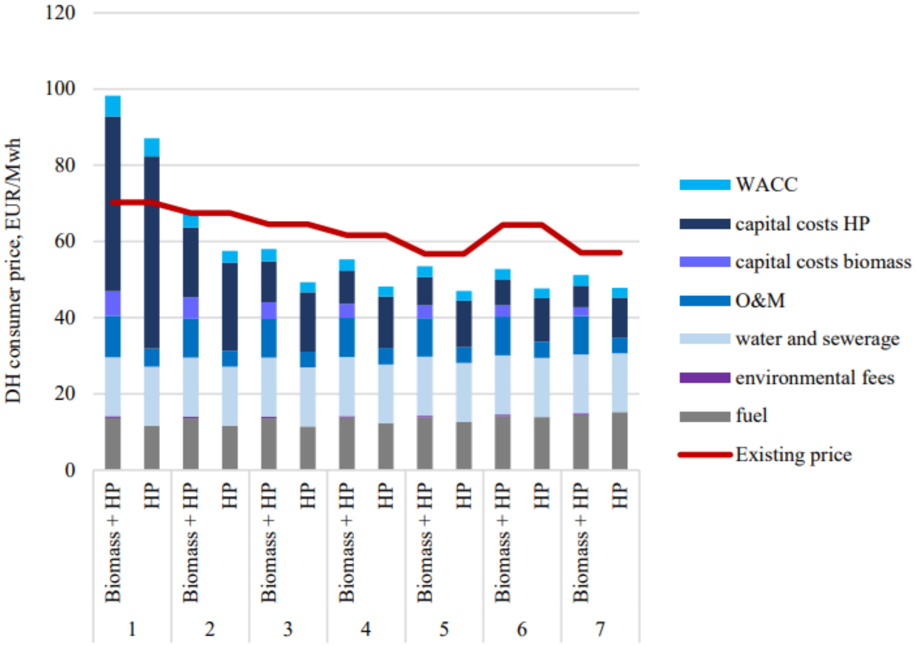


Figure 15. DH consumer price divided by costs for both solutions and existing consumer price [93]

It must be noted that prices shown on Figure 15 are calculated without considering any possible support mechanisms that are considered and used within existing DH price. Investment costs can be significantly reduced through investment support. According to national plans, new renewable heating solutions are going to be installed, including HPs with a capacity of more than 20 MW. When support mechanisms are used, this can reduce the capital costs by 50 % and lead to lower DH consumer prices. DH consumer prices with 50 % investment support are given in Table 14.

Table 14. DH consumer prices [93]

Group no.	Consumer price with 50 % investment support for Option 1, EUR/MWh			Consumer price with 50 % investment support for Option 2, EUR/MWh		
	Ground source	Surface water	Sewage water	Ground source	Surface water	Sewage water
1	67.77	72.04	71.87	57.85	62.20	61.20
2	53.87	55.16	55.05	44.70	46.11	45.11
3	49.69	50.19	50.01	41.24	41.36	40.81
4	48.76	48.87	48.75	41.20	41.45	40.47
5	47.94	47.98	47.68	41.05	41.23	39.42
6	47.76	47.69	47.58	42.09	41.71	41.19
7	47.08	46.96	46.85	42.66	42.64	41.72

The results show that investment support has a greater impact on consumer prices in smaller DH networks (groups 1, 2 and 3). Through investment support, consumer prices can be reduced by up to 31 % (group 1, sewage HP); the reduction is the smallest in group 7 for Option 1 at only 8 %. With investment support, consumer prices will be lower than the existing DH prices in every single case.

The situation for very small DH networks (groups 1, 2 and 3) is difficult anyway, as heat demand density is very low and DH is often not viable. One possible solution for these networks is to give up DH and use individual solutions. This will make it possible to save on heat distribution losses that tend to be high in these DH network groups. If these areas still want to continue using DH, the only possible solution is to increase the annual heat demand by adding new consumers to the network. In conclusion, it should be noted that using HPs in rural DH networks is a solution that is worth considering. This solution can reduce the DH consumer price and is a good alternative to carbon-intensive peak boilers. It can also integrate RES into the heating sector and help to couple the heating and electricity sectors.

4 Discussion and conclusions

In today’s world, where conserving energy and resources is paramount across all sectors, it is imperative to have a profound understanding of the most rational resource management approaches. Ensuring the uninterrupted provision of heat and electricity is a top priority in all developed countries. Since the industrial revolution, the global economy and human well-being have experienced remarkable growth, with societal development advancing at an unprecedented pace. However, despite this progress, societal mindsets and habits have largely remained unchanged, often equating success with economic growth and increasing prosperity. This poses a challenge to the current environmental movement, which advocates for prioritising resource conservation. Balancing economic expansion and maintaining current levels of welfare while simultaneously reducing consumption presents a formidable challenge. This emphasises the crucial role of new technologies, which offer the potential to sustain current levels of well-being while using fewer resources.

Since the majority of society now has access to DH and electricity, it appears obvious that both energy and heat must be provided on a continuous basis. Consequently, companies engaged in electricity or heat production bear significant responsibility towards consumers. However, these same companies, owing to their extensive consumer base, also possess a unique opportunity to influence societal energy consumption patterns. By developing energy-efficient, RES-based energy production methods, these companies can contribute to the green revolution and the achievement of climate goals. In conclusion, navigating the complex interplay between economic growth, resource conservation, and societal well-being requires innovative approaches and technologies. By leveraging advancements in energy production and distribution, we can strive towards a sustainable future where energy needs are met efficiently without compromising the well-being of current and future generations.

4.1 Main contribution of the thesis

This thesis delves into the efficient utilisation of primary energy in CHP production and sector coupling as a strategy to enhance energy efficiency within the energy system. The research initially focused on identifying efficient methods to utilise the waste heat from CHP plants and reduce natural gas consumption. This investigation led to the exploration of heating sector electrification and DC. Electrification aims to decrease natural gas usage and integrate RES into the energy system, while DC contributes to reducing the environmental impact of the cooling sector and enhancing the feasibility and efficient utilisation of primary energy in CHP production.

The first research question centred on enhancing the flexibility of CHP operation, while the second question concentrated on energy efficiency and sector coupling. By addressing these research queries, this thesis makes significant contributions to CHP and DHC research and industry, examining how the DH, DC, and CHP sectors should evolve to accommodate increased RES integration and energy efficiency.

The literature review underscores the pivotal role of CHP production in today’s energy system and asserts that through sector coupling and flexibility enhancements, CHP plants will remain relevant in future energy systems. While CHP plants are crucial for grid frequency regulation and providing base load for the heat and power sectors, their feasibility and energy efficiency can be enhanced through sector coupling, TES, and power-to-heat technologies. Heat sector electrification emerges as a significant advancement within the power-to-heat domain, with HPs identified as key players in many DHC networks due to their technical advantages.

The study reveals that CHP production can be optimised (RQ1) by incorporating TES, power-to-heat, FGC, and coupling with DC. Integrating TES into CHP plants reduces natural gas consumption and heat rejection. When combined with power-to-heat, this effect is amplified. Power-to-heat primarily enhances the feasibility of CHP production by prioritising heat generation over electricity production during periods of RES surplus and low electricity prices, resulting in reduced natural gas consumption. Adding FGC to CHP plants further enhances energy efficiency by recovering heat from flue gases for preheating DH supply water. Coupling CHP production with DC using absorption chillers or HPs reduces heat rejection, with excess heat from CHP production utilised for cooling energy generation. This approach significantly boosts energy efficiency compared to local cooling methods.

As a result of the studies, it can be concluded that coupling different energy sectors will increase energy efficiency in the system (RQ2). By electrifying the heating sector, the electricity and heating sectors will be interconnected, yielding several benefits. Firstly, the consumption of natural gas and other fossil fuels will decrease, while more RES will be integrated into the system, mitigating issues arising from the volatility of solar and wind electricity. Surplus electricity from these sources can be redirected to heat production. Utilising HPs and various natural and industrial low-grade heat sources renders heat production highly flexible and efficient. Additionally, coupling with the cooling sector is advantageous. Notably, HPs can be effectively employed for cooling production as well.

Table 15 illustrates the connections between the articles, research questions, and the main contributions of the thesis.

Table 15. Links between articles, research questions, and key contributions of the thesis

Article no.	RQ1	RQ2	Contribution
Article I	CHP flexibility can be improved by adding power-to-heat and TES	Using TES and power-to-heat can reduce heat rejection and the use of natural gas in the energy system	Electric boilers or HPs, along with TES, should be installed at CHP plants to reduce heat rejection, natural gas consumption, and improve energy efficiency
Article II	CHP excess heat can be used efficiently by absorption chiller for DC and thus increase feasibility	As heat rejection decreases, primary energy efficiency increases, and electricity need for cooling decreases	Using absorption chillers for cooling generation would decrease power production slightly, but this would still be a more efficient use of energy
Article III		A decrease in DH return temperature can increase primary energy efficiency through FGC	Using FGC can significantly increase CHP plant or boiler efficiency, the effect is even bigger with a lower DH return temperature

Article no.	RQ1	RQ2	Contribution
Article IV	CHP excess heat can be transferred to DC by DH networks for efficient cooling production	Transferring excess CHP heat to DC via DH networks is an efficient use of energy for cooling production	Using DH network for excess heat transfer will increase heat loss, but if energy were used for cooling production, then it would increase energy efficiency
Article V	Excess heat from CHP plants can be used by HPs for additional heat production	Using HPs and low-grade heat sources can increase energy efficiency in the heating sector	Mapping of low-grade heat sources in the Baltic states and the creation of an interactive map for sufficient planning for using HPs and low-grade heat sources
Article VI	Excess heat from CHP plants can be used in 5GDHC for additional heat production	In the 5GDGC concept, ultra-low DH temperatures are used decreasing heat losses and piping costs.	Investigation of 5GDHC concept development in the Baltics
Article VII		Using heat pumps in rural DH networks can decrease natural gas consumption and increase the efficiency of primary energy use	Using heat pumps in rural DH networks for heat generation will decrease the DH price for consumers and be good for the atmosphere quality. The electrification of rural DH networks will increase Estonian electricity consumption by approximately 10%.

As can be seen from Table 15, all articles included in the thesis contribute to the investigation of the aforementioned research questions, providing valuable insights for CHP and DHC research and industry.

4.2 Evaluation of the results

The validity of the results can be assessed by evaluating the reduction of PEC, which, along with energy efficiency and the integration of RES, constitutes an overarching theme for all articles included in this thesis. Table 16 illustrates how each article contributes to the investigation into PEC reduction and RES integration into the energy system.

Table 16. Each article's contribution to PEC reduction and RES integration

Article no.	Contribution to primary energy consumption reduction
Article I	The results of this study show that integrating a 150 000 m^3 TES and a 40 MW electric boiler into the Tallinn DH system, can reduce natural gas consumption by 36% and heat rejection by 38%.
Article II	The findings suggest that for effective utilisation of CHP excess heat and efficient cooling production, the use of an 0.8 MW absorption cooler and 11.6 MW HPs is recommended. This system would consume 1.9 times less primary energy for cooling generation than local cooling.
Article III	The results indicate that a reducing the DH return temperature from 45 °C to 41 °C can increase heat recovery through the FGC by 6.7%.
Article IV	The study revealed that if the DH supply flow is used for DC production via absorption chiller, electricity consumption for cooling production and CO_2 emissions would decrease by 27% and seasonal EER for cooling would increase by 35%.
Article V	It was found that the industrial excess heat potential is 3370 GWh in Estonia, 1199 GWh in Latvia, and 2490 GWh in Lithuania. From these quantities, 2601 GWh, 394 GWh, and 436 GWh, respectively, are located within existing DH areas in Estonia, Latvia and Lithuania and can be used for DH.
Article VI	Theoretical excess heat potential from 5GDHC agents was calculated, indicating that the proportion of excess heat obtained would make up only a small portion of the DH supply (15% for Latvia, 14% for Lithuania, and 19% for Estonia).
Article VII	HPs play an important role in the electrification of the heating sector and RES integration. The study revealed that if all rural DH networks use HPs for heat production, power consumption in the Estonian electricity grid will increase by about 10% (160 MW) in the case of peak consumption. The results also highlight the importance of investment support, which can significantly reduce consumer prices. For smaller DH networks, investment support can reduce consumer prices by up to 31 %, while for larger DH networks, the effects of investment support are less noticeable.

4.3 Further research

Further research is essential to study the legal aspects surrounding the use of energy storage and power-to-heat technologies, as these technologies must operate within the framework of the electricity market and adhere to established regulations. While there are no legal issues with TES when thermal energy is produced by conventional combustion boilers, the transition of the heat sector towards electrification warrants the consideration of using HPs or electric boilers for heat generation.

Manipulation of electricity prices is strictly prohibited, meaning any actions intentionally leading to an increase in electricity prices in the market are disallowed.

The integration of power-to-heat technologies alongside TES may divert electric energy away from the grid for heat generation, potentially impacting electricity prices due to reduced market offers. Moreover, the increased consumption of electricity resulting from power-to-heat technologies could further inflate market prices. While power-to-heat technologies are primarily intended for use during RES surplus periods, it is crucial to establish clear rules and strategies for their deployment to prevent potential manipulation of the electricity market, particularly as their usage becomes more widespread.

Another area requiring further investigation is the development of profitable business models for future energy systems. While the pursuit of a clean and sustainable environment is a shared societal goal, profitability remains the driving force behind the development of industries and companies. It is imperative to formulate profitable business models for energy companies to incentivise improvements in energy production and continued investment in RES, especially as energy consumption declines due to enhanced energy efficiency. These business models should also encourage consumers to reduce energy consumption and improve energy efficiency, creating a potential paradox where companies advocate for reduced consumption of their products (energy). To address this paradox, it is crucial to develop business models that benefit both producers and consumers, aligning with their shared goal of environmental sustainability.

List of figures

List of tables

References

[1] European Commission, “Communication From The Commission To The European Parliament, The European Council, The Council, The European Economic And Social Committee And The Committee Of The Regions. The European Green Deal,” 2019.

[2] A. Paist, *Soojuse- ja elektri koostootmise tehnoloogiatest*. Tallinn, 2013.

[3] R. Selegovskis and J. Berzins, “Method for determining consumer heat energy demand profile using heat consumption data from previous periods,” *Engineering for Rural Development*, vol. 18, pp. 1365–1371, 2019, doi: 10.22616/ERDev2019.18.N089.

[4] IRENA, “Power to heat and cooling: Status.” https://www.irena.org/Innovation-landscape-for-smart-electrification/Power-to-heat-and-cooling/Status (accessed Jan. 31, 2024).

[5] M. Alhuyi-Nazari, A. Mukhtar, A. S. H. M. Yasir, M. H. Ahmadi, R. Kumar, and T. N. L. Luong, “Applications of geothermal sources for absorption chillers as efficient and clean cooling technologies for buildings: A comprehensive review,” *Journal of Building Engineering*, vol. 82, p. 108340, 2024, doi: https://doi.org/10.1016/j.jobe.2023.108340.

[6] S. Pierce, F. Pallonetto, L. De Donatis, and M. De Rosa, “District energy modelling for decarbonisation strategies development—The case of a University campus,” *Energy Reports*, vol. 11, pp. 1256–1267, 2024, doi: https://doi.org/10.1016/j.egyr.2023.12.048.

[7] L. M. Dang *et al.*, “Fifth generation district heating and cooling: A comprehensive survey,” *Energy Reports*, vol. 11, pp. 1723–1741, 2024, doi: https://doi.org/10.1016/j.egyr.2024.01.037.

[8] European Commission, “Communication From The Commission To The European Parliament, The Council, The European Economic And Social. Powering a climate-neutral economy: An EU Strategy for Energy System Integration Committee And The Committee Of The Regions.,” 2020.

[9] Elering AS, “Elering Live. Tarbimine ja tootmine.” https://dashboard.elering.ee/et/system/with-plan/production-consumption (accessed Jan. 22, 2024).

[10] Elering AS, “Eesti elektrivarustuskindluse aruanne,” 2023.

[11] J. Augutis, R. Krikštolaitis, L. Martišauskas, S. Urbonienė, R. Urbonas, and A. B. Ušpurienė, “Analysis of energy security level in the Baltic States based on indicator approach,” *Energy*, vol. 199, p. 117427, 2020, doi: 10.1016/j.energy.2020.117427.

[12] Tuuleenergia Assotsiatsioon, “Tuuleenergia Eestis.” https://tuuleenergia.ee/tuuleenergia-eestis/ (accessed Jan. 22, 2024).

[13] Riigi Teataja, *Elektrituruseadus*. 2003.

[14] A. Volkova, E. Latõšov, and A. Siirde, “Heat Storage Combined with Biomass CHP under the National Support Policy. A Case Study of Estonia,” *Environmental and Climate Technologies*, vol. 24, pp. 171–184, 2020, doi: 10.2478/rtuect-2020-0011.

[15] European Commission, “Operational Programme for Cohesion Policy Funding 2014-2020,” 2014.

[16] UNFCCC, “Long-term low greenhouse gas emission development strategy of the European Union and its Member States,” *European Commission*, vol. 2019, no. March, pp. 1–7, 2020, [Online]. Available: http://www4.unfccc.int/submissions/INDC/Published Documents/Latvia/1/LV-03-06-EU INDC.pdf

[17] A. Volkova, E. Latõšov, V. Mašatin, I. Krupenski, and A. Siirde, *Jätkusuutlik kaugküte. 1.2.2 Kaugküte tänapäeva Eestis*. 2022. [Online]. Available: https://kaugkute.taltech.ee/kaugkute-eile-tana-homme-2/

[18] A. Volkova, E. Latõšov, I. Krupenski, V. Mašatin, and A. Siirde, “Jätkusuutlik kaugküte. 1.2.4. Kaugküte Tallinnas,” 2022. [Online]. Available: https://kaugkute.taltech.ee/kaugkute-eile-tana-homme-2/

[19] EED, “Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency,” no. November 2010, pp. 1–56, 2012.

[20] H. Pieper, V. Mašatin, A. Volkova, T. Ommen, B. Elmegaard, and W. Brix Markussen, “Modelling framework for integration of large-scale heat pumps in district heating using low-temperature heat sources: A case study of Tallinn, Estonia,” *International Journal of Sustainable Energy Planning and Management*, vol. 20, no. 0 SE-Articles, Mar. 2019, doi: 10.5278/ijsepm.2019.20.6.

[21] Elering AS, “Oluliste võrgukasutajate nimekiri,” 2020. [Online]. Available: https://elering.ee/sites/default/files/public/elekter/elektrisüsteem/Oluliste võrgukasutajate nimekiri.pdf

[22] A. Volkova, E. Latõšov, M. Andrijaškin, and A. Siirde, “Feasibility of Thermal Energy Storage Integration into Biomass CHP -Based District Heating System,” in *Chemical Engineering Transactions*, 2018, vol. 70. doi: 10.3303/CET1870084.

[23] Y. Ma, H. Tian, H. Cheng, F. Jiang, and Y. Yang, “The economic feasibility and life cycle carbon emission of developing biomass-based renewable combined heat and power (RCHP) systems,” *Fuel*, vol. 353, p. 129177, 2023, doi: https://doi.org/10.1016/j.fuel.2023.129177.

[24] O. Erixno, N. A. Rahim, F. Ramadhani, and N. N. Adzman, “Energy management of renewable energy-based combined heat and power systems: A review,” *Sustainable Energy Technologies and Assessments*, vol. 51, p. 101944, 2022, doi: https://doi.org/10.1016/j.seta.2021.101944.

[25] D. Blumberga *et al.*, “Empirical Model of Cost Reduction in Local DH Systems. Low Temperature Approach,” *Environmental and Climate Technologies*, vol. 23, no. 3, pp. 190–201, 2019, doi: 10.2478/rtuect-2019-0089.

[26] V. Priedniece, V. Kirsanovs, M. Dzikēvičs, Ģ. Vīgants, I. Veidenbergs, and D. Blumberga, “Experimental and analytical study of the flue gas condenser - Fog unit,” *Energy Procedia*, vol. 158, pp. 822–827, 2019, doi: 10.1016/j.egypro.2019.01.215.

[27] S. Soleimanikutanaei, C. X. Lin, and D. Wang, “Numerical modeling and analysis of Transport Membrane Condensers for waste heat and water recovery from flue gas,” *International Journal of Thermal Sciences*, vol. 136, pp. 96–106, 2019, doi: 10.1016/j.ijthermalsci.2018.10.014.

[28] D. Rusovs and V. Zentins, “Steam driven absorption heat pump and flue gas condenser applied for heat recovery in district heating network,” *Engineering for Rural Development*, vol. 19, pp. 1627–1632, 2020, doi: 10.22616/ERDev.2020.19.TF418.

[29] M. Terhan and K. Comakli, “Design and economic analysis of a flue gas condenser to recover latent heat from exhaust flue gas,” *Applied Thermal Engineering*, vol. 100, pp. 1007–1015, 2016, doi: https://doi.org/10.1016/j.applthermaleng.2015.12.122.

[30] T. Pei, S. Ma, G. Zhao, and M. Zhao, “Experimental and numerical studies on capture of SO3 aerosols from flue gas using finned tube condenser with vortex generators,” *Chemical Engineering and Processing - Process Intensification*, vol. 195, p. 109637, 2024, doi: https://doi.org/10.1016/j.cep.2023.109637.

[31] IEEE European Public Policy, “Heating and Cooling Future of Europe and Interactions with Electricity,” no. January, pp. 1–6, 2018.

[32] P. Hiltunen, A. Volkova, E. Latõšov, K. Lepiksaar, and S. Syri, “Transition towards university campus carbon neutrality by connecting to city district heating network,” *Energy Reports*, vol. 8, pp. 9493–9505, 2022, doi: https://doi.org/10.1016/j.egyr.2022.07.055.

[33] A. Hast, S. Rinne, S. Syri, and J. Kiviluoma, “The role of heat storages in facilitating the adaptation of district heating systems to large amount of variable renewable electricity,” *Energy*, vol. 137, pp. 775–788, 2017, doi: https://doi.org/10.1016/j.energy.2017.05.113.

[34] K. Penttilä, “Waste-to-Energy plant as part of combined heat and power strategy – using the example of the Klaipeda case – 1 . 1 . Importance of circular economy is growing,” 2012.

[35] “Case study factsheet Eastern region , ESTONIA Pärnu CHP plant,” no. February, p. 2010, 2010.

[36] S. Monie, A. M. Nilsson, J. Widén, and M. Åberg, “A residential community-level virtual power plant to balance variable renewable power generation in Sweden,” *Energy Conversion and Management*, vol. 228, p. 113597, 2021, doi: https://doi.org/10.1016/j.enconman.2020.113597.

[37] G. Hou *et al.*, “Flexibility oriented adaptive modeling of combined heat and power plant under various heat-power coupling conditions,” *Energy*, vol. 242, p. 122529, 2022, doi: https://doi.org/10.1016/j.energy.2021.122529.

[38] S. M. Esmaeili and P. Pourmoghadam, “Energy exergy and economic evaluation of a CCHP configuration powered by CPVT collectors dynamically,” *Energy Reports*, vol. 9, pp. 6486–6499, 2023, doi: https://doi.org/10.1016/j.egyr.2023.06.003.

[39] European Commission, “Communication from the commission to the European Parliament, the council, the European Economic and Social Committee and the Committee of the regions. A new Circular Economy Action Plan For a cleaner and more competitive Europe,” pp. 233–249, 2020, doi: 10.7312/columbia/9780231167352.003.0015.

[40] V. Arabzadeh, S. Pilpola, and P. D. Lund, “Coupling variable renewable electricity production to the heating sector through curtailment and power-to-heat strategies for accelerated emission reduction,” *Future Cities and Environment*, vol. 5, no. 1, 2019, doi: 10.5334/fce.58.

[41] A. A. Bashir, A. Lund, M. Pourakbari-Kasmaei, and M. Lehtonen, “Minimizing Wind Power Curtailment and Carbon Emissions by Power to Heat Sector Coupling - A Stackelberg Game Approach,” *IEEE Access*, vol. 8, pp. 211892–211911, 2020, doi: 10.1109/ACCESS.2020.3039041.

[42] J.-P. Jimenez-Navarro, K. Kavvadias, F. Filippidou, M. Pavičević, and S. Quoilin, “Coupling the heating and power sectors: The role of centralised combined heat and power plants and district heat in a European decarbonised power system,” *Applied Energy*, vol. 270, p. 115134, 2020, doi: https://doi.org/10.1016/j.apenergy.2020.115134.

[43] D. K. Johar, D. Sharma, and S. L. Soni, “Comparative studies on micro cogeneration, micro cogeneration with thermal energy storage and micro trigeneration with thermal energy storage system using same power plant,” *Energy Conversion and Management*, vol. 220, p. 113082, 2020, doi: https://doi.org/10.1016/j.enconman.2020.113082.

[44] F. B. Tilahun, M. Mamo, and R. Bhandari, “Optimal Solar Field and Thermal Storage Sizing in Hybrid Solar Biomass Cogeneration Plant,” in *2020 IEEE PES/IAS PowerAfrica*, 2020, pp. 1–5. doi: 10.1109/PowerAfrica49420.2020.9219945.

[45] A. Dahash, F. Ochs, M. B. Janetti, and W. Streicher, “Advances in seasonal thermal energy storage for solar district heating applications: A critical review on large-scale hot-water tank and pit thermal energy storage systems,” *Applied Energy*, vol. 239, pp. 296–315, 2019, doi: https://doi.org/10.1016/j.apenergy.2019.01.189.

[46] P. Albertus, J. S. Manser, and S. Litzelman, “Long-Duration Electricity Storage Applications, Economics, and Technologies,” *Joule*, vol. 4, no. 1, pp. 21–32, 2020, doi: 10.1016/j.joule.2019.11.009.

[47] T. M. Gür, “Review of electrical energy storage technologies{,} materials and systems: challenges and prospects for large-scale grid storage,” *Energy Environ. Sci.*, vol. 11, no. 10, pp. 2696–2767, 2018, doi: 10.1039/C8EE01419A.

[48] P. Eser, N. Chokani, and R. Abhari, “Trade-offs between integration and isolation in Switzerland’s energy policy,” *Energy*, vol. 150, pp. 19–27, 2018, doi: https://doi.org/10.1016/j.energy.2018.02.139.

[49] L. Zheng, J. Zhu, D. D.-C. Lu, G. Wang, and T. He, “Incremental capacity analysis and differential voltage analysis based state of charge and capacity estimation for lithium-ion batteries,” *Energy*, vol. 150, pp. 759–769, 2018, doi: https://doi.org/10.1016/j.energy.2018.03.023.

[50] P. A. Østergaard and A. N. Andersen, “Variable taxes promoting district heating heat pump flexibility,” *Energy*, vol. 221, p. 119839, 2021, doi: https://doi.org/10.1016/j.energy.2021.119839.

[51] A. N. Andersen and P. A. Østergaard, “A method for assessing support schemes promoting flexibility at district energy plants,” *Applied Energy*, vol. 225, pp. 448–459, 2018, doi: https://doi.org/10.1016/j.apenergy.2018.05.053.

[52] A. N. Andersen and P. A. Østergaard, “Analytic versus solver-based calculated daily operations of district energy plants,” *Energy*, vol. 175, pp. 333–344, 2019, doi: https://doi.org/10.1016/j.energy.2019.03.096.

[53] P. Sorknæs, S. Nielsen, H. Lund, B. V. Mathiesen, D. Moreno, and J. Z. Thellufsen, “The benefits of 4th generation district heating and energy efficient datacentres,” *Energy*, vol. 260, p. 125215, 2022, doi: https://doi.org/10.1016/j.energy.2022.125215.

[54] U. Trabert, J. Kelch, J. Orozaliev, and K. Vajen, “Decarbonizing building stock with renewable district heating - A case study for a rural area in Germany,” *Proceedings of the ISES Solar World Congress 2019 and IEA SHC International Conference on Solar Heating and Cooling for Buildings and Industry 2019*, pp. 470–481, 2020, doi: 10.18086/swc.2019.11.02.

[55] I. Polikarpova, D. Lauka, D. Blumberga, and E. Vigants, “Multi-Criteria Analysis to Select Renewable Energy Solution for District Heating System,” *Environmental and Climate Technologies*, vol. 23, no. 3, pp. 101–109, 2019, doi: 10.2478/rtuect-2019-0082.

[56] A. Gravelsins, I. Pakere, A. Tukulis, and D. Blumberga, “Solar power in district heating. P2H flexibility concept,” *Energy*, vol. 181, pp. 1023–1035, 2019, doi: 10.1016/j.energy.2019.05.224.

[57] H. Dorotić, M. Ban, T. Pukšec, and N. Duić, “Impact of wind penetration in electricity markets on optimal power-to-heat capacities in a local district heating system,” *Renewable and Sustainable Energy Reviews*, vol. 132, p. 110095, 2020, doi: 10.1016/j.rser.2020.110095.

[58] S. Ben Amer, R. Bramstoft, O. Balyk, and P. S. Nielsen, “Modelling the future low-carbon energy systems - case study of Greater Copenhagen, Denmark,” *International Journal of Sustainable Energy Planning and Management*, vol. 24, no. 0 SE-Articles, Oct. 2019, doi: 10.5278/ijsepm.3356.

[59] A. Bloess, “Impacts of heat sector transformation on Germany’s power system through increased use of power-to-heat,” *Applied Energy*, vol. 239, pp. 560–580, 2019, doi: 10.1016/j.apenergy.2019.01.101.

[60] M. Karmellos, P. N. Georgiou, and G. Mavrotas, “A comparison of methods for the optimal design of Distributed Energy Systems under uncertainty,” *Energy*, vol. 178, pp. 318–333, 2019, doi: 10.1016/j.energy.2019.04.153.

[61] C. Wang, C. Yan, G. Li, S. Liu, and Z. Bie, “Risk assessment of integrated electricity and heat system with independent energy operators based on Stackelberg game,” *Energy*, vol. 198, p. 117349, 2020, doi: 10.1016/j.energy.2020.117349.

[62] O. Terreros *et al.*, “Electricity market options for heat pumps in rural district heating networks in Austria,” *Energy*, vol. 196, p. 116875, 2020, doi: 10.1016/j.energy.2019.116875.

[63] K. E. Woolley *et al.*, “Effectiveness of interventions to reduce household air pollution from solid biomass fuels and improve maternal and child health outcomes in low- and middle-income countries: a systematic review protocol,” *Systematic Reviews*, vol. 10, no. 1, p. 33, 2021, doi: 10.1186/s13643-021-01590-z.

[64] W. Cheng *et al.*, “Mitigation of ultrafine particulate matter emission from agricultural biomass pellet combustion by the additive of phosphoric acid modified kaolin,” *Renewable Energy*, vol. 172, pp. 177–187, 2021, doi: 10.1016/j.renene.2021.03.041.

[65] V. Kažimírová and R. Opáth, “Biomass combustion emissions,” *Research in Agricultural Engineering*, vol. 62, no. 10, pp. S61–S65, 2016, doi: 10.17221/69/2015-RAE.

[66] European Union, “Directive (EU) 2015/ 2193 of the European Parliament and of the Council on the limitation of emissions of certain pollutants into the air from medium combustion plants,” *Official Journal of the European Union EN*, vol. 451, no. 354, pp. 134–23, 2014, [Online]. Available: http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32015L2193&from=EN

[67] European Parliament and Council, “DIRECTIVE (EU) 2016/2284 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 14 December 2016 on on the reduction of national emissions of certain atmospheric pollutants, amending Directive 2003/35/EC and repealing Directive 2001/81/EC,” *Official Journal of the European Union*, vol. L 344, no. 17.12.2016, pp. 1–31, 2016.

[68] A. David, B. V. Mathiesen, H. Averfalk, S. Werner, and H. Lund, “Heat Roadmap Europe: Large-Scale Electric Heat Pumps in District Heating Systems,” *Energies*, vol. 10, no. 4, 2017, doi: 10.3390/en10040578.

[69] B. Leitner, E. Widl, W. Gawlik, and R. Hofmann, “A method for technical assessment of power-to-heat use cases to couple local district heating and electrical distribution grids,” *Energy*, vol. 182, pp. 729–738, 2019, doi: https://doi.org/10.1016/j.energy.2019.06.016.

[70] D. Connolly *et al.*, *Heat Roadmap Europe 2: Second Pre-Study for the EU27*. Department of Development and Planning, Aalborg University, 2013.

[71] A. Inayat and M. Raza, “District cooling system via renewable energy sources: A review,” *Renewable and Sustainable Energy Reviews*, vol. 107, pp. 360–373, 2019, doi: https://doi.org/10.1016/j.rser.2019.03.023.

[72] H. Pieper, T. Ommen, B. Elmegaard, A. Volkova, and W. B. Markussen, “Optimal Design and Dispatch of Electrically Driven Heat Pumps and Chillers for a New Development Area,” *Environmental and Climate Technologies*, vol. 24, no. 3, pp. 470–482, 2020, doi: doi:10.2478/rtuect-2020-0117.

[73] A. Anderson, B. Rezaie, and M. A. Rosen, “An innovative approach to enhance sustainability of a district cooling system by adjusting cold thermal storage and chiller operation,” *Energy*, vol. 214, p. 118949, 2021, doi: https://doi.org/10.1016/j.energy.2020.118949.

[74] United States Department of Energy, “Absorption Chillers for CHP Systems,” *United States Department of Energy: Washington, DC, USA*, 2016.

[75] L. YORK (Wuxi) Air Conditioning and Refrigeration Co., “York Absorption Chiller,” 2021.

[76] P. Lazzeroni, “Design of a polygeneration system with optimal management for a dhc network,” *International Journal of Sustainable Energy Planning and Management*, vol. 22, 2019.

[77] M. Sameti and F. Haghighat, “Hybrid solar and heat-driven district cooling system: Optimal integration and control strategy,” *Solar Energy*, vol. 183, pp. 260–275, 2019, doi: https://doi.org/10.1016/j.solener.2019.03.034.

[78] K. Thakar, R. Patel, and G. Patel, “Techno-economic analysis of district cooling system: A case study,” *Journal of Cleaner Production*, vol. 313, p. 127812, 2021, doi: https://doi.org/10.1016/j.jclepro.2021.127812.

[79] M. Fabricius, D. Øland Tarp, T. Wehl Rasmussen, and A. Arabkoohsar, “Utilization of Excess Production of Waste-Fired CHP Plants for District Cooling Supply, an Effective Solution for a Serious Challenge,” *Energies*, vol. 13, no. 13, 2020, doi: 10.3390/en13133319.

[80] D. M. Alghool, T. Y. Elmekkawy, M. Haouari, and A. Elomri, “Optimization of design and operation of solar assisted district cooling systems,” *Energy Conversion and Management: X*, vol. 6, p. 100028, 2020, doi: https://doi.org/10.1016/j.ecmx.2019.100028.

[81] A. Inayat *et al.*, “Integration and simulation of solar energy with hot flue gas system for the district cooling application,” *Case Studies in Thermal Engineering*, vol. 19, p. 100620, 2020, doi: https://doi.org/10.1016/j.csite.2020.100620.

[82] B. Delač, B. Pavković, and V. Glažar, “Economic and Energetic Assessment and Comparison of Solar Heating and Cooling Systems,” *Energies*, vol. 16, no. 3, 2023, doi: 10.3390/en16031241.

[83] A. Saleh, “Modeling and Performance Analysis of a Solar Pond Integrated with an Absorption Cooling System,” *Energies*, vol. 15, no. 22, 2022, doi: 10.3390/en15228327.

[84] E. Latosov, A. Volkova, A. Siirde, M. Thalfeldt, and J. Kurnitski, “The Impact of Parallel Energy Consumption on the District Heating Networks,” *Environmental and Climate Technologies*, vol. 23, no. 1, pp. 1–13, 3919, doi: doi:10.2478/rtuect-2019-0001.

[85] S. Werner, “International review of district heating and cooling,” *Energy*, vol. 137, pp. 617–631, 2017, doi: https://doi.org/10.1016/j.energy.2017.04.045.

[86] M. Jangsten, P. Filipsson, T. Lindholm, and J.-O. Dalenbäck, “High Temperature District Cooling: Challenges and Possibilities Based on an Existing District Cooling System and its Connected Buildings,” *Energy*, vol. 199, p. 117407, 2020, doi: https://doi.org/10.1016/j.energy.2020.117407.

[87] K. Lepiksaar, V. Mašatin, E. Latõšov, A. Siirde, and A. Volkova, “Improving CHP flexibility by integrating thermal energy storage and power-to-heat technologies into the energy system,” *Smart Energy*, vol. 2, p. 100022, 2021, doi: https://doi.org/10.1016/j.segy.2021.100022.

[88] K. Lepiksaar, V. Mašatin, I. Krupenski, and A. Volkova, “Effects of Coupling Combined Heat and Power Production with District Cooling,” *Energies*, vol. 16, no. 12, 2023, doi: https://doi.org/10.3390/en16124552.

[89] K. Lepiksaar, A. Volkova, P. Ruseljuk, and A. Siirde, “The effect of the District Heating Return Temperature Reduction on Flue Gas Condenser Efficiency,” *Environmental and Climate Technologies*, vol. 24, no. 3, pp. 23–38, 2020, doi: https://doi.org/10.2478/rtuect-2020-0083.

[90] H. Pieper, T. Kirs, I. Krupenski, A. Ledvanov, K. Lepiksaar, and A. Volkova, “Efficient use of heat from CHP distributed by district heating system in district cooling networks,” *Energy Reports*, vol. 7, pp. 47–54, 2021, doi: https://doi.org/10.1016/j.egyr.2021.09.041.

[91] H. Pieper, K. Lepiksaar, and A. Volkova, “GIS-based approach to identifying potential heat sources for heat pumps and chillers providing district heating and cooling,” *International Journal of Sustainable Energy Planning and Management*, vol. 34, pp. 29–44, 2022, doi: https://doi.org/10.54337/ijsepm.7021.

[92] A. Volkova, I. Pakere, L. Murauskaite, P. Huang, K. Lepiksaar, and X. Zhang, “5th generation district heating and cooling (5GDHC) implementation potential in urban areas with existing district heating systems,” *Energy Reports*, vol. 8, pp. 10037–10047, 2022, doi: https://doi.org/10.1016/j.egyr.2022.07.162.

[93] K. Lepiksaar, K. Kalme, A. Siirde, and A. Volkova, “Heat Pump Use in Rural District Heating Networks in Estonia,” *Environmental and Climate Technologies*, vol. 25, no. 1, pp. 786–802, 2021, doi: https://doi.org/10.2478/rtuect-2021-0059.

Acknowledgements

This journey of PhD studies has been more than I could ever imagine. Firstly, I cannot say that at the moment I am an excellent expert because of all this research that I have done. Yes, very many things have become clear to me in the field of energy, yet in many cases I have realised the complexity the problems and the fact that sometimes there can’t be universal solutions.

These studies would have been harder if I there wouldn’t been good coworkers and colleagues. Having a good team for support is the key for success in many cases.

To my supervisor, Igor, I am thankful for having excellent ideas and for giving me motivation when I had none.

To my supervisor, Anna, I am most thankful for showing me how to succeed in the world of science, for giving me excellent opportunities to see the world and meet interesting people. Most of all, I would like to acknowledge Anna for being always inspiring and overall, a good and caring person.

I am also thankful to all the students who I had the opportunity to give lectures, because many times it happened that calculations, ideas and discussions that I used in my research, matured during the process of teaching. Students are infinite source of youthful energy, that can light up the darker days.

Last but not least, I am thankful to my family for giving me the reason for doing things.

Abstract

Smart Energy System Efficiency Improvement Through Combined Heat and Power Production Flexibility

Smart energy systems include smart and efficient thermal and electrical grids. One of the links between them is CHP production, which supplies both heat and power to the grid. CHPs are designed for stable heat and electric loads and their ability to cope with peaks and lows needs to be improved. Furthermore, as power and heat can be produced in other ways, the position of the CHP production in the future becomes questionable. Still, as they are necessary for providing stability and frequency in the power grid and giving base load for heat and power consumption, it would be advisable to improve their primary energy use efficiency. The literature underlines that sector coupling and using proper technical approaches, such as energy storages, power-to-heat solutions and absorption chillers will help to achieve the goals of energy efficiency and introduction of RES. It is also clear that DH will move towards heating sector electrification by heat pumps, which is also coupling heating sector with power sector.

The aim of this thesis is to examine how CHP production and energy system overall should be improved to increase operational flexibility and primary energy efficiency through sector coupling. The starting point of the research was looking for efficient ways to use rejected heat of CHP plants and reduce natural gas consumption. This research led to heating sector electrification topic and DC. Electrification will help to reduce natural gas consumption and integrate RES to energy system, DC helps to reduce environmental impacts of cooling sector and increase feasibility and efficient use of primary energy in CHP production.

This thesis is constructed from seven articles that support the investigation of the thesis topic. The energy system is examined as a whole by using simulation models as well calculation models for process modelling. Simulation models will show the interaction of different technologies and process modelling will show how each technical solution will affect the system. For heating sector electrification geospatial analysis and simulation models are used, as development of 5GDHC contributes to energy system electrification, for that multi-criteria analysis are used.

The results of this thesis show that coupling different energy sectors will increase energy efficiency in the system. Inefficient heat rejection of CHP production can be decreased by using TES and power-to-heat technologies with proper capacity. This will also help to reduce natural gas consumption. Excess heat from CHP production can also be directed to DC which will also decrease heat rejection. Natural gas consumption can be remarkably decreased with heating sector electrification, using heat pumps and low-grade natural and industrial energy sources.

As a result of using these technologies also energy production feasibility increases in several ways, positive effects will be noticed for heating and cooling production and also for consumer price.

Lühikokkuvõte

Targa energiasüsteemi efektiivsuse parendamine läbi koostootmise paindlikkuse tõstmise

Nutikad energiasüsteemid hõlmavad nutikaid ja tõhusaid soojus- ja elektrivõrke. Üheks lüliks nende vahel on soojuse ja elektri koostootmine, mis varustab võrke nii soojuse kui ka elektrienergiaga. Koostootmisjaamad on mõeldud stabiilseks soojuse ja elektri tootmiseks ning nende võimet tulla toime tarbimistippude ja madalseisudega tuleb parandada. Lisaks, kuna elektrit ja soojust saab toota ka muul viisil, muutub koostootmise positsioon tulevikus küsitavaks. Siiski, kuna need on vajalikud elektrivõrgu stabiilsuse ja sageduse tagamiseks ning soojuse ja elektritarbimise baaskoormuse andmiseks, oleks soovitatav nende primaarenergia kasutamise efektiivsust tõsta. Uuritud kirjanduses rõhutatakse, et energiatõhususe ja taastuvate energiaallikate kasutuselevõtu eesmärke aitab saavutada sektorite sidumine ja erinevate tehniliste lahenduste, nagu energiasalvestid, "elekter-soojuseks" lahendused ja absorptsioonjahutid, kasutamine. Samuti on selge, et kaugkütte valdkond liigub küttesektori elektrifitseerimise suunas soojuspumpade abil, mis ühendab soojuse tootmise elektriga.

Käesoleva doktoritöö eesmärk on uurida, kuidas tuleks koostootmist ja energiasüsteemi tervikuna täiustada, et suurendada töö paindlikkust ja primaarenergia efektiivsust läbi sektorite sidumise. Uurimistöö lähtepunktiks oli tõhusate tehniliste lahenduste otsimine, kuidas kasutada koostootmisjaamade heitsoojust ja vähendada maagaasi tarbimist. See uurimus viis küttesektori elektrifitseerimise teema ja kaugjahutuseni. Elektrifitseerimine aitab vähendada maagaasi tarbimist ja integreerida taastuvenergiat energiasüsteemi, kaugjahutus aitab vähendada jahutussektori keskkonnamõjusid ning suurendab primaarenergia tõhusat kasutamist koostootmises.

Käesolev doktoritöö on üles ehitatud seitsmest artiklist, mis toetavad doktoritöö teema uurimist. Energiasüsteemi vaadeldakse tervikuna, kasutades nii simulatsioonimudeleid kui ka arvutusmudeleid protsesside modelleerimiseks. Simulatsioonimudelid näitavad erinevate tehnoloogiate koostoimet ja protsesside modelleerimine näitab, kuidas iga tehniline lahendus süsteemi mõjutab. Küttesektori elektrifitseerimiseks kasutatakse geograafilist ruuminalüüsi ja simulatsioonimudeleid. Viienda põlvkonna kaugkütte- ja jahutuse arendamisel, mis hõlmab ka energiasüsteemi elektrifitseerimist, kasutatakse mitme kriteeriumilist analüüsi.

Doktoritöö tulemused näitavad, et erinevate energiasektorite sidumine suurendab süsteemi energiatõhusust. Ebaefektiivset heitsoojuse jahutitesse suunamist, mis on hetkel levinud praktika mitmetes Eesti koostootmisjaamades, saab vähendada soojusenergia salvestite ja õige võimsusega "elekter-soojuseks" tehnoloogiate kasutamisega. See aitab ka maagaasi tarbimist vähendada. Koostootmise heitsoojust saab suunata ka kaugjahutuse tootmiseks, mis samuti vähendab heitsoojuse jahutitsesse suunamist. Maagaasi tarbimist saab märkimisväärselt vähendada küttesektori elektrifitseerimisega, kasutades soojuspumpasid ja erinevaid looduslikke või tööstuslikke heitsoojuse allikaid.

Nende tehnoloogiate kasutamise tulemusena suureneb mitmel viisil ka energiatootmise kasumlikkus, märgata on positiivseid mõjusid kütte ja jahutuse tootmisele ning ka tarbijahinnale.

Appendix 1

Publication I

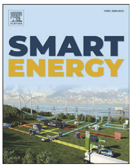
Lepiksaar, K., Mašatin, V., Latõšov, E., Siirde, A., & Volkova, A. (2021). Improving CHP flexibility by integrating thermal energy storage and power-to-heat technologies into the energy system. *Smart Energy*, 2, 100022. https://doi.org/10.1016/j.segy.2021.100022

Smart Energy 2 (2021) 100022

Contents lists available at ScienceDirect

Smart Energy

journal homepage: www.journals.elsevier.com/smart-energy



Improving CHP flexibility by integrating thermal energy storage and power-to-heat technologies into the energy system

K. Lepiksaar [a, *], V. Mašatin [b], E. Latõšov [a], A. Siirde [a], A. Volkova [a]

[a] Tallinn University of Technology, Ehitajate tee 5, 19086, Tallinn, Estonia
[b] AS Utilitas Tallinn, Punane 36, 13619, Tallinn, Estonia

ARTICLE INFO

Article history:
Received 9 December 2020
Received in revised form
6 May 2021
Accepted 27 May 2021
Available online 1 June 2021

Keywords:
Cogeneration
Themal energy storage
Power-to-heat
Heat rejection
Peak boilers
LTDH

ABSTRACT

Smart energy grids include smart thermal and electrical grids. One of the links between them is the combined heat and power (CHP) plant, which supplies both heat and power to the grid. CHPs are designed for stable heat and electric loads and their ability to cope with peaks and lows needs to be improved. This paper explores technical solutions aimed at improving CHP flexibility, considering the potential transition to the 4th generation district heating (4GDH). CHP flexibility extends its operating time and improves the energy efficiency of the system. The solutions examined include coupling CHPs with electric boilers and TES, which will help balance heat and power loads and allow to introduce RES to the system. In this study, these technical solutions are compared in terms of natural gas consumption, heat rejection reduction, and the share of heat supplied to the system by the CHP. The results of this study show that when 150 000 m^3 TES and 40 MW electric boiler are integrated into the Tallinn DH system, natural gas consumption can be reduced by 36% and heat rejection by 38%.

1. Introduction

A coherent and well coupled energy system is the key to the future smart and efficient energy system that consists of thermal and power grids, consumers, and producers. Various technological solutions must be adopted in order to achieve greater energy efficiency in the system.

The European Union has set a very ambitious goal: to become climate neutral by 2050, which means developing an economy with net-zero greenhouse gas emissions. To achieve this, the EU has made it a priority to become the leader in the transition to clean energy by reducing CO_2 emissions by at least 40%, increasing the share of renewable energy by at least 32%, and improving energy efficiency by at least 32.5% by 2030, compared to the 1990 data. The proportion of renewable energy in the EU's energy mix has increased significantly during the implementation of the 2020 energy strategy. However, it varies by sector, with renewable energy reaching 30.8% in the electricity sector and only 19.5% in the heating and cooling sector [1].

The transition from fossil fuel to the integration of an increasing number of renewable energy sources (RES) requires the revision and redesign of the energy system in terms of both generation and consumption. To this end, the future sustainable energy system will have multiple infrastructures for various sectors, such as electrical grids, district heating (DH) networks, and district cooling networks [2].

The proportion of renewable energy sources (RES) in the energy mix has been rapidly increasing due to significant focus on the current issues, such as climate change and energy security. Besides, the number of CHPs in the EU, including Estonia, has been growing over the past decade [3]. These factors have added to the problem of balancing electricity demand and supply. One of the key challenges in the energy sector is the creation of flexible energy supply with an increased number of fluctuating renewable energy sources. When the proportion of RES is high, CHPs are crucial for power grid stabilisation, that is, ensuring and maintaining the frequency and voltage in the power supply [4].

DH is feasible if a sustainable energy system based on RES is introduced. DH plays an incredibly important part, but DH technologies must continue to be developed. Renewable energy, along with energy conservation and CHPs, is a fundamental aspect of Europe's response to climate change [5].

Currently, the 4th Generation District Heating (4GDH) [6] is an attractive topic in the energy domain because this concept by

---

* Corresponding author.
E-mail address: kertu.lepiksaar@taltech.ee (K. Lepiksaar).

https://doi.org/10.1016/j.segy.2021.100022

Abbreviations

4GDH	4th generation district heating
LTDH	low-temperature district heating
CHP	combined heat and power plant
EU	European Union
RES	renewable energy sources
TES	thermal energy storage

means of smart thermal grids assists the appropriate development of sustainable energy systems for delivering heat energy to houses. 4GDH concept is characterized by low temperature in district heating networks (60/30 °C), low heat distribution losses, renewable and excess energy utilization and ability to be part of smart energy systems, leading towards zero carbon footprint. Heat supply from sustainable low-temperature district heating (LTDH) networks can be considered one of the most favourable heat supply options for urban buildings and industrial facilities. Supply temperature under 60 °C is the most important feature of the 4GDH. The energy supply and transition system, along with end users, will benefit from such low temperature [7].

Biomass-based CHPs are widely used in DH systems in Europe [8,9]. As for Estonia, this type of RES is actively supported by the government, which has introduced a feed-in-premium policy instrument [10].

There are two main obstacles to the efficient CHP operation under the current conditions:

- When the heat load is reduced during the warmer months, CHPs cannot operate efficiently at full load
- When market prices for electricity are low, generating and selling electricity through CHPs is not feasible.

The first obstacle is well-known and well-researched, and there are various technical solutions to this problem. The CHP is used to supply heat during the cold months when the heat load is quite high, but when there is no technical ability to consume the heat produced, then the CHP must operate at partial load or stop altogether during periods of low heat demand. When it is possible to generate electricity without selling heat, another possible solution is to install additional auxiliary coolers to remove excess heat during the period of the lowest heat load (summer), as is done at the Järvenpää Biomass CHP (Finland) [11], Klaipeda Waste Incineration CHP (Lithuania) [12], Tallinn CHP2 [13], and Pärnu Biomass CHP (Estonia) [14]. This solution cannot be considered sustainable, because in any case, due to higher energy efficiency in the winter months and increased production efficiency due to the flue gas condenser, the annual heat generation efficiency decreases [15].

Coupling the CHP with thermal energy storage (TES) helps to reduce the dependence of heat and electricity production on consumer heat load fluctuations. Typically, accumulator tanks are used for short-term TES. The feasibility of this technical solution was studied in Refs. [10,16,17], and the main conclusion of these studies is that the implementation of accumulator tanks can extend the period when CHPs can operate at full load and increase the overall efficiency of CHPs. As was studied in Ref. [18], seasonal TES is a better choice if solar energy is also used.

A fairly new problem faced by CHPs is associated with short periods when the price of electricity is very low and the production and sale of electricity is not feasible. Various storage options can be used to deal with peak demands and integrate renewable energy into the system. Electrical storage is the best way to integrate solar PV and wind energy into the grid, but these solutions can often be expensive [19,20]. At the moment, large-scale electricity storage facilities are also limited and very expensive [21–23]. Other energy storage options, such as pumped hydro storage, are location-constrained and not widely available. Power-to-heat is a feasible option when heat is consumed via DH or stored in a short-term heat storage. If the period of low prices coincides with the heating season (e.g., in Nordpool in February 2020, when electricity prices dropped to 0 EUR/MWh for a few hours on 9.02.19, with the average price for the day of 10.07 EUR/MWh), the heat produced from the CHP electricity can replace the heat produced from fossil fuels, reducing CO_2 emissions.

Electric boilers are considered to be an important element necessary for the flexibility of the electric system. The potential for electricity-based heat production to increase the flexibility of energy systems has been investigated in Denmark [24], Germany [25], and Sweden [26]. Electric boilers in DH networks can resolve the system conflict of baseload power plants in the “must run” operation mode in order to provide system services at low residual loads [25].

Andersen et al. have explored various ways to make energy systems more flexible and introduce more RES into the system, with a particular focus on tax incentives [27], government support schemes [28], and developing power plant operating strategies [29]. Using heat pumps for power-to-heat can be very beneficial, but because the investment in the installation is very high, an electricity tax system was proposed in Ref. [27] to help increase the capacity of heat pumps and thermal energy storage units in order to create a basis for flexible operation and match the operation of heat pumps with the dynamic needs of the electric power system. The results showed that 100% of the spot electricity prices could stimulate investment in additional TES capacity but won't do as much for the capacity of DH HPs. In Ref. [28], it is argued that the support scheme must ensure the correct ratio between the production capacity and TES capacity. Before a country achieves intermittent renewable energy production at full volume, it is recommended that production-dependent support schemes be used to increase the displacement of production at condensing power plants running on fossil fuels. When a high level of intermittent renewable energy is achieved, this production covers the electricity demand for most hours, leaving only a few hours for CHP production. Investment support schemes can be considered at this stage as they require less assistance.

The aim of the study is to analyse the integration of power-to-heat technologies, such as electric boilers, together with TES, into the energy system. This technology combination must be integrated into the existing CHP. This will ensure CHP flexibility as there will be more hours of energy efficient operation for both heat and power production. As a result, the use of natural gas-fired peak boilers will be reduced along with heat rejection.

There are studies on individual elements or combinations of elements that can improve the flexibility of CHP operation as described above. After analysing the available studies, it was concluded that many of them focused on trigeneration options [30,31]. The combination of CHP, absorption chiller, and TES was studied in Ref. [32].

Other studies have examined electric boilers as part of energy systems, e.g. Refs. [33,34], and [35]. Some of them also covered the combination of electric boilers and TES units. There is a gap in research on the CHP, electric boiler, and TES combination.

The idea behind the study stems from the following hypothesis: improving the flexibility of a CHP-based energy system by integrating power-to-heat, heat-to-cooling, and heat storage elements will significantly increase the overall efficiency and feasibility of the system. The need to also consider low-temperature district heating

Table 1
Heating units in the Tallinn DH system.

Heating unit	Thermal power, MW	Fuel	Place on priority list (since 2021)	Heat rejection
Iru CHP	50	Municipal waste	1	No
Tallinn CHP2	76	Biomass	2	Yes
Mustamäe CHP	48	Biomass	3	Yes
Tallinn CHP1	67	Biomass	4	No
Natural gas boilers	827	Natural gas	5	No

becomes relevant as temperature levels decrease, affecting heat production, which will therefore be reduced. Since heat demand is important in this study, the effects of the transition to low-temperature district heating must also be taken into account.

The main problem for CHPs has always been that the operation of the plant is determined by heat demand, and fluctuating heat loads have always been an issue for CHP operation. Due to the high share of RES, market prices began to fluctuate greatly, which led to another problem for the efficient operation of CHPs, namely, that economic conditions affect the decrease in electricity generation. An analysis of the technical solution that would include heat storage and power-to-heat options will help solve both heat consumption and electricity consumption fluctuation issues.

Power-to-heat technologies have been studied a lot recently [36], examined the impact of wind penetration in electricity markets on optimal power-to-heat capacities within a local DH system. In Ref. [25], the power-to-heat impact on Germany's power system was discussed, and it was determined that the interaction between heating and electricity sectors will provide flexibility to both sectors when dealing with short-term variations in wind and solar power generation. In Ref. [25], it is also mentioned that when biomass is limited, using power-to-heat solutions in a system where the share of renewable energy is increasing will also help integrate more renewable energy sources into the heating sector. In Ref. [37], various methods for the optimal design of distributed energy systems were compared, and heat pumps were considered as power-to-heat solutions. In Ref. [38], a risk assesment for the integrated heat and electricity systems was performed, and it was determined that using power-to-heat solutions (heat pumps, electric boilers) reduces risks when a higher share of RES is integrated into the system.

The European Commission's EU Strategy for Energy System Integration states that sector coupling will significantly increase electricity consumption, which, in turn, will increase renewable energy production and spread the use of RES technologies [39]. In Ref. [40], it is discussed that heat pumps, as power-to-heat solutions, play a major role in the sectoral coupling of RES and the heating sector, and the amount of heat extracted from RES strongly depends on the type of strategy; the most RES can be integrated into a system using a strategy based on wind power generation. In Ref. [41], it is stated that the residential heat load has significant potential to maximise the use of wind power and minimise carbon emissions when coupling the electricity and heat sectors. It is also stated in Ref. [42] that the operation of existing thermal power plants in cogeneration mode, together with district heating networks and thermal storage, can still contribute to the decarbonisation of the European heating sector.

When using power-to-heat solutions for coupling heating and electricity sectors, it is very important to avoid ‘dirty coupling’ when it comes to environmental aspects. This means that instead of using power-to-heat technologies to integrate RES into the energy system by utilising overproduced RES electricity, more fossil fuels are used to generate heat from power [43]. Currently, most of the existing renewable energy plants receive subsidies or have a long-term power purchase agreement that protects them from decreasing wholesale electricity prices. However, governments are expected to stop subsidies as the costs of wind and solar technology continue to decline, increasing the dependence of such plants on wholesale prices. As a result, renewable energy producers that rely solely on the wholesale electricity market may not earn enough to cover costs and generate returns on equity. Growing demand from sector coupling may instead stimulate additional fossil fuel capacity.

2. Methodology

This study is based on the comparison of simulation results from different scenarios. These simulations were created for CHP-based DH using EnergyPRO simulation software.

EnergyPro software is mainly used for technical and economic analysis of existing and planned energy systems. It can be used to model DH systems, power systems, and a combination of heat and power systems. The scale of the system can range from a single home to several DH networks and power systems. The inputs usually consist of power and heat demand and prices, but there may be various other external conditions like weather parameters that can be added to the system. For example, in Ref. [27], an EnergyPRO model was used to design a tax system that promotes heat pump flexibility in DH systems. In Ref. [27], a typical DH system was analysed, and electricity taxes and heat production costs were added to the system as variables. EnergyPRO can also be used to simulate the integration of fluctuating RES into energy systems, as was done in Ref. [44], which analysed the installation of solar collectors and PV panels in apartment buildings of the Soviet era. In Ref. [45], EnergyPRO was used to simulate the potential use of excess heat from small nuclear reactors in DH systems, and in Ref. [46], it was used to create heat load profiles for building stock decarbonisation in rural Germany using renewable DH.

In this study, EnergyPRO was used to create heat demand profiles and then compare them to Nord Pool electricity prices to assess the feasibility of electric boiler integration. The created heat demand profiles were also used to match TES with heat production. The system has been optimised based on minimal natural gas use and minimal heat rejection.

The parameters selected for comparison include annual natural gas consumption, primary energy, the amount of rejected heat (cooled down by chillers), and CHP operating time. The use of integrated technologies (operating time) is also compared.

2.1. Reference case

This study is based on a case study of the Tallinn DH network in its current state and in the case of LTDH, as well as a comparison of different technological compositions. The Tallinn DH network was used as a reference scenario.

There are four CHPs in the Tallinn system which are used for base load, three of them are biomass CHP and one is municipal waste CHP. There are also five natural gas boilers in the system covering peak load. Despite the fact that there are many natural gas boilers in the Tallinn DH system, they are all considered as one unit in this study, since boilers have nearly identical operating parameters (energy efficiency), and in the context of this study it does not matter which natural gas boiler was operating. The properties of the CHPs and boilers (total) of the Tallinn DH system are given in Table 1.

As for the Tallinn DH system, priority placements of the heat plants (CHPs and boilers) are determined via the lowest heat price competition, which is held by the Estonian Competition Authority every five years. Typically, the heat plant that can provide the lowest heat price is ranked higher on the priority list. There may be exceptions based on network throughput. Tallinn CHP2, which is ranked second on the priority list, and Mustamäe CHP, which is ranked third on the list, are using heat rejection, which allows them to operate full load the entire year. Using heat rejection to produce electricity is profitable for these CHPs due to RES support measures provided by the government. All back-pressure CHPs that use renewable energy sources to produce electricity receive a feed-in premium of 53.7 EUR/MWh_{el}, when electric output is less than 125 MW, CHPs are not older than 12 years, and the annual total energy efficiency is over 40% [47]. Starting in 2021, Tallinn CHP1 will no longer receive feed-in premiums, because by that time it will be 12 years old. This study presents an analysis of possible operating strategies for Tallinn CHP1 for the case where this plant is able to sell electricity at Nord Pool prices, with no feed-in premiums, and different heat selling priority rankings.

This study considers data calculated for the previous three years (2017–2019). The data on the total natural gas consumption and heat rejected into the atmosphere (Tallinn DH network) are given in Table 2.

In the case of low-temperature district heating, it is considered that heat consumption will be slightly reduced as the energy efficiency of buildings will be improved and DH network losses will be reduced due to the lower supply temperature [48]. Tallinn's heat demand in the case of 4GDH has been determined using the methods described in Ref. [48], which links annual heat production to heat consumption in buildings and relative heat losses. Heat consumption in buildings will be factored into the calculation through a base temperature of 13 °C for fully renovated buildings and 17 °C for unrenovated buildings. In the case of Tallinn, the average base temperature will be 16 °C in its current state and 14 °C in the case of the 4GDH scenario. This will reduce the annual heat consumption by 4% using the calculation methods described in Ref. [48].

The relative heat losses were calculated using the method proposed in Ref. [49]. In the current state of the Tallinn DH system, the supply and return temperatures are 70 °C and 45 °C, respectively. In the case of 4GDH, the temperatures will be 60 °C and 30 °C, respectively. In its current state, the relative heat loss in Tallinn's DH system is 16%. At the moment, the network heat transfer coefficient in Tallinn is 0.941 $W/(m^2 \cdot K)$, and with a complete pipeline renovation it will decrease to 0.35 $W/(m^2 \cdot K)$. In the case of a fully renovated network and a lower temperature level, the relative heat loss in Tallinn's DH system will be 4%.

When the previous assumptions are taken into account, the annual heat production in the Tallinn DH system in the case of LTDH will be reduced by 14%. Tallinn's heat consumption in the LTDH case based on 2017–2019 weather parameters is also given in Table 2.

For the calculations performed in this study, the following was also assumed:

- There is a 2-week restriction period for each CHP in the summer for maintenance.
- Iru CHP and Tallinn CHP1 can operate at part load.
- Tallinn CHP2 and Mustamäe CHP will operate at full load at all possible times due to heat rejection and subsidies granted for the RES electricity.

2.2. Power-to-heat only

This study examines electric boilers as power-to-heat solutions. Heat pumps can also be considered as such solutions. This study focuses on electric boilers as they do not require any heat sources and are more flexible. Since heat pumps are more efficient in terms of heat, using a heat pump with the same electric input will result in increased heat output. In terms of balancing the electric system, there is no difference when using an electric boiler or heat pump with the same electric input.

This paper focuses on an electric boiler with a capacity of 40 MW (electric input is equal to thermal output). Sensitivity analysis was also conducted for other boiler capacities.

Another important factor when it comes to using power-to-heat solutions is the electricity price threshold. The threshold marks the highest electricity price at which the electric boiler operates. When the price of electricity is below the threshold, the electric boiler operates. When the price is above the threshold, the boiler does not operate. The threshold price can be related to the selling price of heat or the cost of heat production. In this study, the threshold is considered as 30 EUR/MWh, which is lower than the price of heat in Tallinn, as well as the average electricity price in Estonia. Also, as heat generation from natural gas costs about 35 EUR/MWh, then threshold higher than that would not be economically feasible.

The number of power-to-heat production and usage hours depends on the threshold: when the threshold is lower, power-to-heat is used less.

The number of hours during which the electricity price was below the threshold in the previous three years and the average electricity price (Nord Pool) for each year is shown in Table 3 [50].

As for electric boilers, it does not matter where they are when the electricity comes from the grid. This provides more options for choosing a location. If electricity for the electric boiler comes straight from the CHP and is not sold to the grid at all, then the boiler should be located within the CHP. When electricity comes straight from the CHP, there is no ‘dirty coupling’ because electricity is produced from biomass, which is a renewable energy source. In

Table 3
Average electricity price and number of hours below the threshold in 2017-2019.

	2017	2018	2019
Average electricity price, EUR/MWh	33,20	47,07	45,86
Number of hours below the threshold	3771	672	836

Table 2
Annual heat consumption, use of natural gas, and rejected heat in Tallinn in present DH system and in case of 4GDH in 2017-2019

	Annual heat consumption, MWh			Use of natural gas, MWh			Rejected heat, MWh		
Year	2017	2018	2019	2017	2018	2019	2017	2018	2019
Total	1 805 907	1 773 203	1 647 931	444 691	422 763	342 126	348 017	350 952	363 423
Total 4GDH	1 570 226	1 541 790	1 432 867	290818	276 061	223 121	373 176	376 591	390 973

this study, it is assumed that electricity comes from the grid.

Power-to-heat technologies will not be affected by the temperature level. The reason is that lower temperature levels cause higher flow rates in DH networks, which leads to an increase in the amount of electricity required for pumping. However, the electricity used for pumping is not relevant to this study.

Nevertheless, since there is less heat demand in the case of LTDH, this may affect the use of power-to-heat technologies.

2.3. TES only

In this paper, various sensible heat TES units were considered for increasing CHP flexibility. As for the TES units, in this paper different TES options were compared. 3000 m^3 and 7000 m^3 for a small TES unit. 100 000 m^3 and 150 000 m^3 represent a large TES unit.

Small thermal energy storage units (3000 and 7000 m^3) are suitable for smoothing out heat fluctuations in spring and autumn, bigger TES units (100 000 and 150 000 m^3) are more suitable for storing heat in summer, subsequently using it to maintain production during the heating season.

Since different sizes of TES can lead to different results, this paper focuses on a variety of TES sizes.

As for LTDH, it must also be taken into account that various temperature schedules and differences will affect TES capacity and TES heat loss.

2.4. Electric boiler and TES

Using both power-to-heat and TES can have a great impact on CHP flexibility, since in this case heat production does not depend on heat demand as much, and because of power-to-heat, volatile heat is available more often and can be stored in the storage unit until needed.

In this study, a 40 MW electric boiler was combined with TES units of different sizes. During the sensitivity analysis that was conducted as part of the research, it was determined that the limiting factor for an electric boiler is the heat demand, and there is a point where it is not feasible to integrate a larger electric boiler because it will not lead to greater natural gas savings.

It was also discussed whether this type of electric boiler is suitable for the LTDH system with a lower heat demand, since heat demand is relevant to the capacity of the electric boiler.

3. Results

The following scenarios were compared to the reference scenario and the LTDH scenario: power-to-heat only, TES only (various TES sizes), and power-to-heat and TES (various sizes) combined. The parameters for comparison include natural gas consumption, heat rejection, and the share of heat supplied to the system by each technical unit.

3.1. Natural gas consumption

Average value of natural gas consumption in 2017–2019 in the case of the existing DH system and LTDH is shown in Fig. 1. Overall, the trend is more or less the same for each year; natural gas consumption is slightly lower when an electric boiler is also integrated into the system. The effect is less noticeable with a lower heat demand, as in the case of LTDH and also in 2019 for the existing DH system. An electric boiler is more effective without TES or with smaller TES, although natural gas consumption is lower when both an electric boiler and TES are used.

The average decrease in natural gas consumption in 2017–2019 is shown in Table 4.

The effect of combining these technologies becomes more pronounced when the average electricity price is lower, while the power-to-heat usage potential is increased. Compared to the reference scenario, in the existing DH system, natural gas consumption can be reduced by up to 36% (2017 data, 150 000 TES and a 40 MW electric boiler). In the case of LTDH, the value for the identical technical combination will be 52%.

3.2. Heat rejection

Heat rejection is higher when the heat demand is lower. The trends are similar for all years and the graph shapes are the same. For each year, in the case of LTDH and the existing DH system, heat rejection is slightly lower when an electric boiler is used.

Average heat rejection for various cases in 2017–2019 is shown in Fig. 2.

The average decrease in heat rejection is shown in Table 5.

This effect becomes more pronounced when using a combination of TES and an electric boiler.

3.3. Share of heat produced by units

Theoretically, the integration of TES and an electric boiler will affect the CHP with the lowest priority. In this case, it is Tallinn CHP1, which does not have the ability to reject heat. The other CHP without heat rejection is Iru CHP, and since it is ranked first on the priority list, it will be able to get the necessary heat demand and operate full load the entire year. Other CHPs in the system (Tallinn CHP2 and Mustamäe CHP) have heat rejection.

The average share of heat production (2017–2019) for various technologies with and without an electric boiler in the case of the existing DH system and LTDH is shown in Fig. 3.

In this case, it can be seen that the use of an electric boiler has a negative effect on the heat production of the low-priority CHPs (in the case of Tallinn - Tallinn CHP1), which is less negative when an electric boiler is used. A slight positive effect is observed in the heat production of base load CHPs when using an electric boiler.

It is not surprising that the use of TES increases CHP heat production. This positive effect is visible in all cases shown in Fig. 3.

In terms of reducing the use of natural gas, it can be seen that the best effect can be achieved when TES and an electric boiler are used together, and the potential for reducing natural gas consumption is greater, as in the case of LTDH, resulting in less heat demand.

3.4. Sensitivity analysis

3.4.1. Threshold price

The electricity price threshold affects power-to-heat usage, and, consequently, natural gas consumption and heat rejection. When the threshold is higher, there will be more power-to-heat operating hours and, therefore, more heat will be produced.

The relation between the electricity price threshold and the share of the total heat demand produced by electric and natural gas boilers is shown in Fig. 4 as an average value for 2017–2019. The analysis presented in Fig. 4 was conducted for a 40 MW electric boiler and a 7000 m^3 TES for the existing DH system and LTDH.

As can be seen in Fig. 4, the threshold price should be more than 25 EUR/MWh, otherwise the integration of power-to-heat technologies into the system would have practically no effect, since the electric boiler will only be used for a few hours. The threshold also cannot be too high, because otherwise it would not be economically feasible, since heat generation from natural gas costs about 35 EUR/MWh, and when the electricity price threshold is higher than this,

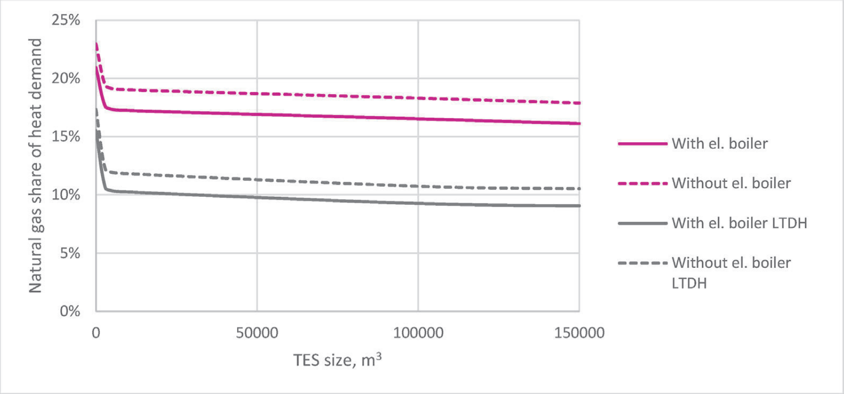


Fig. 1. Natural gas consumption with and without el. boiler for various TES sizes.

Table 4
Average decrease in natural gas consumption in the existing DH system and LTDH in 2017–2019.

	Without TES	With 3000 m^3 TES	With 7000 m^3 TES	With 100 000 m^3 TES	With 150 000 m^3 TES
Without el. boiler	0%	13%	14%	18%	19%
With 40 MW el. boiler	9%	30%	31%	35%	36%
Without el. Boiler LTDH	0%	25%	27%	33%	34%
With 40 MW el. Boiler LTDH	12%	45%	46%	51%	52%

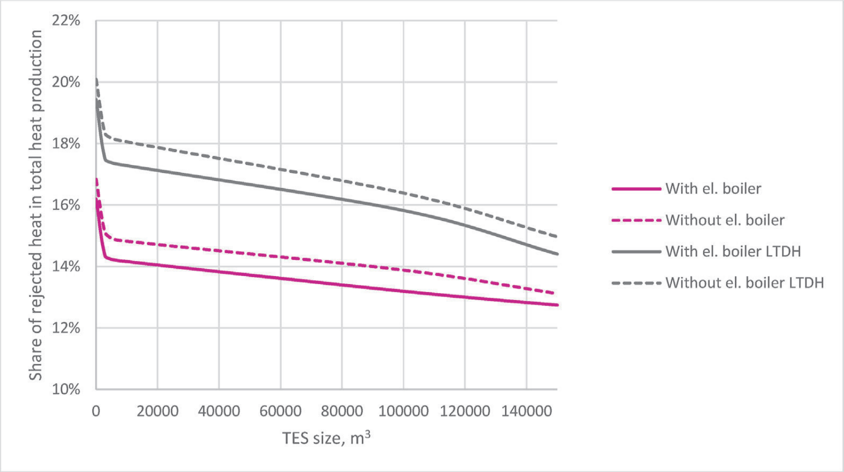


Fig. 2. Average heat rejection with and without el. boiler for various TES sizes in the existing DH system and LTDH in 2017–2019.

Table 5
Average decrease in heat rejection in 2017–2019.

	Without TES	With 3000 m^3 TES	With 7000 m^3 TES	With 100 000 m^3 TES	With 150 000 m^3 TES
Without el. boiler	0%	13%	14%	23%	26%
With 40 MW el. boiler	5%	30%	31%	37%	40%
Without el. Boiler LTDH	0%	11%	12%	19%	30%
With 40 MW el. Boiler LTDH	4%	27%	27%	34%	44%

it is more economically feasible to produce heat from natural gas.

It is interesting to note that the heat demand (existing DH system vs. LTDH) has a strong influence on the share of heat produced from natural gas. The effect is not as noticeable when it comes to the heat generated by the electric boiler. Both the share of natural gas and electric boiler are smaller in the case of LTDH, which means

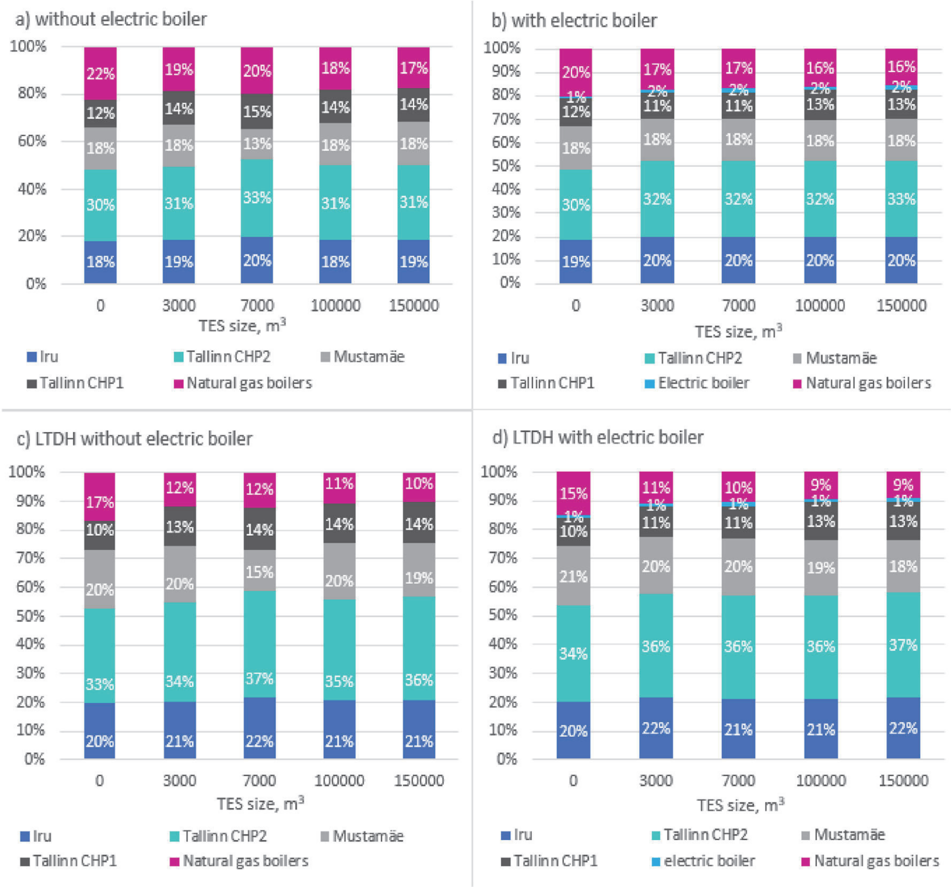


Fig. 3. Distribution of heat production in the DH system for various TESs integrated into system. 3a) DH system without electric boilers. 3b) DH system with electric boilers. 3c) LTDH system without electric boilers. 3d) LTDH system with electric boilers.

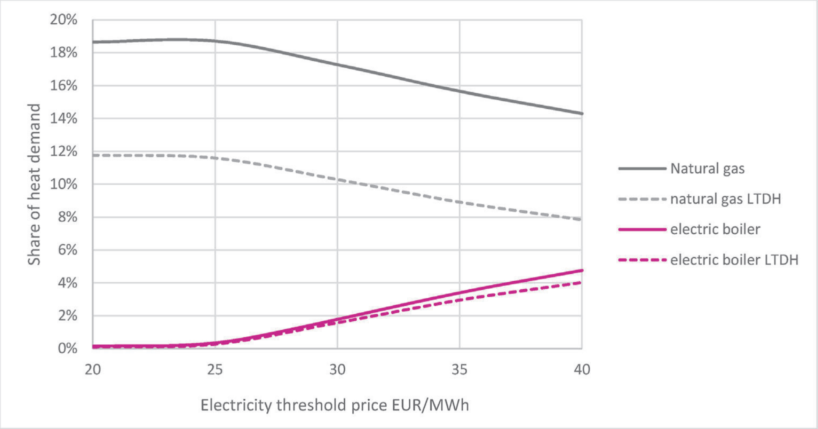


Fig. 4. Share of heat demand covered by electric and natural gas boilers at different threshold prices (2017–2019 average) in the case of a 40 MW electric boiler and 7000 m^3 TES.

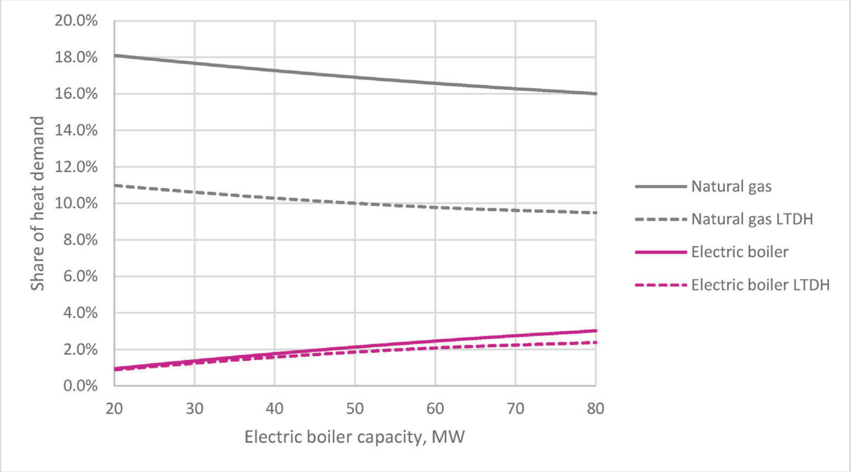


Fig. 5. Share of heat supplied to the system by an electric boiler and natural gas for various electric boiler capacities (2017–2019 average) at 30 EUR/MWh electricity threshold price and 7000 m^3 TES.

that in the case of LTDH, the share of heat produced by CHPs is higher.

3.4.2. Electric boiler capacity

Electric boiler capacity also affects the system, as a bigger electric boiler allows more heat to be produced. Still, the limiting factor here is heat demand. If the demand is not enough, there is no point in installing a larger boiler, and the amount of energy supplied to the system will not be greater when there is just not enough demand.

The greater the share of the electric boiler, the lower the consumption of natural gas. The share of heat supplied to the system by an electric boiler and natural gas for various electric boiler capacities is shown in Fig. 5 as an average value for the existing DH system and LTDH for 2017–2019.

In terms of the share of heat produced from natural gas, an increase in boiler capacity leads to a linear increase in the share of heat supplied by the electric boiler.

4. Conclusions

According to this study, using power-to-heat together with TES will help improve CHP flexibility, since then the system will not depend as much on the heat demand. Even using a small electric boiler will increase the flexibility because it will provide additional heat to the system that can be stored and used later. In the case of Tallinn, the best power-to-heat solution is about 40 MW_{th}.

CHPs with no base load that have no heat rejection can operate more efficiently and produce more heat when they have the ability to produce heat for storage, but the use of an electric boiler will have a negative effect on the heat production of CHPs of the lowest priority.

When economic conditions are not considered, then larger storage will yield better results, but in this case, economic conditions must also be considered for a feasible solution. The advantage of larger storage facilities is the fact that they can also be used to store seasonal solar energy, but the investments for this kind of storage are much greater and such storage requires a lot of space.

As a result, using these technologies together will have a greater impact than using these technologies separately. Using power-to-heat together with TES is a good technical solution for heat demand peak shaving and scientifically reducing natural gas consumption. It can also help stabilise the system when power consumption is too low.

The same effect can be achieved with heat-only boilers or with prosumers that use the same production strategy as described above, since the electricity used for electric boilers is taken from the grid. When the electricity that is used for electric boilers is taken directly from the CHP, this leads to boiler capacity restrictions, since boiler capacity cannot be greater than the electric output of the CHP. In this case, the effect of using an electric boiler is less significant, since the capacity is smaller. On the other hand, electricity will be cheaper, as the price of electircity does not include electrical grid fees.

It can be seen that the effects are more pronounced in the case of LTDH, since the percentage reduction in natural gas consumption and heat rejection is greater. Nevertheless, the shapes of the graphs are very similar in both cases (existing DH system and LTDH).

The flexibility of a CHP depends on whether the CHP uses heat rejection coolers and whether the CHP can operate at part load. When heat rejection is used, integrating power-to-heat and TES together into the system will help reduce heat rejection. Economic feasibility must be studied further. One of the hard-to-predict aspects is electricity prices and overlapping with high heat load.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors would like to acknowledge the support of the Tallinn University of Technology campus' energy management development plan project as well.

References

[1] European Commission. Fourth report on the state of the energy union. COM;

2019. 175 final 2019:27.
[2] Lund H, Østergaard PA, Connolly D, Mathiesen BV. Smart energy and smart energy systems. Energy 2017;137:556–65. https://doi.org/10.1016/j.energy.2017.05.123.
[3] Kurian B, Liyanapathirana R. Renewable energy resources development in the EU zone. Proc 4th Int Conf Electr Energy Syst ICEES 2018;2018:635–9. https://doi.org/10.1109/ICEES.2018.8443223.
[4] IEEE European Public Policy. Heating and cooling future of Europe and interactions with electricityvols. 1–6; 2018.
[5] Rehman H ur, Hirvonen J, Jokisalo J, Kosonen R, Sirén K. EU emission targets of 2050: costs and CO2 emissions comparison of three different solar and heat pump-based community-level district heating systems in nordic conditions. Energies 2020;13. https://doi.org/10.3390/en13164167.
[6] Lund H, Østergaard PA, Chang M, Werner S, Svendsen S, Sorknæs P, et al. The status of 4th generation district heating: research and results. Energy 2018;164:147–59. https://doi.org/10.1016/j.energy.2018.08.206.
[7] Lund R, Østergaard DS, Yang X, Mathiesen BV. Comparison of low-temperature district heating concepts in a long-term energy system perspective. Int J Sustain Energy Plan Manag 2017;12:5–18. https://doi.org/10.5278/ijsepm.2017.12.2.
[8] Höltinger S, Mikovits C, Schmidt J, Baumgartner J, Arheimer B, Lindström G, et al. The impact of climatic extreme events on the feasibility of fully renewable power systems: a case study for Sweden. Energy 2019;178:695–713. https://doi.org/10.1016/j.energy.2019.04.128.
[9] Bartela Ł, Kotowicz J, Dubiel-Jurgaś K. Investment risk for biomass integrated gasification combined heat and power unit with an internal combustion engine and a Stirling engine. Energy 2018;150:601–16. https://doi.org/10.1016/j.energy.2018.02.152.
[10] Volkova A, Latõšov E, Andrijaškin M, Siirde A. Feasibility of thermal energy storage integration into biomass CHP-based district heating system. Chem Eng Trans 2018;70:499–504. https://doi.org/10.3303/CET1870084.
[11] Hast A, Rinne S, Syri S, Kiviluoma J. The role of heat storages in facilitating the adaptation of district heating systems to large amount of variable renewable electricity. Energy 2017;137:775–88. https://doi.org/10.1016/j.energy.2017.05.113.
[12] Penttilä K. Waste-to-Energy plant as part of combined heat and power strategy – using the example of the Klaipeda case – 1 . 1 . Importance of circular economy is growing. 2012.
[13] Volkova A, Latosov E, Siirde A. Heat storage combined with biomass CHP under the national support policy. A case study of Estonia. Environ Clim Technol 2020;24:171–84. https://doi.org/10.2478/rtuect-2020-0011.
[14] CODE2. Case study factsheet Pärnu, Estonia, Pärnu CHP plant. 2014.
[15] Lepiksaar K, Volkova A, Ruseljuk P, Siirde A. The effect of the District heating return temperature reduction on flue gas condenser efficiency. Environmental and Climate Technologies 2020;24(3):23–38. https://doi.org/10.2478/rtuect-2020-0083.
[16] Johar DK, Sharma D, Soni SL. Comparative studies on micro cogeneration, micro cogeneration with thermal energy storage and micro trigeneration with thermal energy storage system using same power plant. Energy Convers Manag 2020;220:113082. https://doi.org/10.1016/j.enconman.2020.113082.
[17] Tilahun FB, Mamo M, Bhandari R. Optimal solar field and thermal storage sizing in hybrid solar biomass cogeneration plant. http://doi.org/10.1109/powerafrica49420.2020.9219945; 2020. 1-5.
[18] Dahash A, Ochs F, Janetti MB, Streicher W. Advances in seasonal thermal energy storage for solar district heating applications: a critical review on large-scale hot-water tank and pit thermal energy storage systems. Appl Energy 2019;239:296–315. https://doi.org/10.1016/j.apenergy.2019.01.189.
[19] Albertus P, Manser JS, Litzelman S. Long-duration electricity storage applications, economics, and technologies. Joule 2020;4:21–32. https://doi.org/10.1016/j.joule.2019.11.009.
[20] Schmidt O, Melchior S, Hawkes A, Staffell I. Projecting the future levelized cost of electricity storage technologies. Joule 2019;3:81–100. https://doi.org/10.1016/j.joule.2018.12.008.
[21] Gür TM. Review of electrical energy storage technologies, materials and systems: challenges and prospects for large-scale grid storage. Energy Environ Sci 2018;11:2696–767. https://doi.org/10.1039/c8ee01419a.
[22] Eser P, Chokani N, Abhari R. Trade-offs between integration and isolation in Switzerland's energy policy. Energy 2018;150:19–27. https://doi.org/10.1016/j.energy.2018.02.139.
[23] Zheng L, Zhu J, Lu DDC, Wang G, He T. Incremental capacity analysis and differential voltage analysis based state of charge and capacity estimation for lithium-ion batteries. Energy 2018;150:759–69. https://doi.org/10.1016/j.energy.2018.03.023.
[24] Ben Amer S, Bramstoft R, Balyk O, Nielsen PS. Modelling the future low-carbon energy systems-case study of greater Copenhagen, Denmark. Int J Sustain Energy Plan Manag 2019;24:21–32. https://doi.org/10.5278/ijsepm.3356.
[25] Bloess A. Impacts of heat sector transformation on Germany's power system through increased use of power-to-heat. Appl Energy 2019;239:560–80. https://doi.org/10.1016/j.apenergy.2019.01.101.
[26] Schweiger G, Rantzer J, Ericsson K, Lauenburg P. The potential of power-to-heat in Swedish district heating systems. Energy 2017;137:661–9. https://doi.org/10.1016/j.energy.2017.02.075.
[27] Østergaard PA, Andersen AN. Variable taxes promoting district heating heat pump flexibility. Energy 2021;221:119839. https://doi.org/10.1016/j.energy.2021.119839.
[28] Andersen AN, Østergaard PA. A method for assessing support schemes promoting flexibility at district energy plants. Appl Energy 2018;225:448–59. https://doi.org/10.1016/j.apenergy.2018.05.053.
[29] Andersen AN, Østergaard PA. Analytic versus solver-based calculated daily operations of district energy plants. Energy 2019;175:333–44. https://doi.org/10.1016/j.energy.2019.03.096.
[30] Jamaluddin K, Alwi SRW, Manan ZA, Hamzah K, Kleme JJ. A process integration method for total site cooling, heating and power optimisation with trigeneration systems. Energies 2019;12. https://doi.org/10.3390/en12061030.
[31] Nami H, Anvari-Moghaddam A, Arabkoohsar A. Thermodynamic, economic, and environmental analyses of a waste-fired trigeneration plant. Energies 2020;13:2476. https://doi.org/10.3390/en13102476.
[32] Pina EA, Lozano MA, Serra LM. Optimal operation and marginal costs in simple trigeneration systems including thermal energy storage. Energy 2017;135:788–98. https://doi.org/10.1016/j.energy.2017.06.101.
[33] Sinha R, Bak-Jensen B, Pillai JR, Zareipour H. Flexibility from electric boiler and thermal storage for multi energy system interaction. Energies 2019;13:1–21. https://doi.org/10.3390/en13010098.
[34] Valinejad J, Marzband M, Korkali M, Xu Y, Al-Sumaiti AS. Coalition formation of microgrids with distributed energy resources and energy storage in energy market. J Mod Power Syst Clean Energy 2020;8:906–18. https://doi.org/10.35833/MPCE.2019.000116.
[35] Wiryadinata S, Morejohn J, Kornbluth K. Pathways to carbon neutral energy systems at the University of California, Davis. Renew Energy 2019;130:853–66. https://doi.org/10.1016/j.renene.2018.06.100.
[36] Dorotić H, Ban M, Pukšec T, Duić N. Impact of wind penetration in electricity markets on optimal power-to-heat capacities in a local district heating system. Renew Sustain Energy Rev 2020;132. https://doi.org/10.1016/j.rser.2020.110095.
[37] Karmellos M, Georgiou PN, Mavrotas G. A comparison of methods for the optimal design of Distributed Energy Systems under uncertainty. Energy 2019;178:318–33. https://doi.org/10.1016/j.energy.2019.04.153.
[38] Wang C, Yan C, Li G, Liu S, Bie Z. Risk assessment of integrated electricity and heat system with independent energy operators based on Stackelberg game. Energy 2020;198:117349. https://doi.org/10.1016/j.energy.2020.117349.
[39] European Commission. Powering a climate-neutral economy: an EU strategy for energy system integration. http://doi.org/10.1155/2010/706872; 2020.
[40] Arabzadeh V, Pilpola S, Lund PD. Coupling variable renewable electricity production to the heating sector through curtailment and power-to-heat strategies for accelerated emission reduction. Futur Cities Environ 2019;5:1–10. https://doi.org/10.5334/fce.58.
[41] Bashir AA, Lund A, Pourakbari-Kasmaei M, Lehtonen M. Minimizing wind power curtailment and carbon emissions by power to heat sector coupling - a Stackelberg game approach. IEEE Access 2020;8:211892–911. https://doi.org/10.1109/ACCESS.2020.3039041.
[42] Jimenez-Navarro JP, Kavvadias K, Filippidou F, Pavičević M, Quoilin S. Coupling the heating and power sectors: the role of centralised combined heat and power plants and district heat in a European decarbonised power system. Appl Energy 2020;270:115134. https://doi.org/10.1016/j.apenergy.2020.115134.
[43] BloombergNEF. Sector coupling in Europe: powering decarbonization. 2020.
[44] Valančius K, Mikučionienė R. Solar energy as a tool of renovating soviet-type multi apartment buildings. Sol Energy 2020;198:93–100. https://doi.org/10.1016/j.solener.2020.01.046.
[45] Teräsvirta A, Syri S, Hiltunen P. Small nuclear reactor—nordic district heating case study. Energies 2020;1–15.
[46] Trabert U, Kelch J, Orozaliev J, Vajen K. Decarbonizing building stock with renewable district heating - a case study for a rural area in Germany. Proc ISES Sol World Congr 2019 IEA SHC Int Conf Sol Heat Cool Build Ind 2019;2020:470–81. https://doi.org/10.18086/swc.2019.11.02.
[47] Riigi Teataja. Elektrituruseadus 2003.
[48] Volkova A, Latõšov E, Mašatin V, Siirde A. Development of a user-friendly mobile app for the national level promotion of the 4 th generation district heating 2019;20:21–36.
[49] Masatin V, Latõšev E, Volkova A. Evaluation factor for district heating network heat loss with respect to network geometry. Energy Procedia 2016;95:279–85. https://doi.org/10.1016/j.egypro.2016.09.069.
[50] Nord Pool AS. Nord Pool. https://www.nordpoolgroup.com/; 2020.

Appendix 2

Publication II

Lepiksaar, K., Mašatin, V., Krupenski, I., & Volkova, A. (2023). Effects of Coupling Combined Heat and Power Production with District Cooling. *Energies*, 16(12). https://doi.org/10.3390/en16124552

energies

MDPI

Article

Effects of Coupling Combined Heat and Power Production with District Cooling

Kertu Lepiksaar, Vladislav Mašatin, Igor Krupenski and Anna Volkova *

Department of Energy Technology, School of Engineering, Tallinn University of Technology, Ehitajate tee 5, 19086 Tallinn, Estonia; kertu.lepiksaar@taltech.ee (K.L.); vladislav.masatin@taltech.ee (V.M.); igor.krupenski@taltech.ee (I.K.)
* Correspondence: anna.volkova@taltech.ee

Abstract: Over the past decades, combined heat and power production (CHP) has proven itself to be an efficient means of meeting both heat and power demands. However, high efficiency can be achieved with CHP plants when the heat load is sufficient, while lower-priority CHP plants must deal with the excess heat associated with power generation. This excess heat can be used for district cooling with absorption chillers. Although the absorption chiller is an efficient technology for using excess heat for cooling generation, its efficiency is very sensitive to driving hot water temperature. This paper provides a detailed analysis of how cooling generation in CHP plants using absorption chillers affects power generation and primary energy consumption. This study is based on the operational parameters of the Mustamäe CHP plant (Tallinn, Estonia) and the cooling demand of the Tehnopol science and business campus and proposes a sufficient cooling production capacity based on the estimation of the campus' cooling demand. Additional cooling production opportunities to meet district cooling demand are discussed and compared in this paper in terms of primary energy savings and economic profit. The study finds that for the effective use of CHP excess heat and efficient cooling production, the use of an 0.8 MW absorption cooler and 11.6 MW heat pumps is recommended. This system would use 1.9 times less primary energy for cooling generation than local cooling.

Keywords: absorption chiller; cogeneration; cooling demand; district cooling; energy planning; power generation

check for updates

Citation: Lepiksaar, K.; Mašatin, V.; Krupenski, I.; Volkova, A. Effects of Coupling Combined Heat and Power Production with District Cooling. *Energies* **2023**, *16*, 4552. https://doi.org/10.3390/en16124552

Academic Editors: Antonio Rosato, Inga Konstantinaviciute, Daiva Dumciuviene, Viktorija Bobinaite, Vaclovas Miškinis and Saulius Gudžius

Received: 13 March 2023
Revised: 8 May 2023
Accepted: 29 May 2023
Published: 6 June 2023

1. Introduction

Final energy consumption for cooling purposes has been increasing in recent years. In the European Union (EU), it was 2.7% in 2019 for commercial buildings [1]. The cooling demand is expected to triple by 2050 [2]. The building sector accounts for about 40% of the total final energy consumption in Europe and about 36% in the world [3]. Local energy grids, including district heating (DH), cooling and electricity networks, can be maintained, energy consumption reduced and efficiency improved with the help of district energy networks and careful planning [4,5].

Compared to local cooling, district cooling (DC) has several advantages. First, DC is more environmentally friendly than local cooling because DC can often use a variety of renewable energy sources to produce cooling energy. There are several technologies that can be used to generate cooling energy in DC systems. The most common techniques are absorption chillers, free cooling, heat pumps and cooling towers [6]. For example, DC can use free cooling from lakes, rivers and seawater [7]. The aforementioned natural sources can be also used for heat pump cooling when the temperature of the heat source is too high for free cooling [8,9]. Free cooling requires about 0.05 kW of electricity per 1 kW of cooling power [10]. When cooling is produced using heat pumps, the energy efficiency ratio is normally around 13–16, which means that 0.25 kW of electricity is needed per 1 kW [11]. Industrial waste heat and excess heat from combined heat and power (CHP) plants can also be used with absorption chillers [12]. In this case, the energy consumption for cooling generation is almost as low as for free cooling, about 0.2 kW per 1 kW of cooling energy [13]. Local cooling units usually use electricity, and the electricity consumption for 1 kW of cooling energy production is up to 1.2 kW [14]. Even if electricity is produced using renewable energy sources, DC production usually is more energy efficient.

Similarly, the authors of [15] conducted extensive research into the establishment of a DC network in Italy. In [15], various installations were evaluated in addition to the absorption chiller. The goal was to find an economically viable solution that could contribute to primary energy savings. The Italian study [15] compared four different scenarios, each with a different technical configuration involving electric chillers, boilers, CHP plants, absorption chillers, thermal energy storage units and heat pumps. It has been demonstrated that combining many different technologies produces the best results in terms of energy and economic compromise.

More renewable energy can be introduced into the system using solar energy [16]. Solar DC systems also use absorption chillers for cooling generation, but their main difference from CHP plants is that instead of excess heat, solar energy is used to generate hot water to drive the process. The main components of a typical solar absorption cooling system are a solar thermal collector, an absorption chiller, storage tanks, and an auxiliary boiler [16]. In addition to solar heat, hot flue gases can also be used as a heat source for absorption chillers. A similar system was explored in [17]. Like DH systems, solar-powered DC systems also need thermal energy storage to function optimally. It is argued that by using both cold and hot storage, the overall coefficient of performance (COP) of the system can be increased and the cooling plant's capacity can be lower than peak demand, which can also reduce costs.

When absorption chillers are used, special attention should be paid to their heat rejection systems. Typically, the heat rejection system capacity of an absorption chiller is about 2.35 times the cooling capacity of the chiller [18]. When thermal energy storage units are also integrated into the system and there is a demand for DH, the rejected heat from the cooling process can be used for heating.

Absorption chillers can help alleviate the problem of low summer heat loads in CHP plants because absorption chillers require hot water to start the cooling process in the summer, when the cooling demand is high. Over the past decade, the number of CHP plants in Estonia has increased, and there are currently over 20 CHP plants in Estonia, four of which are located in Tallinn [19]. The main operational issues of CHP plants are related to fluctuating and low heat loads during the summer period. In the case of low heat demand, the plant either does not work at all or uses coolers to reject heat. Heat rejection can allow the CHP system to continue producing electricity; however, since all heat energy is wasted, this is an inefficient use of energy. This kind of practice is only feasible when subsidies are provided for producing electricity. In case of Estonia, this refers to biomass CHP plants that are not older than 12 years. These types of CHP plants receive 53.7 EUR/MWh$_{el}$, which makes heat rejection feasible. In Tallinn, there are three CHP plants that have coolers installed on the roof [20].

CHP plants are important for power grid stabilisation, that is, for ensuring and maintaining the frequency and voltage in the power grid [21]. In light of climate change, when non-combustion heat sources are more relevant than ever, the importance of CHP plants in the energy system may be questionable. While there are several ways to generate electricity and/or heat from non-combustion sources such as solar, wind, geothermal, etc., CHP plants have advantages compared with these technologies, such as the generation of electricity and heat in a single process with very little loss and non-fluctuating energy production. In addition, CHPs plan an important role in balancing the energy system. When CHP plants run on biomass, the energy produced can be considered renewable.

Absorption chillers play an important part role in coupling DC with CHP plants. Various absorption designs are available, mainly single-stage and two-stage absorption chillers. Single-stage machines can be driven by hot water (90–115 °C) or low-pressure steam (1 bar) and are often used with reciprocating engine CHP plants. Compared to single-stage chillers, two-stage machines require higher-temperature hot water (e.g., 175 °C) or higher-pressure steam (e.g., 8 bar) and are often used with combustion turbine CHP plants. Typically, the COP for a single-stage absorption chiller is about 0.75, while for a two-stage absorption chiller, the COP is 1.35 or higher [22].

Absorption chillers also couple well with solar collectors and solar ponds. In [23] a thorough review and comparison of solar enhanced heating and cooling systems was provided. As a result, the study showed that although solar radiation intensity graphs and cooling consumption graphs have similar profiles, absorption chillers require an extra heat flow that can be provided by natural gas boiler, as was demonstrated in [23]; however, in terms of primary energy usage and the cost of energy, they also suggest the use of heat pumps. To gain even more savings on a primary energy CHP, excess heat can be used. In [24], a novel solar pond and absorption chiller conception is introduced for cooling energy production. Using solar ponds can increase the flexibility of using solar energy, but it was also pointed out that as driving hot water temperature is crucial to the absorption chiller's coefficient of performance (COP), a sufficient amount of solar radiation is necessary, and the pond must be designed carefully.

For coolant temperatures of 4 °C and above (for example, in air conditioning systems in buildings), a mixture of water (refrigerant) and lithium bromide (LiBr) (absorbent) is usually used. For coolants with temperatures below 4 °C (e.g., cold storage), the usual mixture is ammonia (refrigerant) and water (absorbent) [22]. Absorption chillers are most cost-effective in facilities that have significant air conditioning needs or year-round cooling loads. Facilities with significant year-round air conditioning loads include hospitals, hotels, large commercial office buildings and college campuses. Facilities that may require constant year-round cooling include manufacturing plants with process cooling needs, cold storage warehouses, data centres and district energy plants [22].

Another advantage of DC is cooling load diversification [25]. In [25], a techno-economic analysis of a DC system was carried out in which a cold storage unit was also integrated into the system to smooth the load profile. The effect was similar to using thermal energy storage in DH systems [26]. It provided more flexibility for load switching, made the system more reliable and helped integrate more renewable energy sources into the system.

Similar to DH, DC systems can also be more beneficial if more consumers are connected to the network [27], although DC systems are never as large as DH systems because DH consumers are mostly multi-family buildings and office buildings, while DC is mainly only for office buildings and very large consumers such as hospitals, supermarkets, etc. As the temperature difference between supply and return in DC systems is much smaller compared to DH systems, the pipe diameter in a DC system is therefore also larger compared to a DH network with same capacity. This leads to the need for larger pipes and greater investments to establish a DC network [6].

This study focuses on coupling CHP plants with DC using absorption chillers and offers advice on how to plan for flexible and cost-effective cooling production. In this study, the Mustamäe CHP plant and the nearby Taltech university campus and Tehnopol science and business park were used as a case study. The paper investigates the relationship between electric power and cooling energy generation. There are several studies on the efficiency of trigeneration [24–26], improving the absorption chiller's coefficient of performance (COP) through various operational changes and the use of thermal energy or cold storage [28]. This article fills the gap between trigeneration power and cooling energy production. As in the case of cogeneration of heat and electricity, the more heat is generated, the less power is produced [29,30]. The same can be said for cooling and power cogeneration. However, because the processes are different, the relationship between the two technologies—heat and power cogeneration vs. cooling and power cogeneration—is different since cooling production is not as simple as the production of heat [31,32].

In the Ülemiste district of Tallinn, a DC network is being constructed that will use the excess heat from the Tallinn CHP plant [33]. According to the absorption chiller datasheet, the cooling capacity corresponds to the temperature at the hot water inlet, where a 39% loss in cooling capacity is indicated when the driving hot water temperature is lowered to 77 °C. This study hereby investigates the roots of these problems.

The future of Tallinn's DC network was postulated and thoroughly examined in [34]. A comprehensive planning procedure was followed, beginning with an analysis of potential DC network locations, followed by an assessment of potential cooling needs and piping, and finally a suggestion of potential facilities for cooling production. The Mustamäe district was not evaluated in [34] because it is not located in the city centre and there may not be sufficient cooling demand for the district energy company. Nevertheless, this paper investigates the cooling demand in the Mustamäe district to determine whether it would be beneficial to couple the CHP plant with district cooling. As in [34], potential consumers were identified, and appropriate production facilities were recommended based on their cooling demand.

This paper thoroughly explores the cooling energy production process, examining each step. For the analysis, calculations were performed for the Mustamäe CHP plant using the data from the Tallinn DH system on the heat load and the estimated DC demand in the Mustamäe district. In this study, the following research caps are addressed:

- How does coupling with an absorption chiller affect the operation and electricity production of the CHP?
- Which operational regime would be the most energy efficient for cooling production, and which would be the most energy efficient for electricity production? Which regime should be preferred?
- Would using an absorption chiller be cost-effective, and how large of a cooling load could it cover?

The Mustamäe CHP plant was launched in 2019. The plant uses woodchips as fuel and provides heat to the united DH network of Tallinn, which is about 470 km long, with an annual heat consumption pf around 1750 GWh [35]. Flow temperatures in the Tallinn DH network are rather high—the supply temperature is around 65 °C, and the return temperature is around 44 °C. The Mustamäe CHP plant's nominal thermal power is 47 $\mathrm{MW_{th}}$, and its electrical power is 10 $\mathrm{MW_{el}}$. The plant has auxiliary coolers installed to maintain sufficient heat load for electricity generation.

Since the absorption chiller load is largely dependent on the available heat flow, it is clear that an auxiliary cooling unit is required in the event of a fluctuating cooling demand. In this study, various auxiliary cooling technologies were evaluated in terms of cost efficiency and primary energy savings.

This paper could be useful to district energy planners, district heating and cooling companies, CHP plant engineers, and real estate developers.

2. Method

This section explains how to determine the cooling production volume of an absorption chiller based on hot water temperature. The Method section also provides an estimate of the Mustamäe district's cooling demand. The system boundaries are shown in Figure 1.

As can be seen on Figure 1, the study concentrates on the generation of cooling by the absorption chiller and auxiliary cooling generation, which could be achieved, for example, by a heat pump, and the devices that either have effect on cooling generation or are affected by it. Within these boundaries are also the turbine that effects the absorption chiller and drives the generator. Within the boundaries there is also DC heat exchanger, which is connected to cooling sink, that is the DC network.

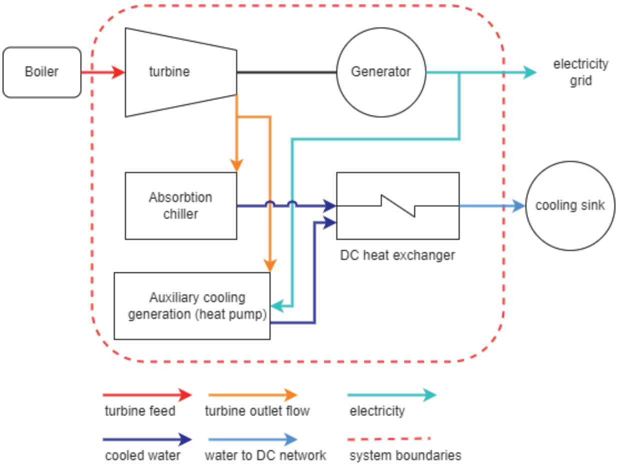


Figure 1. System boundaries.

2.1. Technical Process

In this study, the effects of coupling DC with CHP plants on electricity production are examined via the technical processes that take place in absorption chillers. Many simultaneous, interdependent processes take place in an absorption chiller, and all these processes and the interrelationships between these processes are examined in this paper. The aim of this study is to determine the effects of coupling DC with CHP plants.

Absorption chillers require a heat flow to initiate processes that ultimately create a cooling effect. When DC and a CHP system are connected, this heat flow comes from the CHP turbine condenser. The heat flow is necessary for the desorption process to separate the strong lithium–bromide (LiBr) solution from the water prior to the absorption process that creates the cooling effect.

A diagram of the absorption chiller processes and their interconnections is shown in Figure 2. Driving hot water flow form the turbine is marked with red lines, cold water flow to DC heat exchanger is marked with light blue lines, strong LiBr solution flow from desorber to absorber is marked with orange line, weak LiBr solution flow from evaporator to desorber is marked with yellow line. Condensate flow from the desorbtion process from condenser to evaporator is marked with green line and chiller condenser cooling circuit is marked with dark blue lines.

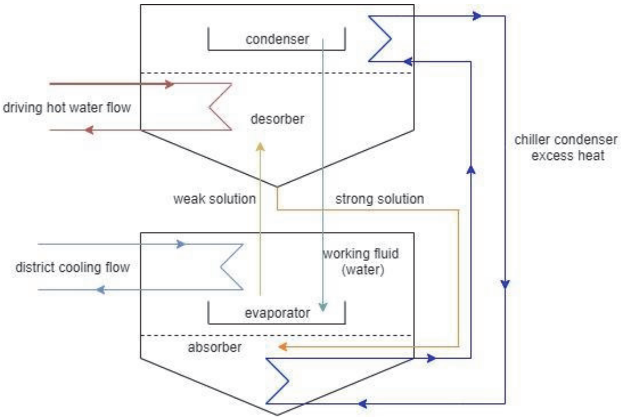


Figure 2. Absorption chiller flow diagram.

In this study, the following parameters of the absorption chiller's flows and the CHP turbine condenser's flow are most relevant: the temperature t (°C), pressure p (bar) and flow rate G (kg/s).

The cooling effect in the absorption chamber of an absorption chiller is caused by near-vacuum pressure, which causes the water to evaporate at very low temperatures (around 3–7 °C, depending on the chamber pressure). Water that is sprayed into the absorption chamber evaporates, creating the cooling effect. The cooling effect is greater when the desorption of water and LiBr is caused by the driving hot water flow. The more intense the desorption, the greater the flow of the strong LiBr solution and the greater the flow of water vapour into the absorption chamber. The water that evaporates during the desorption process is condensed again and then sent to the absorption chamber as well. The flows of the strong LiBr solution and condensate water are important for maintaining near-vacuum pressure in the absorption chamber. The condensate water flow is also necessary for obtaining the cooling effect from the evaporation of water in the absorption chamber.

The relationship between the specific enthalpy h_1 (J/kg) of the driving hot water flow and the desorption of a weak LiBr solution can be illustrated using Figure 3. The driving hot water flow is from the same flow as the turbine inlet flow. The mass concentration of a weak solution x_W is usually 60%, and the mass concentration of a strong solution x_S is usually around 64–65%. The higher the specific enthalpy of the driving hot water flow, the higher the concentration of the strong solution [36].

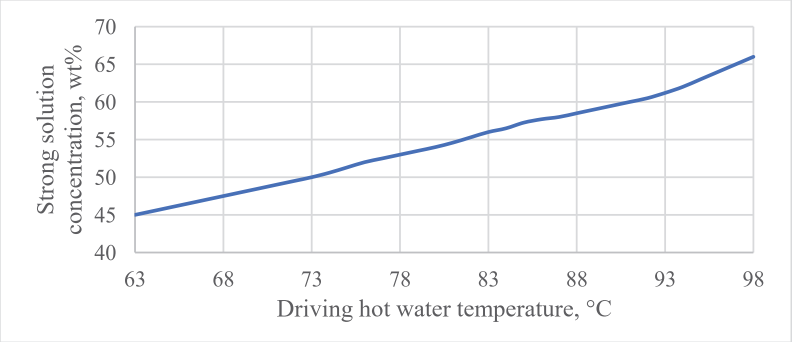


Figure 3. Strong solution concentration in relation to driving hot water temperature [37].

As can be seen in Figure 2, the higher the specific enthalpy and temperature of the flow, the more intense the process is. However, there is a limiting factor for the flow temperature that is set by the turbine condenser that the driving hot water flow comes from. For the electricity generation process, it is important that the steam passing through the turbine condenses in the condenser, so it sets a limiting factor for the maximum driving hot water specific enthalpy, which is about 2680 kJ/kg, that is, about 95 °C at a low vacuum (about 0.5 bar).

The low pressure in the absorption chamber is important for obtaining the cooling effect from water evaporation. Low pressure is created by the absorption of the water and the strong LiBr solution. The higher the concentration of the LiBr solution, the more intense the absorption process is, and the lower the pressure that can be maintained in the absorption chamber. The relationship between the concentration of the strong solution, the pressure in the absorption chamber and the saturation temperature of water vapour is shown in Figure 4.

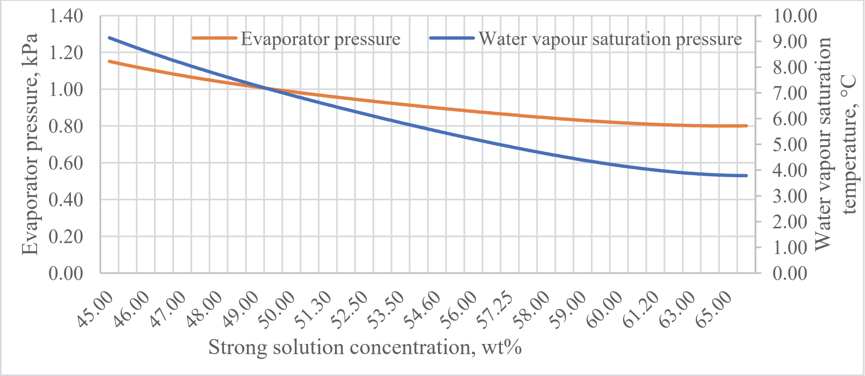


Figure 4. Evaporator pressure and water vapour saturation temperature at strong solution concentrations from 45 to 66%.

As seen in Figure 4, a strong solution concentration is crucial for the cooling effect because the lower the saturation temperature of the water vapour, the more water that can be evaporated and the more heat that can be absorbed.

The district cooling water flow rate determines the COP of the system since the DC supply temperature affects the heat transfer during the cooling process. The higher the temperature of the DC return flow, the more intense the evaporation process is and the better the COP and cooling capacity are.

Figure 5 depicts the relationship between the driving hot water flow temperature and the COP of an absorption chiller.

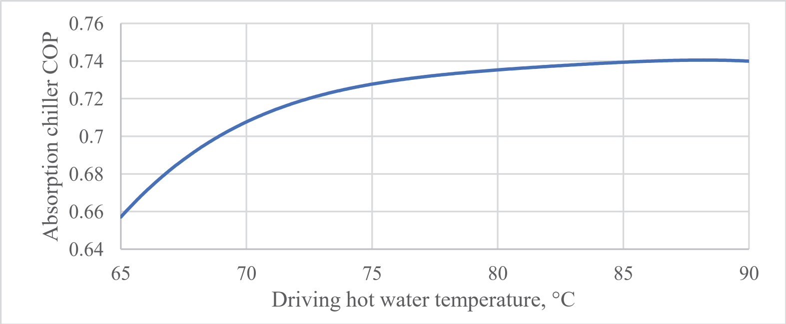


Figure 5. Absorption chiller COP at driving hot water temperatures ranging between 65 and 90 °C.

For power generation, the turbine output power E (W) can be determined via the enthalpies of the steam at the inlet and outlet of the turbine using Equation (1):

$$E = G_T(h_1 - h_2), \tag{1}$$

where G_T is the turbine steam mass flow rate (kg/s), h_1 (J/kg) is the turbine steam inlet specific enthalpy and h_2 (J/kg) is the turbine steam outlet specific enthalpy.

As can be seen in Equation (1), if the specific enthalpy of the flow at the outlet of the turbine is lower, then more power can be generated. Since the specific enthalpy of the flow at the turbine inlet is fixed, and the outlet flow can be adjusted to fit the needs of DH (or, in our case, DC) power generation depending only on the flow at the turbine outlet.

2.2. Mustamäe District Cooling Demand Estimation

The influence of district cooling on power generation was studied using a case study of the Mustamäe CHP plant and potential district cooling consumers in Mustamäe. First, potential consumers located near the Mustamäe CHP plant were selected. Figure 6 provides a map showing the Mustamäe CHP plant (marked with red lines), Tallinn University of Technology campus buildings (marked with pink lines) and Tehnopol Science park office buildings (marked with yellow lines).

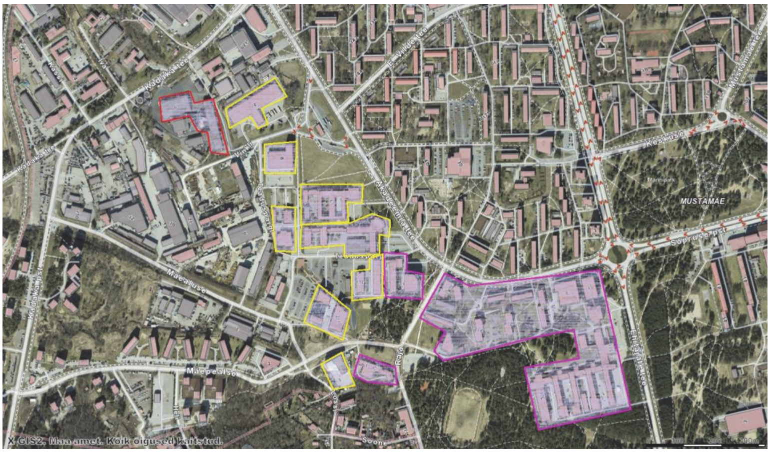


Figure 6. Mustamäe DC region. Mustamäe CHP plant—red lines; Tallinn University of Technology campus—pink lines; Tehnopol Science Park—yellow lines.

At the moment, there is no district cooling in the Mustamäe district. There is the Mustamäe CHP plant, which supplies heat to the entire Tallinn DH network. The thermal capacity of the Mustamäe CHP plant is 47 MW, of which 9 MW comes from the flue gas condenser, and during summer period, the heat is rejected. The plant's electric capacity is 10 MW.

Since there are several office buildings on the Tallinn University of Technology campus and other types of public buildings that could be excellent potential consumers of DC, local utilities are in the process of planning a district cooling region there.

The TalTech campus consists of 26 buildings, including administrative buildings, research laboratories and auditoria. The campus is partially connected to the DH network (14 buildings), while the remaining buildings (12 buildings) are connected to a small local, gas-fired DH network. Cooling is provided by local electric chillers. A climate-neutral TalTech campus is one of the university's ambitious sustainable development goals and is set in its strategic development plan until 2035. Cooling decarbonisation will reduce energy-related CO_2 emissions. Data on the cooling demand of the Tallinn University of Technology were provided by the university's administrative department. The plan to achieve a carbon neutral university campus for TalTech was developed in [38].

The Tehnopol Science Park is located near the Tallinn University of Technology and provides offices for over 200 technology companies and working spaces for over 4000 employees. Two laboratories and more than 55,000 m^2 of office space are leased. The Science Park was designed with an emphasis on the well-being of workers and the park's small ecological footprint. In addition to offices, the Science Park has several eating areas, sports facilities and other amenities [39].

For Tehnopol Science Park's cooling demand, data from the Estonian Building Register [39] about the buildings' useable surface were used. It was multiplied with the average cooling demand per 1 m^2, which in case of Tallinn, Estonia, is about 50 W/m^2 [40]. For the Tallinn University of Technology campus, the cooling demand is 7.4 MW, and for Tehnopol Science Park, the cooling capacity should be around 5 MW. Part of the cooling energy will be provided by absorption chillers, which will use the excess heat from the Mustamäe CHP plant. It should be noted that there are several other potential DC consumers located nearby.

According to the technical specifics of a conventional absorption chiller, the maximum capacity of the absorption chiller for the Mustamäe CHP plant is about 0.8 MW. This means that other cooling units are needed to cover the area's cooling demand, and the absorption chiller would have to operate at full load almost 24/7. The best location for the prospective absorption chiller would be in the territory of the CHP plant, which is marked with red borders in Figure 5, so it would be convenient to access driving hot water with minimal losses.

To obtain accurate operational data for the absorption chiller, a cooling demand profile was generated for the Tallinn University of Technology campus and the Tehnopol Science Park using EnergyPRO software. For input data, temperatures from 2018 to 2021were used. The cooling demand profile for the Mustamäe district and the proportion of the cooling demand that can be covered by the Mustamäe CHP plant's absorption chiller are shown in Figure 7. Figure 7 also takes into account the availability of excess heat as DH has a higher priority than district cooling, meaning that if heat is needed for heating purposes, it cannot be used for absorption.

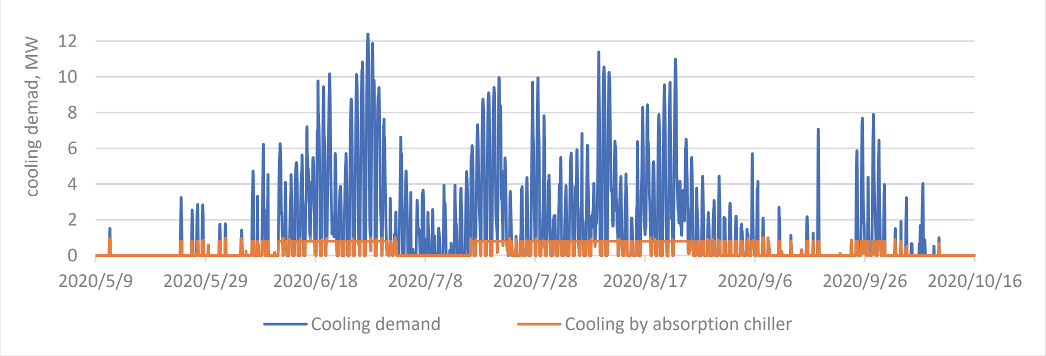


Figure 7. Tallinn University of Technology and Tehnopol Science Park cooling needs, and the cooling produced by the absorption chiller.

As can be seen in Figure 7, absorption chillers need some type of backup since in the summer, when the cooling demand is the highest, there is a two-week period during which the CHP plant undergoes repairs and maintenance and the plant ceases operation. There is another two-week period when the CHP plant must cover the heat demand of the DH network since a CHP plant with a higher priority is undergoing annual maintenance. Thus, there are about four weeks in the summer when the absorption chiller cannot operate due to a lack of heat. This issue can be solved by using auxiliary boilers or extra chillers.

Technical specifics of the proposed absorption chiller are provided in Table 1.

Table 1. Technical specifics of the absorption chiller.

Parameter	Value
Absorption chiller type	Single-stage
Heat input	1.1 MW
Cooling output	0.8 MW
Required condenser heat rejection	2 MW
Driving hot water input temperature	90 °C
Driving hot water output temperature	68 °C
Driving hot water flow rate	43.7 m^3/h
Chilled water input temperature (DC return)	15 °C
Chilled water output temperature (DC supply)	7 °C
Chilled water flow rate	86.5 m^3/h

2.3. Mustamäe District Cooling Demand Estimation

To cover the cooling needs of the Tallinn University of Technology campus and the Tehnopol Science Park, extra cooling units must be used in addition to the absorption chiller. The capacity of the extra cooling units can be discussed as cooling peak loads, as the cooling demand depends upon the outdoor temperature. The number of peaks in the demand graph can vary over the years, as can the height of the peaks. In this study, normalised temperatures for the year 2020 were used. This means that temperatures were generated according to long-time climate average so that they would represent the annual average temperature and normal temperature amplitude. Nevertheless, the peaks should be considered for the determination of cooling capacity to provide a sufficient load for covering the demand on the days when it is the most necessary. As the climate is warming and the frequency of heat waves in the summer is increasing, installing a sufficient amount of cooling generation is justified. There are several possible solutions for cooling generation. In the case of Mustamäe, cooling towers and heat pumps can be recommended. Cooling towers are recommended since there is land available for the installation. Heat pumps can also be a good solution if located at the CHP plant since they can be used as similar power-to-heat technologies. In the summer, it would be beneficial to use electricity for cooling generation rather than supply it to the power grid due to low electricity consumption and the greater availability of solar electricity. In addition, there are photo-voltaic panels installed in the power plant that can be used in the summer period for powering heat pumps. Since there are no natural sources of free cooling in the vicinity of Mustamäe, free cooling will not be an option to meet the cooling demand. Table 2 provides the data required to assess the best technical solution for cooling production in the district.

Table 2. Parameters for cooling technology evaluation.

Cooling Technology	Installation Costs, EUR/MW	Annual O&M Costs, EUR/MW/year	Estimated Service Life, Years
Absorption chiller [22,41]	68,000	900	30
Cooling towers [42,43]	12,000	11,000	20
Heat pumps [44,45]	44,000	2000	20

Cooling towers are a common cooling solution due to their low installation costs and ease of use. The biggest disadvantage of this technology concerns the high operation and maintenance (O&M) costs, which are caused by sewage costs, which account for approximately 58% of total operation and maintenance costs, and the costs of treated cooling water, which account for approximately 31% [46]. High investment costs can be a barrier to using an absorption chiller to produce cooling, but when the installation costs are divided by the estimated service life, it turns out to be the least expensive option, even with the O&M costs.

In the case of the Mustamäe district, there are several possible technology combinations for cooling production:

1. The use of 12.4 MW cooling towers;
2. The use of 12.4 MW heat pumps;
3. The use of 11.6 MW cooling towers and a 0.8 MW absorption chiller;
4. The use of 11.6 MW heat pumps and a 0.8 MW absorption chiller;
5. The use of a 0.8 MW absorption chiller and various combinations of heat pumps and cooling towers.

Cooling towers are not recommended in this case since their annual costs are higher than the annual costs of the heat pumps [47]. They would only be recommended and economically feasible for smaller loads, where the benefit of low investment costs is greater. As a result, technical options that contain only heat pumps or a combination of heat pumps and an absorption chiller were compared based on their economic parameters, with the results provided in Table 3.

Table 3. Economic parameters for technical solutions proposed.

Technical Solution	Total Investments, EUR	Annual Costs, EUR
12.4 MW heat pumps	545,600	52,100
0.8 MW absorption chiller and 11.6 MW heat pumps	564,800	51,250

The annual costs are determined by dividing the investment costs of the equipment by its service life and then adding its O&M costs. The economic difference between these two solutions is negligible, as shown in Table 3. The electricity consumption of the heat pumps and the absorption chiller is considered in the O&M costs. The main difference is that using an absorption chiller improves the overall primary energy efficiency of a CHP plant, whereas using heat pumps has no effect on this.

3. Results

This section investigates the possible annual production and operating hours of an absorption chiller. According to the methodology that was provided in the previous section, the power loss caused by the absorption chiller maintaining a hot water temperature is discussed, in addition to the proper temperature for a hot water supply using the methodology described in the previous section.

Absorption Chiller Operation Mode

According to the data provided in Figure 7, the absorption chiller will operate for about 1530 h per year at normal year temperatures. For about 1260 h, the chiller will operate at full load, which is 82% of the operating time. The annual cooling demand of the chosen DC network will be 5713 MWh, and the absorption chiller can cover 1104 MWh, which is 19.3% of the total cooling demand.

According to the absorption chiller processes described in the Methods section and the proposed absorption chiller capacity, the power produced and the cooling capacity for the driving hot water temperatures between 63 and 98 °C are shown in Figure 8.

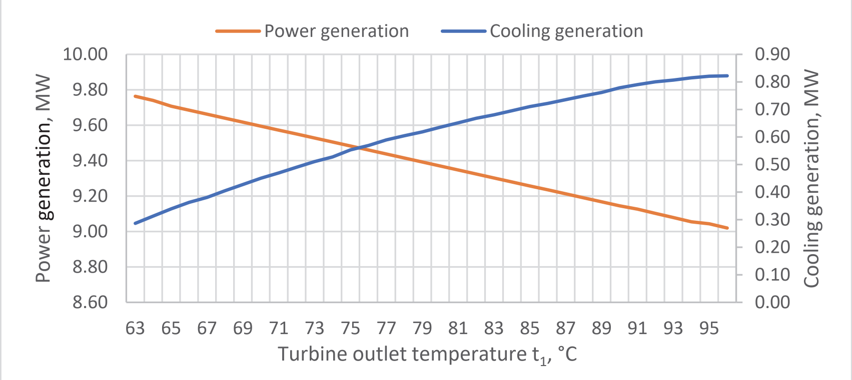


Figure 8. Mustamäe CHP plant power generation and absorption chiller cooling generation at driving hot water temperatures ranging between 63 and 98°.

As shown in Figure 8, when the absorption chiller is operating at full load, i.e., 0.8 MW, then the turbine's electrical power will be 9.14 MW, which means that using the absorption chiller at full load will reduce the turbine's power generation by 6.3%. If the turbine is operated at maximum load and the chiller is using 70 °C driving hot water, then the absorption chiller will only be able to operate at a capacity of 0.45 MW, with a 45% reduction in capacity.

When using local cooling, the annual primary energy consumption (PEC) for cooling will be calculated according to Equation (2):

$$PEC = \frac{Q_c \cdot PEF_{el}}{COP_{ac}} \quad (2)$$

where Q_c (MWh) stands for the cooling consumption, PEF stands for the primary energy factor and COP is the coefficient of performance. When the primary energy factor for electricity is PEF_{el} = 2 [48], the COP of a normal air conditioning and cooling system is estimated to be COP_{ac} = 3 [49,50] and the cooling demand for the observed district is 5713 MWh, then the PEC of Mustamäe local chillers would be also 3808 MWh. In the case of using an absorption chiller and heat pumps for cooling generation, the PEC would then be calculated according to Equation (3):

$$PEC_{abs+hp} = Q_{c,abs} \cdot PEF_{abs} + \frac{Q_{c,hp} \cdot PEF_{el}}{COP_{hp}} \quad (3)$$

where $Q_{c,abs}$ (MWh) stands for the cooling demand covered by the absorption chiller, which, according to this study, is Q_{abs} = 1104 MWh, and PEF_{abs} is the primary energy factor for cooling generation using an absorption chiller, which is PEF_{abs} = 0.7 according to the methodology for calculating building energy efficiency in Estonia [51], this gives a PEC value for the cooling energy provided by absorption chiller of 773 MWh. The $Q_{c,hp}$ (MWh) represents the cooling demand covered by the heat pump, which is $Q_{c,hp}$ = 4609 MWh in the case of this study. The COP value for the heat pump is estimated to be COP_{hp} = 4 [11]. This provides 2304 MWh for cooling energy generated by the heat pumps. The total PEC for the absorption chiller and heat pump solution for cooling generation is therefore 3077 MWh, which is 19% lower than the energy consumption for local cooling.

If all cooling demands were covered by heat pumps, the annual PEC would then be 2857 MWh, which would be even lower than using an absorption chiller with heat pumps; this would be a PEC of 25% less than local cooling and a PEC of 7% less than using an absorption chiller with heat pump. Table 4 shows the PEC results of each cooling generation option.

Table 4. Primary energy consumption (PEC) for technical solutions proposed.

Technical Solution	Primary Energy Consumption, EUR
12.4 MW local cooling (air conditioners)	3808
12.4 MW heat pumps	2857
0.8 MW absorption chiller and 11.6 MW heat pumps	3077

For future development, it is recommended to install solar collectors in combination with thermal energy storage units. Since the absorption chiller's condenser needs cooling, this excess heat can also be utilised. It should be noted that this is low-grade excess heat, the temperature of which can be around 35–40 °C. The absorption chiller at the Mustamäe CHP plant will produce 2760 MWh of excess heat during the operating period. This heat can be used to preheat the DH supply or for DH via heat pumps. Thermal energy storage will make the system more flexible.

4. Discussion

District cooling can help improve the efficiency of primary energy use in CHP plants as in this way, excess heat from electricity production can be used for cooling generation. District cooling is a more environmentally friendly option than local cooling as it uses less primary energy to generate cooling energy. In the case of the Tallinn University of Technology and the Tehnopol Science Park, the annual primary energy consumption for cooling will be 19% less when using an absorption chiller and heat pumps compared to local cooling solutions.

A reduction in power generation should not be a concern if an absorption chiller is installed. As can be seen from this study, the impact on power generation is insignificant. In the case of the Mustamäe CHP plant, an absorption chiller operating at full load would only reduce power generation by 6.3%. The effect will be different when the absorption chiller's driving hot water is reduced, since lowering the temperature of the driving hot water from 90 °C to 70 °C will result in a 45% decrease in cooling generation. Installing absorption chillers at the CHP plant will certainly have a positive effect on the plant's energy efficiency since it utilises excess heat from power generation instead of rejecting it via coolers.

It should also be noted that absorption chillers that use excess heat from CHP power generation will require auxiliary boilers or other cooling generation units to cover the cooling demand because CHP plants have a two-week downtime period during the summer for maintenance and repairs. If there are other CHP plants in the area, there may be another two-week period without excess heat because the CHP has to cover the heat load, compensating for the higher-priority CHP while it undergoes its annual maintenance.

Absorption chillers work very well with both cold and thermal energy storage. Cold storage can help smooth out peaks in cooling demand, while thermal energy storage can provide driving hot water for absorption chillers or store excess heat from the chiller's condenser for DH. Thermal energy storage using option should be further studied.

The cooling demand can also be covered by using only heat pumps, which was also a proposed in this paper as an option. This would result in an even smaller PEC, 7% smaller, than a solution in which absorption chiller and heat pumps are combined. In addition, when only heat pumps are used for cooling generation, the CHP electricity production would not be affected because unlike absorption chillers, heat pumps do not require a high-temperature heat source. The negative aspect of this solution is that the CHP plant would need to reject heat with chillers during the summer period, which would not be an effective use of energy. When an absorption chiller is used for cooling generation, it uses the excess heat of the power plant that would have otherwise been rejected by chillers.

5. Conclusions

As a conclusion it can be said that for cooling generation for a DC network, heat pumps would result with the best primary energy consumption, as is shown in Table 4. Nevertheless, heat pumps can be used only in a district where are also low-grade energy sources or industrial heat sources available, which, in case of this study, is a CHP plant. The aim of this study was to find a good solution for cooling generation for a DC network that is located near a CHP plant. Another aim of the study was to find a good way to utilise the CHP plant's excess heat that is normally rejected by chillers, which is not an efficient use of energy. As an option that could do both—produce cooling and utilise excess heat—an absorption chiller is examined. In this study, the operation of an absorption chiller is thoroughly analysed, and the results show that when absorption chillers are used, power generation would decrease by 6.3%. As absorption chillers cannot cover the whole cooling load of the district, heat pumps should also be used. Heat pumps could be used for cooling generation without absorption chiller; however, in this case, the excess heat of the CHP plant would not be completely utilised.

Both proposed solutions would result in a smaller PEC than local cooling and would have approximately the same installation and operation and maintenance costs.

Author Contributions: Methodology, K.L.; Validation, V.M.; Investigation, K.L. and I.K.; Data curation, V.M.; Writing—original draft, K.L.; Writing—review & editing, A.V.; Supervision, I.K. and A.V.; Project administration, A.V.; Funding acquisition, A.V. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Nordic Energy Research in the frame of the joint Baltic-Nordic Energy Research Program project project no. 117686, "Waste heat in smart energy systems".

Data Availability Statement: Publicly available datasets were analyzed in this study. This data can be found here: https://livekluster.ehr.ee/ui/ehr/v1 (accessed on 28 May 2023).

Acknowledgments: The results presented in the paper were made possible thanks to funding from Nordic Energy Research in the frame of the joint Baltic-Nordic Energy Research Program project project no. 117686, "Waste heat in smart energy systems".

Conflicts of Interest: Author Vladislav Mašatin was employed by Utilitas Tallinn AS. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflicts of interest.

Nomenclature

Abbreviation	
CHP	combined heat and power
COP	coefficient of performance
DC	district cooling
DH	district heating
EU	European Union
Parameters	
E	output power, W
G	flow rate kg/s
G_T	turbine steam mass flow rate, kg/s
h_1	turbine steam inlet specific enthalpy, J/kg
h_2	turbine steam outlet specific enthalpy, J/kg

References and Note

1. European Commission. Heating and Cooling 2021. Available online: https://ec.europa.eu/energy/topics/energy-efficiency/heating-and-cooling_en (accessed on 28 May 2023).
2. International Energy Agency (IEA). *The Future of Cooling: Opportunities for Energy-Efficient Air Conditioning*; International Energy Agency (IEA): Paris, France, 2018; p. 92.
3. IEA. *World Energy Outlook 2018: Highlights*; International Energy Agency (IEA): Paris, France, 2018; Volume 1, pp. 1–661.
4. Bornand, B.; Girardin, L.; Belfiore, F.; Robineau, J.L.; Bottallo, S.; Maréchal, F. Investment Planning Methodology for Complex Urban Energy Systems Applied to a Hospital Site. *Front. Energy Res.* **2020**, *8*, 1–18. [CrossRef]
5. Zhang, K.; Troitzsch, S.; Zhang, S.Y.; Teh, E.S.P.; Subramanian, L.; Massier, T. Transactive Energy in an Urban Environment: A Case Study of Local Generation and Flexibility Potentials in a Singaporean Urban District. *Front. Energy Res.* **2021**, *9*, 1–18. [CrossRef]
6. Werner, S. International review of district heating and cooling. *Energy* **2017**, *137*, 617–631. [CrossRef]
7. IRENA (International Renewable Energy Agency). *Renewable Energy in District Heating and Cooling. A Sector Roadmap for Remap*; IRENA (International Renewable Energy Agency): Masdar City, Abu Dhabi, 2017.
8. Wirtz, M.; Neumaier, L.; Remmen, P.; Müller, D. Temperature control in 5th generation district heating and cooling networks: An MILP-based operation optimization. *Appl. Energy* **2021**, *288*, 116608. [CrossRef]
9. Pieper, H.; Ommen, T.; Elmegaard, B.; Volkova, A.; Markussen, W.B. Optimal Design and Dispatch of Electrically Driven Heat Pumps and Chillers for a New Development Area. *Environ. Clim. Technol.* **2020**, *24*, 470–482. [CrossRef]
10. Euroheat & Power. *Ecoheatcool Work Package 3. Guidelines for Assessing the Efficiency of District Heating and District Cooling Systems*; Euroheat & Power: Brussels, Belgium, 2006.
11. Government of Canada. Heating and Cooling with a Heat Pump 2021. Available online: https://www.nrcan.gc.ca/energy-efficiency/energy-star-canada/about/energy-star-announcements/publications/heating-and-cooling-heat-pump/6817#d6 (accessed on 28 May 2023).
12. Nami, H.; Anvari-Moghaddam, A.; Nemati, A. Modeling and analysis of a solar boosted biomass-driven combined cooling, heating and power plant for domestic applications. *Sustain. Energy Technol. Assess.* **2021**, *47*, 101326. [CrossRef]
13. Intelligent Energy Europe. *Energy Distribution: District Heating and Cooling*; Intelligent Energy Europe: Brussels, Belgium, 2016; pp. 1–51.
14. International Energy Agency (IEA). Cooling 2020. Available online: https://www.iea.org/reports/cooling (accessed on 28 May 2023).
15. Lazzeroni, P.; Olivero, S.; Repetto, M.; Stirano, F.; Verda, V. Design of a polygeneration system with optimal management for a dhc network. *Int. J. Sustain. Energy Plan. Manag.* **2019**, *22*. [CrossRef]
16. Alghool, D.M.; Elmekkawy, T.Y.; Haouari, M.; Elomri, A. Optimization of design and operation of solar assisted district cooling systems. *Energy Convers. Manag. X* **2020**, *6*, 100028. [CrossRef]

17. Inayat, A.; Ang, H.H.; Raza, M.; Yousef, B.A.A.; Ghenai, C.; Ayoub, M.; Gilani, S.I. Integration and simulation of solar energy with hot flue gas system for the district cooling application. *Case Stud. Therm. Eng.* **2020**, *19*, 100620. [CrossRef]
18. YORK (Wuxi) Air Conditioning and Refrigeration Co., Ltd. York Absorption Chiller. 2021.
19. Elering, A.S. B, C ja D-tüüpi tootmismoodulite nimekiri:139–46. Available online: https://elering.ee/sites/default/files/public/elekter/elektris%C3%BCsteem/Oluliste%20v%C3%B5rgukasutajate%20nimekiri.pdf (accessed on 28 May 2023).
20. Volkova, A.; Latõšov, E.; Siirde, A. Heat Storage Combined with Biomass CHP under the National Support Policy. A Case Study of Estonia. *Environ. Clim. Technol.* **2020**, *24*, 171–184. [CrossRef]
21. IEEE European Public Policy. *Heating and Cooling Future of Europe and Interactions with Electricity*; IEEE European Public Policy: Vienna, Austria, 2018; pp. 1–6.
22. United States Department of Energy. *Absorption Chillers for CHP Systems*; United States Department of Energy: Washington, DC, USA, 2016; pp. 3–6.
23. Delač, B.; Pavković, B.; Glažar, V. Economic and Energetic Assessment and Comparison of Solar Heating and Cooling Systems. *Energies* **2023**, *16*, 1241. [CrossRef]
24. Saleh, A. Modeling and Performance Analysis of a Solar Pond Integrated with an Absorption Cooling System. *Energies* **2022**, *15*, 8327. [CrossRef]
25. Thakar, K.; Patel, R.; Patel, G. Techno-economic analysis of district cooling system: A case study. *J. Clean. Prod.* **2021**, *313*, 127812. [CrossRef]
26. Lepiksaar, K.; Mašatin, V.; Latõšov, E.; Siirde, A.; Volkova, A. Improving CHP flexibility by integrating thermal energy storage and power-to-heat technologies into the energy system. *Smart Energy* **2021**, *2*, 100022. [CrossRef]
27. Latõšov, E.; Volkova, A.; Siirde, A.; Thalfeldt, M.; Kurnitski, J. The Impact of Parallel Energy Consumption on the District Heating Networks. *Environ. Clim. Technol.* **2019**, *23*, 1–13. [CrossRef]
28. Arabkoohsar, A.; Andresen, G.B. Supporting district heating and cooling networks with a bifunctional solar assisted absorption chiller. *Energy Convers. Manag.* **2017**, *148*, 184–196. [CrossRef]
29. Sdringola, P.; Proietti, S.; Astolfi, D.; Castellani, F. Combined Heat and Power Plant and District Heating and Cooling Network: A Test-Case in Italy with Integration of Renewable Energy. *J. Sol. Energy Eng. Trans. ASME* **2018**, *140*, 1–8. [CrossRef]
30. Cavalcanti, E.J.C.; Ferreira, J.V.M.; Carvalho, M. Exergy assessment of a solar-assisted combined cooling, heat and power system. *Sustain. Energy Technol. Assess.* **2021**, *47*, 101361. [CrossRef]
31. Tuma, M.; Leban, M.; Oman, J. Stromabfall infolge der Wärmeerzeugung bei der Kraft-Wärme-Kopplung. *Forsch. Im Ing.* **1998**, *64*, 251–255. [CrossRef]
32. Cimdina, G.; Blumberga, D.; Veidenbergs, I. Analysis of Wood Fuel CHP Operational Experience. *Energy Procedia* **2015**, *72*, 263–269. [CrossRef]
33. Pieper, H.; Kirs, T.; Krupenski, I.; Ledvanov, A.; Lepiksaar, K.; Volkova, A. Efficient use of heat from CHP distributed by district heating system in district cooling networks. *Energy Rep.* **2021**, *7*, 47–54. [CrossRef]
34. Volkova, A.; Hlebnikov, A.; Ledvanov, A.; Kirs, T.; Raudsepp, U.; Krupenski, I.; Latõšov, E. District Cooling Network Planning. A Case Study of Tallinn. *Int. J. Sustain. Energy Plan. Manag.* **2022**, *34*, 63–78. [CrossRef]
35. Utilitas Tallinn AS. Utilitas Tallinn AS Homepage. Available online: https://www.utilitas.ee/as-utilitas-tallinn/ (accessed on 28 May 2023).
36. SWEP International AB. 10.9 Absorption Chillers. Available online: https://www.swep.net/refrigerant-handbook/10.-systems/asdf1/ (accessed on 28 May 2023).
37. Prasartkaew, B. Performance test of a small size LiBr-H2o absorption chiller. *Energy Procedia* **2014**, *56*, 487–497. [CrossRef]
38. Hiltunen, P.; Volkova, A.; Latõšov, E.; Lepiksaar, K.; Syri, S. Transition towards university campus carbon neutrality by connecting to city district heating network. *Energy Rep.* **2022**, *8*, 9493–9505. [CrossRef]
39. Available online: https://www.tehnopol.ee/meist/ (accessed on 12 March 2023).
40. Ehitisregister 2021. Available online: https://livekluster.ehr.ee/ui/ehr/v1/ (accessed on 28 May 2023).
41. Jakob, U.; Cooling, S. *Final Deliverable Best Practice Brochure IEA Solar Heating and Cooling Program*; IEA: Paris, France, 2015; Volume 49, pp. 1–43.
42. Hebei Feiyu Cooling Equipment Co. Counter Flow Cooling Tower with Opposite Spray Water & Air Inlet Flows. Technical Data. 2023. Available online: https://www.flycoolingtower.com/products/closed-circuit-cooling-towers/counter-flow.html (accessed on 28 May 2023).
43. Darmanto, P.S.; Sutanto, N.J.; Astina, I.M.; Marjianto, A. Study of the district cooling implementation opportunity in Jakarta. *AIP Conf. Proc.* **2018**, *1984*, 020029. [CrossRef]
44. Pieper, H.; Ommen, T.; Buhler, F.; Lava Paaske, B.; Elmegaard, B.; Brix Markussen, W. Allocation of investment costs for large-scale heat pumps supplying district heating. *Energy Procedia* **2018**, *147*, 358–367. [CrossRef]
45. Pieper, H.; Mašatin, V.; Volkova, A.; Ommen, T.; Elmegaard, B.; Markussen, W.B. Modelling framework for integration of large-scale heat pumps in district heating using low-temperature heat sources: A case study of Tallinn, Estonia. *Int. J. Sustain. Energy Plan. Manag.* **2019**, *20*, 67–86. [CrossRef]
46. AWEB Supply. *Cooling Tower vs. Slim Jim®/Geo Lake Plate®Operating Cost Comparison*; AWEB Supply: Baton Rouge, LA, USA, 2020; p. 70806.

47. Delta Cooling Towers Inc. Cooling Tower Cost Estimate: Average Price in 2022. 2022. Available online: https://deltacooling.com/resources/faqs/cooling-tower-costs (accessed on 28 May 2023).
48. Tallinna Tehnikaülikool, Soojustehnika Instituut. Kaugkütte kaalumistegurid. 2016. Available online: http://www.epha.ee/images/docs/Osa_1_Kaugktte_kaalumistegurid_26_04_16.pdf (accessed on 28 May 2023).
49. Hansberger Refrigeration and Electric Company. SEER, EER and COP: Understand These Terms before You A/C Shop 2023. Available online: https://blog.hansbergerrefrig.com/2014/07/15/seer/ (accessed on 28 May 2023).
50. Alves, O.; Monteiro, E.; Brito, P.; Romano, P. Measurement and classification of energy efficiency in HVAC systems. *Energy Build.* **2016**, *130*, 408–419. [CrossRef]
51. Riigi Teataja. Hoone Energiatõhususe Arvutamise Metoodika. 2018. Available online: https://www.riigiteataja.ee/akt/107072020012 (accessed on 28 May 2023).

Appendix 3

Publication III

Lepiksaar K, Volkova A, Ruševljuk P, Siirde A. The effect of the District Heating Return Temperature Reduction on Flue Gas Condenser Efficiency. *Environmental and Climate Technologies* 2020;24:23–38. http://doi:10.2478/rtuect-2020-0083

Environmental and Climate Technologies
2020, vol. 24, no. 3, pp. 23–38
https://doi.org/10.2478/rtuect-2020-0083
https://content.sciendo.com

The effect of the District Heating Return Temperature Reduction on Flue Gas Condenser Efficiency

Kertu LEPIKSAAR[1]*, Anna VOLKOVA[2], Pavel RUSELJUK[3], Andres SIIRDE[4]

[1, 2, 4]*Tallinn University of Technology, Ehitajate tee 5, 19086 Tallinn, Estonia*
[3]*AS Narva Soojusvõrk, Oru tn 2, 20203 Narva, Estonia*

Abstract **– The use of flue gas condensers proved to be effective in increasing boiler efficiency and achieving primary energy savings. The transition to the 4th generation district heating will lead to temperature reduction in district heating networks. The aim of this study is to determine the effects of the reduction in the district heating return temperature on flue gas condenser efficiency. Different DH return temperatures and fuel moisture contents were examined, and a calculation model was created. The results show that a reduction in district heating return temperature can lead to an increase in heat recovery through the flue gas condenser. Primary energy savings were estimated based on the amount of heat recovered.**

Keywords **– CHP (combined power and heat); condensation; 4GDH (4th generation district heating); heat- and mass transfer; heat recovery; PES (primary energy savings)**

Abbreviations		
4GDH	4th Generation District Heating	–
CHP	Combined Heat and Power	–
DH	District Heating	–
FGC	Flue Gas Condenser	–
NCV	Net Calorific Value	–
PES	Primary Energy Savings	–
Parameters		
a	Excess air coefficient	–
A	Heat transfer surface area of the flue FGC	m^2
b	Flue gas consumption	kg/s
c_p	Specific heat at constant pressure	J/(kg·K)
d	Diameter	m
g	Gravitational acceleration	m/s^2
G_{return}	District heating return mass flow	kg/s
h	Heat transfer coefficient	$W/(m^2 \cdot K)$
H	Height of heat transfer surface	m

---

* Corresponding author.
E-mail address: kertu.lepiksaar@taltech.ee

j	Diffusion flow	kg/(s·m^2)
k	Thermal conductivity	W/(m·K)
l	Flow lenght	m
m	Mass fraction per 1 kg of consumed fuel	kg/kg
M	Molar mass	kg/mol
Nu	Nusselt number	–
PES_{1MWh}	Primary energy savings per 1 MWh generated	MWh/MWh
PES_{inc}	Increase in primary energy savings through DH return temperature reduction	MWh/(MWh·K)
Pr	Prandtl number	–
q	Heat flux	W/m^2
Q_{air}	Heat of combustion air	W
Q_{comp}	Heat required for heating fuel components in the boiler	W
Q_{cond}	Total recoverable heat from condensation	W
Q_{latent}	Heat from water vapour condensation	W
Q_{NCV}	Net calorific value of fuel	MJ/kg
$Q_{rec.heat}$	Amount of heat recovered	W
$Q_{sensible}$	Cooling heat from non-condensable gases	W
r	Heat of condensation	J/kg
rd	Relative difference	–
Re	Reynolds number	–
t_{return}	District heating return temperature,	°C
δ	Thickness	m
Δt	Temperature difference	K
Δt_{log}	Logarithmic mean temperature difference	K
η	Efficiency	
v	Kinematic viscosity	m^2/s
Subscripts		
calc	Calculated	
cyl	Cylinder heat transfer surface	
D	Diffusion	
dp	Dew point	
dry	Flow sans moisture	
fg	Contained in flue gases	
FGC	Flue gas condenser	
flat	Flat heat transfer surface	
flow	Prandtl number based on flow temperature	
meas	Measured	
Nu	According to Nusselt's analogy	

th	Thermal
w	Water
wall	Prandtl number based on wall temperature

1. INTRODUCTION

There are many different ways to achieve savings in terms of primary energy consumption. District heating improvements hold great potential for a subsequent increase in energy efficiency. The European Union's energy policy promotes district heating (DH) and combined heat and power (CHP) generation in accordance with the Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012. The Directive states that energy-efficient DH is a DH system that uses at least 50 % renewable energy, 50 % waste heat, 75 % cogenerated heat, or 50 % a combination of such energy and heat [1]. One option for improving heat production efficiency is to install flue gas condensers (FGC) to recover waste heat from flue gases.

The transition to the 4th generation district heating (4GDH) will lead to significant energy savings since the required temperatures are low and low-grade energy sources can be used. Volkova et al. studied the dynamics of the transition process towards the 4GDH and identified the main requirements that must be met for the successful transition [2]. The main objectives are:

- Use of renewable (non-fuel) energy;
- Low network heat loss;
- Integration of CHP plants;
- Thermal energy storage integration;
- Intelligent metering.

As can be seen from the key requirements, the transition will lead to the reduction of DH temperatures, both supply and return. The decrease of DH flow temperatures has several benefits for CHPs, including increased electricity production and lower heat losses and pumping costs [3].

The impact of low-temperature DH, including low return temperatures, can be assessed in many ways. A life-cycle assessment of low-temperature district heating was conducted in [4], and it was determined that solar photovoltaic technology should be introduced to decrease the environmental impact of DH. Integration of low temperature heat sources, such as solar energy [5], [6] seawater or sewage water [7] has an impact on return temperature reduction. Exergy analysis method for thermal networks was described in [8] which can be also used to evaluate DH environmental impact.

Market competitiveness of heat largely depends on the temperature of the return network water. The return DH temperature is a parameter that cannot be controlled by the operator only; it is regulated via the operating mode of the entire DH system, including heat sources, network and consumer [2]. The technical state of the consumer heat supply systems and the organisation of their operation have a great influence on the temperature of the return network water. There are numerous reasons for this, from errors in system design, heat exchangers, circulation pumps, automatic regulating fittings, heat energy meters and automatic control devices to various human factors and each has individual capabilities.

The design of heating devices in buildings: when space heating is done by radiators, the heat transfer surface area is rather small compared to underfloor heating, which requires lower temperatures than radiator heating due to larger heat transfer surface areas [9]. Improper management of heating substations in buildings could also cause high temperatures in DH [10]. When other heat sources are used simultaneously with DH, it can also affect DH return temperatures. Parallel consumption was studied in [11]. Due to the fact that there is additional heat in the DH system, the return temperature of the DH network will be higher in the case of parallel consumption than without.

There are different ways to reduce return temperature from the consumer's side, such as refurbishment of older buildings and construction of new low-energy buildings [12]. However, housing is a rather slow process that can last for decades. When new low-temperature consumers are added to the network using the energy-cascade method or any other method that promotes the use of low-temperature heating sources, it also helps reduce the return temperature. It is possible that the DH sector will go through a transition period where different technical solutions will be implemented simultaneously [13].

Under modern economic conditions, the reduction of the return temperature is not so much a technical issue, as it is an economic one. However, the problem of the DH return temperature reduction is very complex and cannot be solved quickly, because there are a lot of consumers, and each has individual capabilities. Consumers should be motivated to reduce return temperature. There are various economic measures that can affect consumer behaviour. One of the measures is a tariff system which was discussed in [14]. Another solution is to introduce multi-component rates with a bonus-malus component based on the return temperature, as for example in DH of Copenhagen, Stockholm and Saclay [15]. Fines paid for increased return temperature can motivate consumers. For example, in the Narva DH system (Estonia), the deviation of the return water temperature from the set value was recalculated for those consumers who exceeded the temperature. To compensate for the temperature in heat energy, it was necessary to increase the amount of water supplied to the DH network and introduce fines for consumers in the case the return temperature was too high. This forced most consumers to set up their own heating substations, and as a result, the DH water consumption rate decreased significantly in these heating systems [16].

Total energy cost savings in buildings can also prove to be motivating for consumers. The correlation between the decrease in energy costs and DH temperature reduction was examined in [17].

In recent years, FGC has been often used to increase the efficiency of a CHP or boiler plant. FGC can improve the efficiency of both the heating and CHP plants. FGC improves efficiency by recovering latent and sensible heat from flue gases and water vapours. FGC provides significant heat recovery when using fuels with high moisture content. The proportion of heat recovery in the total amount of heat supplied can be up to 30 %, increasing total plant efficiency by up to 15 % [18]. An experimental study on the best FGC operational regime for small-scale boilers was conducted in [19], examining different water flow regimes while measuring moisture content of flue gases before and after fog unit and heat recovery.

Major factors that influence the proportion of FGC heat recovery include fuel moisture content, condensing temperature, fuel composition and flue gas temperature [18]. There are also other factors that affect mainly heat and mass transfer in FGC. These factors include flue gas flow velocity and regime (laminar or turbulent) and the construction of FGC. FGC efficiency is also studied in [20] and [21]. The method proposed in [20] was designed for heat and mass transfer in tubular FGC. In [21], different configurations for combined-cycle power plant to recover heat from flue gases were examined.

Fuel moisture content also affects temperature in boilers. Higher moisture content means that more energy must be used to evaporate the moisture that is introduced to the boiler with the fuel. High moisture content reduces fuel net calorific value (NCV) (MJ/kg) and flame temperature in the boiler. It is important that the temperature in the boiler does not exceed the temperature limits, as it may damage the boiler. FGC efficiency can be used as an indirect method for estimating fuel moisture content. Striūgas *et al.* proposed a methodology for assessing fuel moisture content based on the efficiency of FGC [22].

When FGC is not used, too high moisture content in the fuel can be considered as loss of efficiency. Typically, woodchip moisture content ranges anywhere from 30 % to 50 %. When the moisture content exceeds 87.1 %, the lower calorific value is negative, and it is impossible to obtain any useful heat without condensing water vapour in flue gases.

This study explores the impact of the return temperature reduction on FGC by creating FGC efficiency and heat recovery models based on different fuel moisture values and DH return temperature values. Since FGC is most beneficial for high-moisture fuels, woodchips were chosen as fuel. However, the model is also applicable to other types of fuel. FGC heat recovery potential based on the DH return temperature was estimated using different fuel moisture content values. To calculate FGC efficiency and primary energy savings (PES) potential for different DH return temperatures, the most common fuel moisture content value was used.

A mathematical model was created in MS Excel for theoretical analysis. To validate the model, the theoretical results were compared with the actual measurements from the Mustamäe CHP plant (Mustamäe Koostootmisjaam), which uses woodchips as fuel.

2. METHOD

A diagram of all model components and system parameters is available in Appendix 1.

A scheme for mathematical tool described in this method is shown in Appendix 2.

The model for the theoretical analysis was created in MS Excel in accordance with the following methodology which is added as Appendix 3. The model can be applied to any CHP and/or boiler plant that uses any type of flue gas condenser.

In practice, 100 % efficiency is unrealistic (according to gross calorific value). Heat and mass transfer aspects must also be considered, since not all latent heat can be recovered even if flue gases are cooled down to ambient temperature. Some heat recovery losses are caused by heat and mass transfer effects that can be considered when designing an FGC.

FGC can theoretically be viewed as a heat exchanger in which one of the heat flows has a phase transition, while heat transferred in the process is equal to recoverable sensible and latent heat, which is summed as Q_{cond} (W). Flue gas is heat supplying flow and heat consuming flow is district heating return water that is returning to the boiler and can be preheated with the FGC-recovered heat. Q_{cond} (W) can be calculated as follows (Eq. (1)):

$$Q_{cond} = Q_{sensible} + Q_{latent}\,, \tag{1}$$

where

$$Q_{sensible} = m_{fg,gry} \cdot (c_{p,fg1,dry} \cdot t_{fg} - c_{p,fg2,dry} \cdot t_{return}) \cdot b \tag{2}$$

and

$$Q_{latent} = \left[m_{fg1,H2O} \cdot (c_{p1,H2O} \cdot t_{fg} + r_1) - m_{fg2,H2O} \cdot (c_{p2,H2O} \cdot t_{return} + r_2) \right] \cdot b\,. \tag{3}$$

In Eq. (1), sensible heat $Q_{sensible}$ (W) (Eq. (2)) is the heat that is released by cooling non-condensable gases. Latent heat Q_{latent} (W) (Eq. (3)) is the heat that is released by cooling and condensing water vapours in flue gases. In Eq. (2) and (3), index '1' refers to the FGC entering flow, and index '2' to the outgoing flow. Index '*dry*' refers to dry, moisture-free flue gases. To consider the exact amount of condensation heat, fuel consumption b (kg/s) must also be considered, as it is done in Eq. (2) and Eq. (3). Since the specific heat of non-condensable gases is quite small compared to the sum of the specific heat of water and condensation heat, the proportion of sensible heat in total recoverable heat Q_{cond} is approximately 30 %, but this depends on the moisture content m_{H2O} (kg/kg) of the fuel. When the moisture content is higher, the proportion of sensible heat in recoverable heat is smaller.

The amount of water vapours entering the FGC $m_{fg,1,H2O}$ (kg/kg) depends on fuel composition and moisture content. If flue gas moisture content is not measured, then it can be calculated stoichiometrically taking excess air coefficient a into account. The excess air coefficient a shows how much extra air is supplied to the boiler for combustion, if $a = 1$, then the amount of combustion air is minimal, which is necessary for complete combustion. If $a > 1$, then some extra air was introduced to the boiler, resulting in oxygen (O_2) content found in flue gases. When $a = 1$, then all oxygen from the incoming air should be used up, and flue gases should not contain any oxygen. Usually, the necessary excess air coefficient of a boiler is constant and is indicated in the boiler manual. Typically, the excess air coefficient a is about 1.05…1.15 [23].

The amount of flue gas can also be determined using a method described in DIN EN 12952-15 [24]. The standard proposes a slightly different approach, using numerical constants and special methods for various types of fuels.

In order to determine the amount of dry flue gas, $m_{fg,dry}$ and water vapour $m_{fg1,H2O}$, the following calculations (Eq. (4)–Eq. (9)) must be performed. The analytical content of the dry fuel should also be known. Typically, the analytical components that ultimately turn into dry flue gases are carbon (C) and sulphur (S). As for the burning of woodchips, the temperature is too low for nitrogen (N) to oxidize, so it can be viewed as inertial [25]. Since the sulphur content in woodchips is marginal (less than 0.5 %), there is no need to take it into account for FGC calculations [26]. Therefore, dry flue gases mainly contain carbon dioxide (CO_2), nitrogen (N_2) from fuel and nitrogen that entered the boiler with the air and excess oxygen (O_2), which was not used for combustion.

According to stoichiometry and the excess air coefficient, the amount of CO_2 $m_{fg,CO2}$ (kg/kg) emitted by burning 1 kg of fuel is calculated by Eq. (4).

$$m_{fg,CO2} = (1 - m_{H2O}) \cdot m_{c,dry} \cdot \frac{M_{CO2}}{M_C} + \frac{m_{O2} \cdot 0.046\%}{23.1\%}, \tag{4}$$

where m_{H2O} is fuel moisture content (kg/kg), and $m_{c,dry}$ is carbon content in dry fuel (kg/kg). 0.046 % refers to the mass fraction of CO_2 fraction in the inlet air, and 23.1 % refers to the mass fraction of O_2 fraction in the inlet air.

In order to calculate the amount of nitrogen (N_2) in flue gas, it is necessary to calculate how much oxygen is necessary for complete combustion, which can be done using Eq. (5).

$$m_{O2} = \left[a \cdot (1 - m_{H2O}) \cdot M_{O2} \cdot \left(\frac{m_C}{M_C} + \frac{0.5 m_{H2}}{M_{H2}} \right) \right] - m_{O,dry}, \tag{5}$$

where $m_{O,dry}$ is oxygen content in dry fuel (kg/kg).

The amount of oxygen in flue gases $m_{fg,O2}$ (kg/kg) after the combustion of 1kg of fuel can be determined by Eq. (6).

$$m_{fgO2} = (a-1) \cdot m_{O2} \tag{6}$$

To determine the amount of nitrogen $m_{fg,N2}$ (kg/kg) in flue gases after the combustion of 1 kg of fuel, Eq. (7) is used. In Eq. (7), 75.5 % refers to the mass fraction of dinitrogen in the inlet air. 1 % of inertia gases in air is considered insignificant for flue gas mass flow.

$$m_{fg,N2} = m_{O2} \cdot \frac{75.5\%}{23.1\%} + m_{N,dry} \cdot (1 - m_{H2O}) \tag{7}$$

The amount of dry flue gas can be determined by adding all dry flue gas components (Eq. (8)).

$$m_{fg.dry} = m_{fg,CO2} + m_{fg,N2} + m_{fg,O2} \tag{8}$$

The amount of water vapours in flue gas before FGC $m_{fg1,\,H2O}$ depends on fuel moisture and hydrogen content in dry fuel. The specific amount of water vapours in flue gas is determined by Eq. (9).

$$m_{fg1,H2O} = (1 - m_{H2O}) \cdot m_{H,dry} \cdot \frac{M_{H2O}}{M_{H2}} + m_{H2O} \tag{9}$$

To determine $m_{fg2,H2O}$ (kg/kg) a psychrometric chart of dew point (Fig. 1) can be used, as Fig. 1 shows the saturating amount of water vapour in dry flue gases x ($kg_{H2O}/kg_{dry\ gas}$).

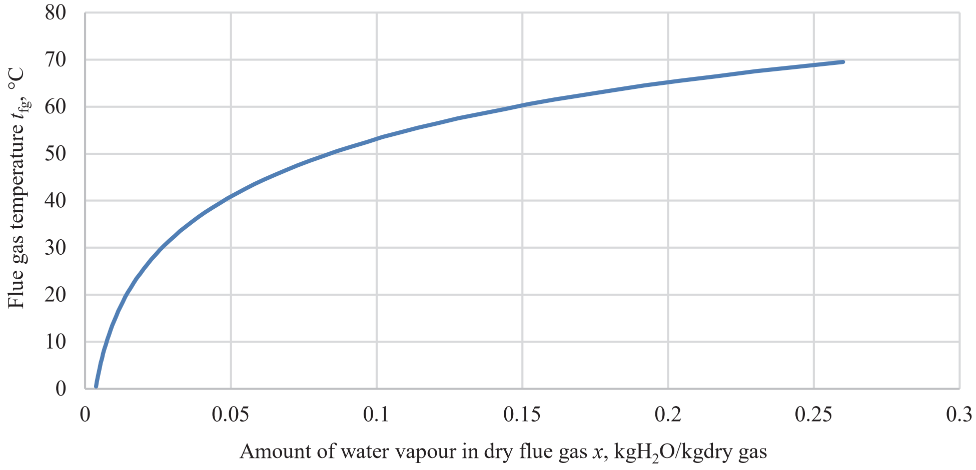


Fig. 1. Saturating amount of water vapour kg_{H2O}/kg_{gas} from 0 °C ... 70 °C at normal pressure.

To find $m_{fg2,H2O}$ Eq. (10) can be used.

$$m_{fg,H2O} = m_{fg,dry} \cdot x \tag{10}$$

The water vapour content in the gas decreases as flue gas cools down in FGC. The lower the cooling temperature, the more water can be condensed, as saturating amount of water vapour decreases. The temperature of the FGC exhaust gas is the same as the dew point temperature. Since the relative humidity of outgoing gases is 100 % then Eq. (10) is valid. This leads to conclusion that when the cooling temperature is lower, more water can be condensed and more heat can be recovered. In FGC, the outgoing gases are cooled down to the district heating return temperature t_{return} (°C). To find the mass flow rate of flue gases, $m_{fg1,H2O}$, $m_{fg2,H2O}$ and $m_{fg,dry}$ must be multiplied by boiler fuel consumption b.

The amount of total recovered heat $Q_{rec.heat}$ (W) depends on heat and mass transfer in the FGC. The energy balance in the FGC is shown in Eq. (11).

$$Q_{cond} = Q_{rec.heat} + Q_{loses} \tag{11}$$

As was mentioned before, FGC can be viewed as a heat exchanger, so the amount of total recovered heat $Q_{rec.heat}$ can be calculated similarly to the heat flux q (W/m^2) transferred through a heat exchanger with a surface A (m^2) (Eq. (12)).

$$Q_{rec.heat} = A \cdot q \tag{12}$$

For flat heat transfer surfaces, Eq. (13) is used.

$$q_{flat} = \frac{\Delta t_{log}}{\frac{1}{h_1} + \frac{\delta}{k} + \frac{1}{h_2}} \tag{13}$$

In Eq. (13), index 1 refers to heat transfer from flue gases to the wall of the condenser, index 2 refers to heat transfer from the condenser wall to cooling water.

As FGCs have usually tubular structure then linear heat flux (W/m) for cylinder heat transfer surfaces must be used (Eq. (14)).

$$q_{cyl} = \frac{\pi \cdot \Delta t_{log}}{\frac{1}{h_1 \cdot d_1} + \frac{\delta}{2k} \ln\left(\frac{d_2}{d_1}\right) + \frac{1}{h_2 \cdot d_2}} \tag{14}$$

In Eq. (14), index 1 refers to the inside diameter of the cylinder and heat transfer from inside the cylinder to the inner surface. Index 2 refers to the outer diameter of the cylinder and heat transfer from the outer surface of the cylinder to the environment. Δt_{log} can be found by Eq. (15).

$$\Delta t_{log} = \frac{\Delta t_{fg} - \Delta t_{return}}{\ln \frac{\Delta t_{fg}}{\Delta t_{return}}} \tag{15}$$

The difference between the flue gas temperature after FGC and DH return temperature is minor, so these temperatures can be considered equal.

The decrease in temperature of the DH return water Δt_{return} (K) can be determined by Eq. (16).

$$\Delta t_{return} = \frac{Q_{cond}}{c_{p,return} \cdot G_{return}} \tag{16}$$

It is important to evaluate heat and mass transfer processes in a condenser, as these processes occur simultaneously. The processes that affect heat and mass transfer in FGC are: convection, conduction, heat transfer by radiation, absorption, evaporation, and condensation [27]. In this study radiation, absorption and evaporation are considered to have minimal effect in heat and mass transfer processes in FGC, so these processes are neglected. The estimation of heat and mass transfer coefficients is important for determining FGC capacity. The coefficients include thermal conductivities of the construction materials, heat carriers, and heat and mass transfer effects, such as flow velocity and regime (laminar or turbulent).

Heat transfer in FGC is depicted in Fig. 2.

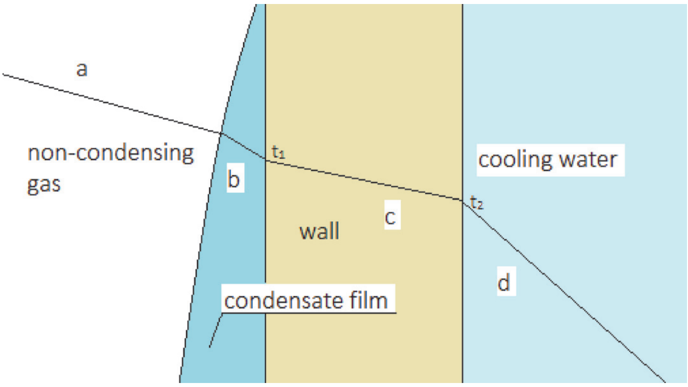


Fig. 2. Heat transfer in FGC. a – heat transfer of sensible heat of non-condensable gases; b – thermal conduction through condensate film; c – thermal conduction through wall; d – convective heat transfer from wall to cooling water.

Colburn and Hougen noted that during the condensation of vapours from their admixture of non-condensable gases, the properties of the gas stream vary greatly as the vapour is removed [28]. As for FGC, the wall temperature is lower than the dew point temperature, which means that part of the vapour condenses and forms a thin liquid film on the walls [29]. This must be considered when calculating h_1 [J/(m^2·K)] in Eq. (17). The Nusselt's analogy can be used for condensation heat transfer. For non-condensable gases, heat transfer can be viewed as steam diffusion through the non-condensable gas [30]. The total h_1 from Eq. (13) and (14) can be calculated as follows (Eq. (17)):

$$h_1 = \frac{1}{\dfrac{1}{h_{Nu}} + \dfrac{1}{h_D}}, \tag{17}$$

where heat transfer coefficient h_{Nu} [W/(m^2·K)] for a vertical wall with a height H (m) can be found by Eq. (18) [31].

$$h_{Nu} = 0.943 \cdot \sqrt[4]{\frac{g \cdot r \cdot \rho \cdot k^3}{\nu \cdot H \cdot (t_{dp} - t_{return})}} \tag{18}$$

The dew point temperature t_{dp} in Eq. (18) and (19) is the psychrometric dew point temperature for the water vapour fraction for flue gases entering the FGC.

The heat transfer coefficient h_D [W/(m^2·K)] can be calculated by Eq. (19) [32].

$$h_D = \frac{t_{fg} - t_{dp}}{h_1(t_{fg} - t_{dp}) + r \cdot j} \tag{19}$$

Eq. (17) and (19) show that an iterative method is necessary to calculate h_1 and h_D.

As for h_2 [W/(m^2·K)] from Eq. (13), it can be determined as convective heat transfer Eq. (20) [31]:

$$h_2 = \frac{Nu \cdot k_w}{l}, \tag{20}$$

where the average Nusselt number Nu of the flow depends on the flow regime of the cooling water.

The Reynolds number of the cooling water (DH return water) flow in the FGC can be estimated considering FGC design and cooling water flow rate.

For laminar flow ($\mathrm{Re} < 10^5$) Eq. (21) is applied [32].

$$Nu = 0.67 \cdot \mathrm{Re}^{0.5} \cdot \mathrm{Pr}_{flow}^{0.33} \cdot \left(\frac{\mathrm{Pr}_{flow}}{\mathrm{Pr}_{wall}} \right)^{0.25} \tag{21}$$

For turbulent flow ($\mathrm{Re} > 10^5$) Eq. (22) is applied [32].

$$Nu = 0.037 \cdot \mathrm{Re}^{0.8} \cdot \mathrm{Pr}_{flow}^{0.33} \cdot \left(\frac{\mathrm{Pr}_{flow}}{\mathrm{Pr}_{wall}} \right)^{0.25} \tag{22}$$

The Prandtl number Pr in Eq. (21) and Eq. (22) can be determined according to flow temperatures. The Prandtl number with the index *flow* must be determined based on the average cooling water flow temperature; the Prandtl number with the index *wall* refers to the Prandtl number for flowing water near the wall, where the water temperature is approximately equal to the wall temperature.

The wall temperature, which is mandatory for determining the Prandtl number near the wall, can be found by Eq. (23) and Eq. (24) [31].

For a flat wall:

$$t_{wall,flat} = t_{return} + \frac{1}{h_2} \cdot \frac{t_{fg} - t_{return}}{\frac{1}{h_1} + \frac{\delta}{k} + \frac{1}{h_2}}. \tag{23}$$

For a cylinder wall:

$$t_{wall,cyl} = t_{return} + \frac{q_{cyl}}{\pi} \cdot \left[\frac{1}{h_1 \cdot d_1} + \frac{1}{2k} \ln\left(\frac{d_2}{d_1} \right) \right]. \tag{24}$$

Iterative method must be used to determine the wall temperature. FGC efficiency can be calculated by Eq. (25).

$$\eta_{FGC} = \frac{Q_{rec.heat}}{Q_{cond}} \tag{25}$$

PES for 1 MWh are directly related to FGC recovered heat $Q_{rec.\ heat}$, and also considering the heat that enters the boiler with the combustion air Q_{air} (W), and the heat that is used for heating the components in the boiler Q_{comp} (W). PES_{1MWh} (MWh/MWh) can be calculated by Eq. (26).

$$PES_{1MWh} = \frac{Q_{FGC} - Q_{air} - Q_{comp}}{Q} \tag{26}$$

As for the PES increase potential PES_{inc} for the DH return temperature reduction by 1 °C, Eq. (27) can be used.

$$PES_{inc} = \frac{\Delta PES_{1MWh}}{\Delta t_{return}} \tag{27}$$

3. MODEL APPROBATION

To validate the model, the results were compared with real measurements obtained at the Mustamäe Combined-Heat-and-Power Plant, which was launched in 2019. The parameters used as input data for the model are listed in Table 1.

The following indicators were calculated: heat recovery, FGC efficiency and primary energy savings. To compare the results obtained using the methodology described in the previous section and operational data, the following parameters were measured over the period of September 16, 2019 – December 5, 2019; heat recovery, flue gas supply and return temperature, fuel moisture content, overall thermal power of the plant and DH return temperature. Both the calculated and measured results are shown in Fig. 3. The design capacity of the FGC at the Mustamäe CHP is 9 MW.

TABLE 1. CALCULATION PARAMETERS

Parameter	Value
Flue gas temperature t_{fg}	162.34 °C
Boiler output power Q	44.1 MW
Fuel	woodchips
FGC gas flow Reynolds number Re	5000
Heat transfer surface area A	56 m^2
Water flow through FGC G	215.79 kg/s
Thermal conductivity of the heat exchanger wall k	0.399 kW/(m·K)
Fuel gross calorific value Q_{GCV}	19.94 MJ/kg
Median fuel moisture content m_{H2O}	0.39 kg/kg
Dry fuel carbon content $m_{C,dry}$	0.500 kg/kg
Dry fuel hydrogen content $m_{H,dry}$	0.065 kg/kg
Dry fuel oxygen content $m_{O,dry}$	0.400 kg/kg
Excess air coefficient a	1.05

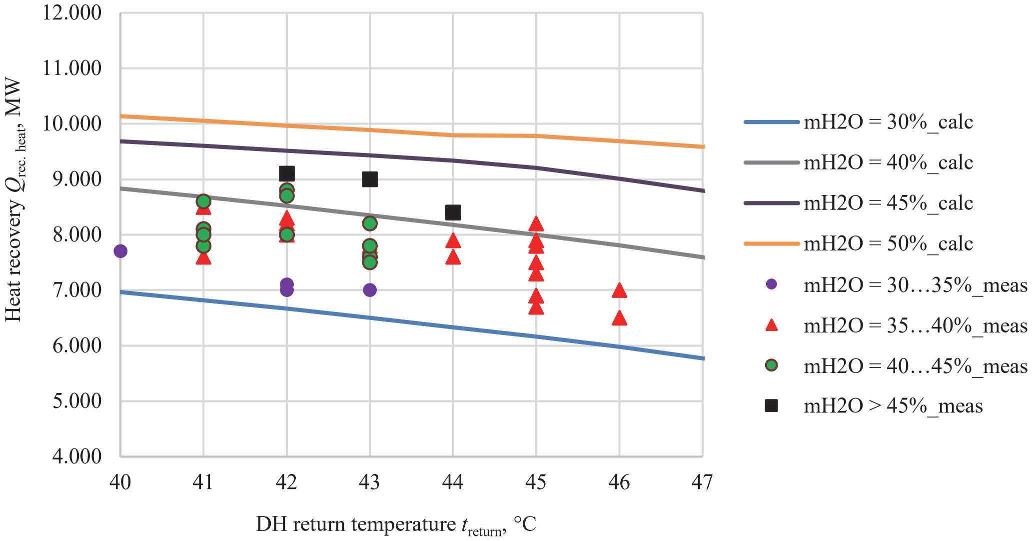


Fig. 1. Measured and calculated results, Mustamäe CHP.

The average relative difference between the measured and calculated results is 4.3 %. Relative difference *rd* can be found by Eq. (28).

$$rd = \frac{\left|Q_{rec.heat.meas.} - Q_{rec.heat.calc.}\right|}{Q_{rec.heat.meas.}} \tag{28}$$

The problem with the fuel moisture content in this theoretical model is that although power plants measure the moisture content of each load of fuel, it is still unclear when the load is going to be incinerated. There is a tendency that the loads of woodchips that are delivered to the plant on weekdays will be used the next day.

The FGC recovered heat is used to pre-heat water, therefore it is added to the boiler heat output to determine the plant's overall thermal power. Since the FGC recovered heat depends on the return temperature, the overall thermal efficiency of the plant is also related to the DH return temperature. The DH return temperature also affects efficiency of the FGC. This can be explained by the FGC's heat exchanger properties: like a heat exchanger, FGC also has a certain heat capacity which is determined by heat transfer area *A* (Eq. (11)) and other constructional properties (flat or cylinder surfaces, surface thickness, materials, etc.). This leads to the conclusion that when the condensation heat Q_{cond} reaches the FGC's design capacity, lowering the DH return temperature will not increase the amount of recovered heat. The correlation between the FGC efficiency and the DH return temperature is illustrated in Fig. 4. The data presented in Fig. 4 was calculated using the parameters listed in Table 1, which are also the average operational parameters of the observed case.

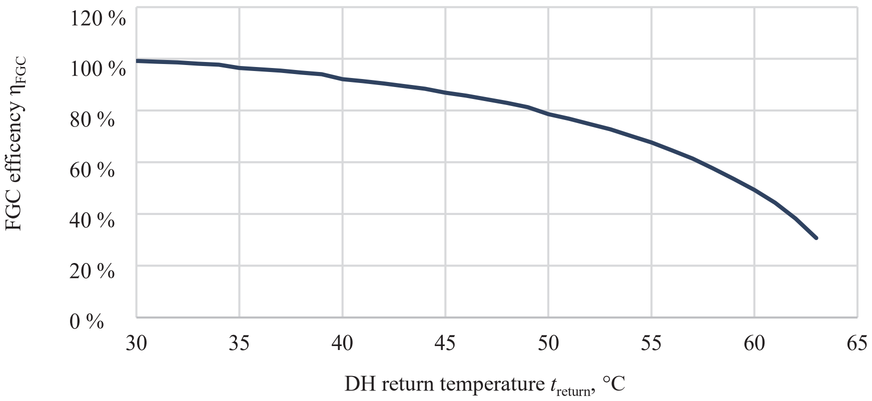


Fig. 4. FGC efficiency at different DH return temperatures.

The potential for increased heat recovery with FGC is greater when DH return temperatures are higher. This can be seen in Fig. 5. The calculations for Fig. 5 were also made using the data from Table 1.

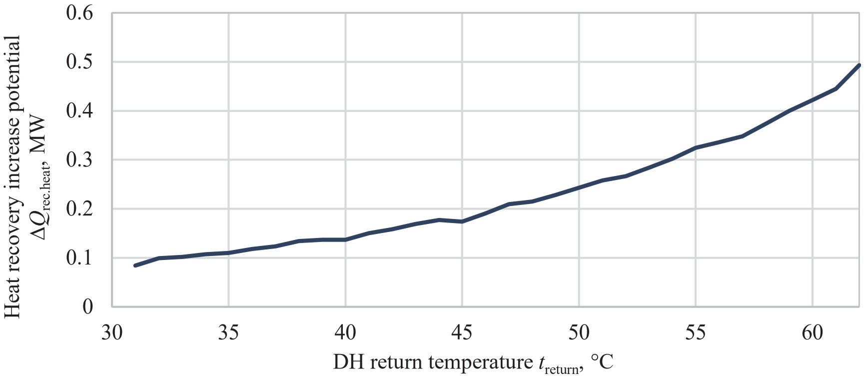


Fig. 5. Heat recovery increase potential when the DH return temperature is reduced by 1 °C at different DH return temperatures.

Since the average moisture content of woodchips is 40 %, then the NCV of woodchips is 10.3 MJ/kg. Therefore, 349.2 kg of woodchips are required to produce 1 MWh of thermal energy when condensation heat is not used. When condensation heat is used to produce thermal energy, fuel consumption can be reduced. Since the DH return temperature decreases, the FGC recovered heat increases, therefore reducing the DH return temperature also decreases boiler fuel consumption which leads to PES. Fig. 6 illustrates PES potential per 1 MWh, when the DH return temperature is reduced by 1 °C. The PES potential is greater at higher temperatures. When the temperature drops below 40 °C, further reduction will bring about 2 kWh/(MWh·K) PES, which is about 1 kg of woodchips per MWh produced.

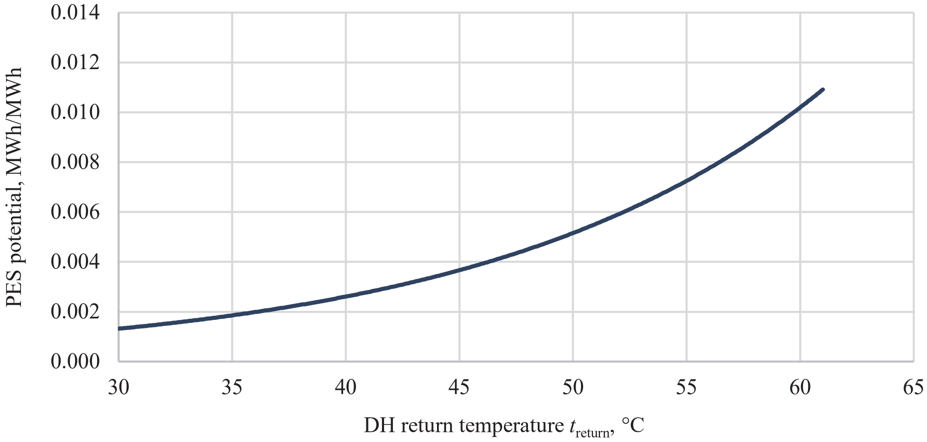


Fig. 6. PES increase potential per 1 MWh with DH return temperature reduction by 1 °C at different DH return temperatures.

The main possibility of DH return temperature reduction for examined CHP is adding new low-temperature consumers to DH network and also refurbishment of existing consumers.

4. CONCLUSIONS

The aim of this study was to evaluate the effect of low DH return temperatures on the FGC efficiency. The methodology was based on FGC heat recovery calculations, that determine the amount of sensible and latent heat in flue gases and considering also heat and mass transfer processes in FGC. There are other methodologies that can also be used to assess the impact of the return temperature impact on the FGC efficiency, but the advantage of the method proposed in this study is that this method is more flexible and it is not based on one specific construction model. Due to this advantage, the model developed in this study can also be used to calculate the profitability of the FGC installation, if DH temperatures and boiler capacities are known. The model can also be used in preparing the FGC installation at a boiler house or CHP to calculate the necessary capacity of the FGC. This model can also estimate the minimum profitable temperature for various fuels with different moisture content. In addition, the proposed method includes tools for PES increase potential.

The amount of flue gas that is mentioned in this study can also be found using DIN EN 12952-15 standard. However, flue gas estimation method proposed in this study is more versatile and can be applied to various types of fuels because physical constants, such as molar mass, chemical reaction coefficients, and specific heat are used instead of numerical constants. The choice to use either method does not affect the results.

The input parameters of the new Mustamäe CHP were used for model approbation. Additionally, operational data was collected at the CHP and compared with the calculated parameters.

The following parameters were calculated: the amount of FGC-recovered heat $Q_{rec,heat,calc}$, FGC efficiency η_{FGC}, and PES potential per 1 MWh PES_{1MWh}.

The following parameters were measured: the DH return temperature t_{return}, the amount of FGC-recovered heat $Q_{rec,heat,meas}$, total thermal output of the boiler Q, flue gas temperature t_{fg}, fuel moisture content m_{H2O}, and dry fuel analytical content.

Both the results of the modelling and measurements confirm that the reduction of the DH return temperature has a positive effect on the FGC efficiency, since the reduction of DH return temperatures increases efficiency and the amount of FGC-recovered heat. FGC can provide significant PES when used with boilers that use high-moisture fuel, such as woodchips.

Unfortunately, due to the warm winter, the range of DH return temperatures t_{return} that were measured is very limited. Nevertheless, the measured and calculated results coincide, and this trend is obvious.

DH producers will benefit directly from an increase in the FGC efficiency. Since fuel costs can be reduced as a result, this can have a positive effect on the price of DH, since lowering the return temperature affects the amount of FGC-recovered heat. The specific PES for various DH return temperatures was evaluated, and it turned out that the PES potential by reducing DH return temperature is exceptional when DH return temperatures are high. When DH return temperatures drop below 40 °C, further temperature reduction will not increase the potential of PES.

REFERENCES

[1] European Parliament Council of the European Union. Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency, amending Directives 2009/125/EC and 2010/30/EU and repealing Directives 2004/8/EC and 2006/32/EC Text with EEA relevance. *Official journal of the European Union* 2012:L 315/1.

[2] European Parliament Council of the European Union. Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012. Official journal of the European Union. https://doi:10.3000/19770677.L_2012.315.eng

[3] Volkova A., Mašatin V., Siirde A. Methodology for evaluating the transition process dynamics towards 4th generation district heating networks. *Energy* 2018:150:253–261. https://doi.org/10.1016/j.energy.2018.02.123

[4] Köfinger M., Basciotti D., Schmidt R. R. Reduction of return temperatures in urban district heating systems by the implementation of energy-cascades. *Energy Procedia* 2017:116:438-451. https://doi.org/10.1016/j.egypro.2017.05.091

[5] Feofilovs M., Pakere I., Romagnoli F. Life Cycle Assessment of Different Low-Temperature District Heating Development Scenarios: A Case Study of Municipality in Latvia. *Environmental and Climate Technologies* 2019:23(2):272–290. https://doi.org/10.2478/rtuect-2019-0068

[6] Pakere I., Blumberga D. Solar Energy in Low Temperature District Heating. *Environmental and Climate Technologies* 2019:23(3):147–158. https://doi.org/10.2478/rtuect-2019-0085

[7] Polikarpova I., Lauka D., Blumberga D., Vigants E. Multi - Criteria Analysis to Select Renewable Energy Solution for District Heating System. *Environmental and Climate Technologies* 2019:23(3):101–109. https://doi.org/10.2478/rtuect-2019-0082

[8] Pieper H., Volkova A., Mašatin V. Large-scale heat pump integration model: A case study of Tallinn district heating. 4th Int. Conf. Smart Energy Syst. 4th Gener. Dist. Heating, Aalborg, Denmark, 2018.

[9] Nardecchia F., *et al*. An alternative tool for the energy evaluation and the management of thermal networks: The exergy analysis. *EEEIC* 2016:1–6. https://doi.org/10.1109/EEEIC.2016.7555645

[10] Karkaba H., Habchi C., Al Takash A. Numerical Analysis of Different Indoor Heating Methods. *Proceeding of the 4th International Conference Advanced Computer Tools Engineering Applications (ACTEA)* 2019:1–7. https://doi.org/10.1109/ACTEA.2019.8851075

[11] Guelpa E., Marincioni L. Demand side management in district heating systems by innovative control. *Energy* 2019:188:116037. https://doi.org/10.1016/j.energy.2019.116037

[12] Latõšov E., *et al*. The Impact of Parallel Energy Consumption on the District Heating Networks. *Environmental and Climate Technologies* 2019:23(1):1–13. https://doi.org/10.2478/rtuect-2019-0001

[13] Brand M., Svendsen S. Renewable-based low-temperature district heating for existing buildings in various stages of refurbishment. *Energy* 2013:62:311–319. https://doi.org/10.1016/j.energy.2013.09.027

[14] Volkova A., *et al*. Energy cascade connection of a low-temperature district heating network to the return line of a high-temperature district heating network. *Energy* 2020:198:117304. https://doi.org/10.1016/j.energy.2020.117304

[15] Ziemele J., *et al*. Sustainability of heat energy tariff in district heating system: Statistic and dynamic methodologies. *Energy* 2017:137:834–845. https://doi.org/10.1016/j.energy.2017.04.130

[16] Galindo Fernández M., *et al*. Efficient district heating and cooling systems in the EU Case studies analysis, replicable key success factors and potential policy implications. Luxembourg: Publications Office of the European Union, 2016. https://doi.org/10.2760/371045

[17] AS Narva Soojusvõrk. Technical report. 2019.

[18] Blumberga D., *et al*. Empirical Model of Cost Reduction in Local DH Systems Low Temperature Approach. *Environmental and Climate Technologies* 2019:23(3):190–201. https://doi.org/10.2478/rtuect-2019-0089

[19] Vigants G., *et al*. Cost Analysis of a Wood Chip Boiler House with a Gas Condenser. *Energy Procedia* 2015:75:1214–1220. https://doi.org/10.1016/j.egypro.2015.07.159

[20] Priedniece V., *et al*. Experimental and analytical study of the flue gas condenser - fog unit. *Energy Procedia* 2019:158:822–827. https://doi.org/10.1016/j.egypro.2019.01.215

[21] Soleimanikutanaei S., Lin C.X., Wang D. Numerical modeling and analysis of Transport Membrane Condensers for waste heat and water recovery from flue gas. *International Journal of Thermal Sciences* 2019:136:96–106. https://doi.org/10.1016/j.ijthermalsci.2018.10.014

[22] Vannoni A., Sorce A., Bosser S., Buddenberg T. Heat recovery from Combined Cycle Power Plants for Heat Pumps. *E3S Web Conference* 2019:113:1–9. https://doi.org/10.1051/e3sconf/201911301011

[23] Striūgas N., *et al*. Estimating the fuel moisture content to control the reciprocating grate furnace firing wet woody biomass. *Energy Conversion Management* 2017:149:937–949. https://doi.org/10.1016/j.enconman.2017.04.014

[24] Paraschiv L. S., Serban A., Paraschiv S. Calculation of combustion air required for burning solid fuels (coal / biomass / solid waste) and analysis of flue gas composition. *Energy Reports* 2019:6:36–45. https://doi.org/10.1016/j.egyr.2019.10.016

[25] European Standards, DIN EN 12952-15:2003. Water-tube boilers and auxiliary installations - Part 15: Acceptance tests. 2003.

[26] Li P.W., Chyang C.S. A comprehensive study on NOx emission and fuel nitrogen conversion of solid biomass in bubbling fluidized beds under staged combustion. *Journal of the Energy Institute* 2019:93:324–334. https://doi.org/10.1016/j.joei.2019.02.007

[27] Kuznetsov G. V., *et al*. Mechanism of Sulfur and Nitrogen Oxides Suppression in Combustion Products of Mixed Fuels Based on Coal and Wood. *Combustion Science and Technology* 2019:191(11):2071–2081. https://doi.org/10.1080/00102202.2018.1543285

[28] Blumberga D., Vigants E., Veidenbergs I. Analysis of flue gas condenser operation. *Latvian Journal of Physics and Technical Science* 2011:48(4):58–65. https://doi.org/10.2478/v10047-011-0028-3

[29] Colburn A. P., Hougen O. A. Design of Cooler Condensers for Mixtures of Vapors with Noncondensing Gases. *Industrial Engineering and Chemistry* 1934:26:1178–1182. https://doi.org/10.1021/ie50299a011

[30] Jia L., *et al*. Effects of water vapor condensation on the convection heat transfer of wet flue gas in a vertical tube. *Int. J. Heat & Mass Transfer* 2001:44(22):4257–4265. https://doi.org/10.1016/S0017-9310(01)00082-5

[31] Jeong K., *et al*. J., Analytical modeling of water condensation in condensing heat exchanger. *International Journal of Heat and Mass Transfer* 2010:53(11–12):2361–2368. https://doi.org/10.1016/j.ijheatmasstransfer.2010.02.004

[32] Käär H., *et al*. Soojus- ja massilevi. I osa. Põhikursus. (Heat and mass transfer. Part I. Basic course.) Tallinn: Tallinn University of Technology, 1998. (in Estonian)

[33] Poobus A., Tiikma T. Soojus- ja massilevi II. (Heat and mass transfer. Part II.) Tallinn: Tallinn University of Technology, 2000.

Appendix 4

Publication IV

Pieper H, Kirs T, Krupenski I, Ledvanov A, Lepiksaar K, Volkova A. Efficient use of heat from CHP distributed by district heating system in district cooling networks. *Energy Reports* 2021;7:47–54. http://doi.org/10.1016/j.egyr.2021.09.041

Available online at www.sciencedirect.com
ScienceDirect

Energy Reports 7 (2021) 47–54

www.elsevier.com/locate/egyr

17th International Symposium on District Heating and Cooling, Nottingham Trent University, 06–09 September 2021, Nottingham, UK

Efficient use of heat from CHP distributed by district heating system in district cooling networks

Henrik Pieper[a], Tanel Kirs[b], Igor Krupenski[a,c,*], Aleksandr Ledvanov[c], Kertu Lepiksaar[a], Anna Volkova[a]

[a] *Tallinn University of Technology, Department of Energy Technology, Ehitajate tee 5, Tallinn, 19086, Estonia*
[b] *AS Utilitas Tallinn Punane 36, 13619 Tallinn, Estonia*
[c] *HeatConsult OÜ, Valukoja 8, Tallinn, 11415, Estonia*

Received 29 August 2021; accepted 12 September 2021

Abstract

District cooling (DC) can play an important role in smart energy systems. With the global trend of reducing heat loss in buildings, cooling demand will continue to increase. Considering the potential for free cooling and waste heat utilisation in DC systems, a practical approach is needed to develop new DC networks. Tallinn has over 60 years of experience in developing district heating (DH) networks. The city has installed large capacities of biomass-based combined heat and power plants (CHPs). National support mechanisms allow the DH operator to generate power from CHPs and reject heat during warmer months when the heat load is insufficient. This heat can be used for DC. This study investigates an applied approach to DC development in Tallinn's Ülemiste City. Ülemiste City is a business park with an existing developed area of 160 000 m 2 . The main source of cooling for the DC network is an absorption chiller that uses rejected heat from a CHP 7 kilometres away from the DC plant. The current DH supply temperature in Tallinn during the non-heating season is 70 °C. To determine the optimal technical solution for an effective energy efficiency ratio of the absorption chiller and heat transmission in the DH network, various scenarios were evaluated where the DH supply temperature was 70 °C, 80 °C, and 90 °C. An assessment of the technical parameters is provided for these scenarios. The paper presents an overview of the efficient use of rejected heat from CHPs in DC.

Peer-review under responsibility of the scientific committee of the 17th International Symposium on District Heating and Cooling, Nottingham Trent University, 2021.

Keywords: Absorption chiller; CHP; District cooling; District heating

1. Introduction

In recent years, district cooling (DC) has proven to be an efficient and high-quality technology for maintaining a comfortable indoor environment in residential and commercial buildings. According to [1], 2.7% of the final

---

[*] Corresponding author at: Tallinn University of Technology, Department of Energy Technology, Ehitajate tee 5, Tallinn, 19086, Estonia.
E-mail address: igor@heatconsult.ee (I. Krupenski).

https://doi.org/10.1016/j.egyr.2021.09.041

Peer-review under responsibility of the scientific committee of the 17th International Symposium on District Heating and Cooling, Nottingham Trent University, 2021.

Nomenclature

CDD	Cooling degree day
DC	District cooling
EER	Energy efficiency ratio
HPs	Heat pumps
PEF	Primary energy factor
TES	Thermal energy storage
CHPs	Combined heat and power plants
DH	District heating
GHG	Greenhouse gases
PEC	Primary energy consumption
RES	Renewable energy sources

energy consumption in commercial buildings in the EU is used for cooling. Energy consumption for space cooling is expected to triple by 2050 [2]. Although Europe's cooling energy needs are low compared to the United States and Japan, its growth potential is enormous [3]. The main reasons why municipalities engage with DC projects are synergies with existing district heating (DH) systems, increased use of excess heat from combined heat and power plants (CHPs), and the need for more sustainable energy profiles [3]. Currently, the main consumers of DC in Europe are commercial buildings, which typically require large connection capacities and cooling throughout the year [3]. In Europe, DC systems exist in many countries, including France, Sweden, Denmark, Finland, Estonia, Austria, and the Netherlands [2]. The largest DC system in Europe is located in Paris and has a total cooling capacity of 215 MW. It has six large cooling plants in the network and four additional cooling plants outside the central network. The DC network supplies water that is taken from the Seine River and cooled to an average temperature of 5 °C. The length of the DC network is about 71 km. The majority of the customers are hotels, offices, government buildings, theatres, and museums [2].

DC technologies have evolved over the years and many studies have been conducted to find the most sustainable approach. The most environmentally friendly solution is free cooling, where chilled water is taken from a nearby reservoir, such as the river in Paris [4]. If there are no natural bodies of water nearby, large-scale heat pumps (HPs), chillers, absorption chillers, or other novel technologies such as hybrid solar power can be used. In [5], an optimisation model was developed for large-scale HPs and cooling plants to determine the most economical and/or sustainable production and storage capacities, heat sources, and demand profiles for DH and DC supply. Modelling results showed that HPs, together with DC networks, can create a sustainable symbiosis, as HPs can use the DC network as a heat source, which has great potential for reducing CO_2 emissions. As shown in [6], DC systems, cold thermal energy storage (TES), and cooling towers can be introduced into the system to achieve even greater energy savings when properly operated. Exergy assessment shows that chillers perform well when integrated with cooling towers. With cold TES, chilled water can be stored and matched to the cooling load during the hottest hours of the day to prevent excess loads on chillers. By adjusting the charging and discharging times of the cold TES, it is possible to keep the discharge temperature more constant and avoid the discharge of water that is too warm for the cooling system [6]. As described in [7], solar energy can also be used in DC systems by harnessing the heat generated by solar collectors for absorption chillers. Furthermore, solar energy can also be used in DC to power electric chillers.

DC network temperatures are typically 6–16 °C on the supply side and 8–25 °C on the return side. In [8], high-temperature DC was discussed in the context of the Gothenburg DC system in Sweden. Supply temperature of 12–14 °C and return temperature of 20–22 °C have been proposed, which will make it possible to increase the use of free cooling and enhance temperature reduction in DH systems. Consequently, if higher temperatures are introduced into the system, it can support its development toward a future smart energy system with higher efficiency and energy savings [8].

In [9], the use of surplus heat from waste incineration CHPs in DC was analysed. An actual 73 MW CHP plant, located in Denmark, was simulated. It has been found that 20 MW of DC can be supplied by absorption chillers and cold TES with a payback period of less than 5 years. Such a solution would be a win-win for CHPs and cooling supply. The CHP operator can earn money by providing heat for cooling instead of rejecting it into the ambient air or allowing others to burn it at their expense. DC supply via absorption is more economical and sustainable than using individual electric chillers.

There are other alternatives to using the CHP surplus heat in summer, for example, the use of long-term thermal energy storage units. The options for coupling the Tallinn CHP with short-term thermal energy storage were examined in [10], and it was concluded that using power-to-heat together with thermal energy storage would help increase CHP flexibility, as well as provide an excellent technical solution for heat demand peak shaving and reduction of natural gas consumption through curbing the need for natural gas boilers. Using power-to-heat together with heat storage can also help stabilise the system when power consumption is too low. According to [10], natural gas consumption can be reduced by up to 19% with seasonal TES, and heat rejection can be reduced by 26% in the case of Tallinn. However, when there is also a need for cooling but no free cooling source nearby, coupling CHPs with absorption chillers may be an option worth considering.

Comparison of DC configurations, including electric chillers coupled with CHPs, absorption chillers, TES, solar thermal plants, and HPs, showed that the most feasible option is to add CHP with TES and absorption chiller to electric chillers [11].

1.1. Development of district cooling in estonia

Estonia is one of the European countries where DH has been used for decades [12]. In this regard, the concept of DC was not entirely new for both consumers and producers of DC energy. The development of technologies in the energy sector, stricter environmental requirements, reduction of greenhouse gas (GHG) emissions, and lower energy consumption have all influenced the creation of DC networks in Estonia.

At present, district cooling networks have been installed in Tartu, Pärnu and Tallinn. The networks in Tartu and Parnu also use free cooling from nearby rivers, in addition to HPs and chillers.

In Tallinn, three DC regions have been identified with potential cooling needs of 60 MW, 10 MW, and 30 MW. The latter is Ülemiste City, a new development area with limited cooling needs (at the moment) [13]. Master plans exist for each of the three identified DC regions [13]. The first DC substation and network in Tallinn were built in 2019 with a design capacity of 10 MW.

The parameters of the cooling medium in all Estonian networks are currently the same for the supply/return pipeline: 6/16 °C, pressure 16/10 bar. In the future, it is planned to increase the temperature of the cooling medium to improve the efficiency of the entire system and reduce harmful emissions.

Climate change is also relevant to the development of DC. The annual cooling degree day (CDD) index, equivalent to the heating degree day index, has been monitored for the past 42 years, starting in 1979. Until the mid-1990s, Estonia did not have a significant CDD index. It has been increasing since then, so the CDD index is often available. In 2010, the index was particularly high at 43. Looking at the EU average, it can be seen that the CDD index continues to rise, indicating a high demand for cooling in the future.

Another important aspect for DC is the development of biomass-based CHPs due to the national policy that supports biomass-based CHPs, which were recently introduced into the system. Under the feed-in-premium scheme, electricity from biomass CHPs is sold on the electricity spot market, and producers receive a premium on top of the market price of electricity. The reason these CHPs were commissioned is to provide heat during the heating season. This support measure is not constrained to producing power only in CHP mode and using all the power and heat that were produced simultaneously for DH. The situation today is that heat is rejected to the ambient air using dry coolers. Thus, extra auxiliary coolers can be placed at CHPs to remove excess heat from the DH system in summer, during the period of the lowest heat load. A more efficient way to utilise this surplus heat while still receiving the biomass CHP support would be to use it to supply DC via absorption chillers.

1.2. Purpose of the study

The aim of this study is to evaluate DC supply options that take advantage of the excess heat generated by biomass CHPs during the summer and transfer the heat to an absorption chiller via the DH network. The main objective of this study is to find the optimal technical solution for the energy efficiency ratio (EER) of the absorption chiller and heat transfer loss in the DH network by comparing scenarios with different average DH supply temperatures. The DC supply options were also compared with a power-based central cooling solution with free cooling and electric chillers.

2. Methodology

Three scenarios were compared, each using an absorption chiller that is supplied with rejected heat from a CHP located 7 kilometres away from the DC plant. The current DH supply temperature in Tallinn during the non-heating season is 70 °C. It was investigated what effect an increase in the DH supply temperature during this period had on the EER of the absorption chiller and how such an increase in temperature affected the DH network losses and CHP efficiency. Thus, three scenarios were evaluated to determine the optimal technical solution for an effective EER of the absorption chiller and heat transmission in the DH network for DH supply temperatures of 70 °C, 80 °C, and 90 °C. The three scenarios were then compared with a reference scenario based only on electric cooling plants supplying DC using free cooling and electric chillers.

2.1. Case study

A DC network was developed for the Ülemiste City business park in Tallinn. DC can be supplied from two different locations. The design cooling capacity of the DC plant located next to the DC network is 14.2 MW. It will be used to supply current and future customers in Ülemiste City. The customers mainly include office buildings, several industrial buildings, and a school. Most of the cooling load accounts for comfort cooling, process cooling does not exceed 5% of the maximum required capacity. The customers use ventilation cooling, fan coil units, and chilled beams. DC temperature for ventilation is 9–14 °C, 10–15 °C for fan coil units, and 14–18 °C for chilled beams. Experience shows that in modern office buildings in Tallinn, the cooling capacity is equally divided between ventilation cooling and fan coil units or chilled beams. Considering the 5% base load, a balance temperature of 13 °C and hourly measured temperatures, we can create a potential cooling profile shown in Fig. 1. The average annual cooling load is 1.85 MW, and the average cooling load in summer is 4.35 MW.

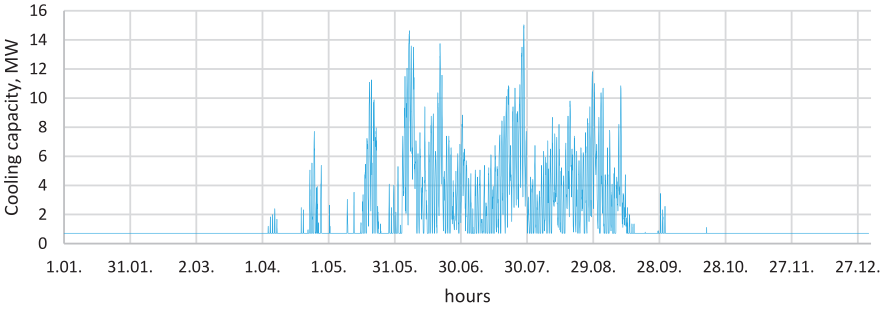


Fig. 1. Cooling load profile.

The abovementioned district cooling parameters, typical for the Estonian network, have been taken into account: supply/return pipeline −6/16 °C; pressure −16/10 bar. In some cases, the district cooling supply temperature may depend on the outside temperature, but it must still be 6 °C (+−1°) to ensure stable network operation.

Cooling technologies selected for DC plants include absorption chillers that use excess heat from biomass CHPs, electric chillers, and free cooling with closed circuit cooling towers. This production plan makes the most of the free cooling from the air. If the DC return temperature is high enough, the free cooling period can be increased by using partial free cooling. For free cooling, the following assumptions were taken into account:

- The free cooler can be used at full capacity (0.71 MW) if the outside air temperature is below 5 °C.
- Free cooling is not possible when the outside air temperature is above 15 °C.
- Free cooler capacity decreases linearly based on the outside air temperature when the outside air temperature is between 5 °C and 15 °C. The capacity is 100% at 5 °C and 0% at 15 °C.

When the outside air temperature increases and the DH load decreases, free cooling cannot be used. In this case, absorption chillers are used with rejected heat from CHPs as input heat. This helps to achieve a higher EER and utilise excess heat generated by biomass CHPs. Absorption chillers are used for base and intermediate loads in summer, while electric chillers are used for peak loads.

An additional option would be to install a heat pump that will utilise excess heat from cooling and supply heat to the DH network in spring and autumn when the DH heat demand is sufficient. But this option was not considered in this study.

One of the options for absorption chillers is to use surplus heat from CHPs to supply cooling, which will also increase the overall efficiency of the CHP. In our case, the excess heat is from the biomass-based Tallinn CHP 2. This CHP plant was introduced to cover the semi-base load and provide heat mainly in winter, spring, and autumn. The plant was put into service in 2017 and until 2018 operated only in CHP mode (monitoring heat load profiles), since there were no specialised facilities for rejecting heat into the ambient air. Nevertheless, since 2018, it has been possible to produce power using rejected heat due to the introduction of dry coolers [14], making it possible to receive the support for biomass CHPs in the summer.

The data for the absorption chiller capacity and EER calculation was taken from the equipment data sheets of the Ülemiste DC plant. Absorption chillers require a hot water inlet temperature of 90 °C, but the DH supply temperature in summer is usually only 70 °C. A supply temperature of 90 °C and a return temperature of 68 °C ensure maximum chiller capacity. Fig. 2 shows how the capacity and EER change depending on the supply temperature. At maximum temperature, its cooling capacity is 2863 kW, and at an inlet temperature of 70 °C from the DH network, it has a cooling capacity of 1500 kW. This is a 48% loss in cooling capacity.

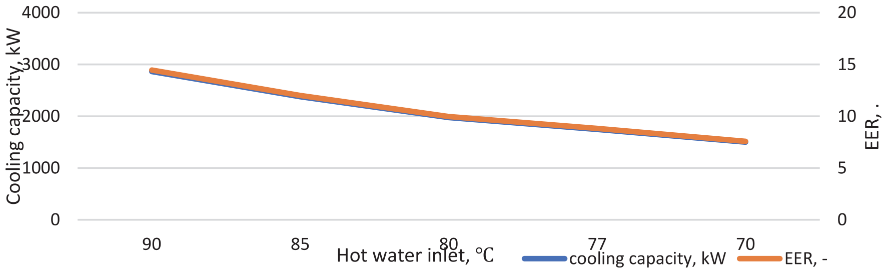


Fig. 2. Absorption chiller capacity (blue) and EER (orange) depending on inlet temperature. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

A loss in cooling capacity means also a loss in the EER if the flow rates in the absorption heat exchangers are kept constant for lower inlet temperatures and thus at the same electricity consumption. The EER decreases accordingly, as shown in Fig. 2. At maximum cooling capacity, the EER is 14.5, while at the chiller's minimum capacity, the EER is 7.6.

The excess heat will be transferred to the cooling plant from the biomass CHP via Tallinn's DH network. Since this CHP is the only one operating in summer and there are no heat exchangers between sections of the DH network, an increase in the DH supply temperature for DC will lead to an increase in the DH supply temperature in the entire DH network. Therefore, additional heat loss must be assessed in the technical analysis. The investigated DH network has the following parameters:

- The total length is 450 km, the DH pipe sizes range from DN25 to DN1200, the length of the non-heating season is 160 days, and the average outside air temperature during the non-heating season is 14.5 °C.
- Proper pipe dimensions were used for annual heat loss calculations using Logstor software.

Electric chillers, unlike absorption chillers, start up easily and quickly, making them suitable for operation during peak loads. The EER of the electric chiller based on the outside air temperature was calculated using thermodynamic models developed using the Engineering Equation Solver (EES). The following equation was developed based on the models presented and described in [5]:

$$\mathrm{EER} = -0.1822 \text{ x } T_{\mathrm{air}} + 10.238 \tag{1}$$

Excel was used to calculate the heat supply based on the type of production plant with hourly time steps. The plants were controlled to provide the highest possible free cooling, followed by absorption chillers with a relatively high EER. Electric chillers were used to handle cooling peak loads, i.e. when the absorption chiller is already at full capacity

2.2. Performance indicators

The evaluation parameters used to compare and determine the optimal solution take into account the technical characteristics related to both the cooling plant and the DH system. Heat loss, flow rate, pump electricity consumption, annual CHP energy efficiency, and overall system efficiency were calculated for the DH system. Higher DH supply temperatures increase the heat loss. For example, comparing the DN500 section of the DH pipeline, heat losses at the DH supply temperature of 70 °C will be 39.32 W/m, 44.18 W/m at 80 °C, and 49.03 W/m at 90 °C. Higher supply temperatures will reduce the flow rate and pump electricity consumption.

Another efficiency parameter was used to evaluate system performance. As discussed above, using district heating to supply district cooling will reduce heat rejected to the ambient air, thereby increasing CHP energy efficiency. But it would be wrong to compare the heat supplied to the district heating network and the unused heat, because an increase in the supply temperature will lead to an increase in heat loss, which will affect the amount of heat supplied to the system. That is why the CHP-DHC energy efficiency (summer) was calculated using Eq. (2).

$$\mathrm{EE}_{CHP-DHC} = \frac{P_{CHP} + Q_{DHW} + Q_{DC}}{F_{CHP}} \tag{2}$$

where

P_{CHP} is the electricity generated by CHP (MWh);

Q_{DHW} is the heat used for domestic hot water heating, sold to consumers (MWh);

Q_{DC} is the heat used for cooling in absorption chillers.

The total EER of the absorption chiller, the share of free cooling and absorption cooling, the electricity consumption and the decrease in CO_2 emissions are the cooling performance indicators that will be calculated and compared. Biomass in Estonia is considered carbon neutral, and the electricity from the national energy mix has a CO_2 emission factor of 0.891 tonnes CO_2/MWh_{el}, as of 2019 [15].

3. Results

Table 1 shows the results of calculations of technical indicators related to the DH network for each of the three scenarios. As shown, an increase in the DH supply temperature will lead to an increase in heat loss, but the amount of electricity needed for pumping will not change significantly at different supply temperatures.

Table 1. Technical DH parameters for three temperature scenarios (non-heating season).

Parameter	70 °C scenario	80 °C scenario	90 °C scenario
Heat loss, MWh	37,535	42,169	46,804
Increase in heat loss, MWh	0	4634	9269
Flow, kg/h	2 012 410	1 508 435	1 205 902
Electricity used for pumping, MWh	1008	755	602
Heat utilised for district cooling, MWh	4963	6124	8195
$\mathrm{EE}_{\mathrm{CHP-DHC}}$, %	35.12%	35.55%	36.31%

As mentioned earlier, it is not possible to increase the DH supply temperature for only one section of the DH network. The temperature will increase in the entire system, resulting in a significant increase in heat loss. However, this additional heat would anyway be rejected into the atmosphere due to the specific structure of tariff support for biomass CHPs. In this case, no additional fuel will be consumed regardless of the supply temperature. As explained earlier, using heat to generate cooling will increase system performance efficiency. Without cooling integration, the EE will be 33.29%, according to Eq. (2). Integration of cooling will increase the amount of utilised heat and improve the energy efficiency of the system. Table 2 shows a comparison of the cooling performance indicators for each scenario and for the electricity-only scenario for DC supply without the use of absorption chillers.

Table 2. Technical DC parameters for three temperature scenarios and DC supply via electric chiller and free cooling.

Parameter	Chiller + free cooling	70 °C scenario	80 °C scenario	90 °C scenario
Electricity consumption, MWh	1869	1831	1653	1365
CO_2 from electricity, tonnes CO_2	1665	1631	1473	1216
Seasonal EER of cooling, –	8.48	8.55	9.48	11.47
Share of free cooling, %	24.7	24.7	24.7	24.7
Share of cooling via absorption chiller, %	–	26.8	32.8	43.0
Share of cooling via electric chiller, %	75.3	48.5	42.4	32.3

In addition, an increase in temperature will lead to a decrease in the flow rate in the entire network, thereby reducing the amount of electricity required for pumping.

It can be seen that electricity consumption will reduce at a higher DH supply temperature, which will lead to a decrease in CO_2 emissions from electricity generation. The seasonal EER increases at higher DH supply temperatures and compared to the electricity-only DC supply, it has a better EER for higher hot water inlet temperatures to the absorption chiller, and the EER of the absorption chiller in summer is higher than the EER of the electric chiller at high outside air temperatures. The proportion of cooling provided by the absorption chiller is higher in the case of an increased DH supply temperature due to the higher capacity of the absorption chiller. The proportion of the cooling supplied by the electrical chiller decreases accordingly.

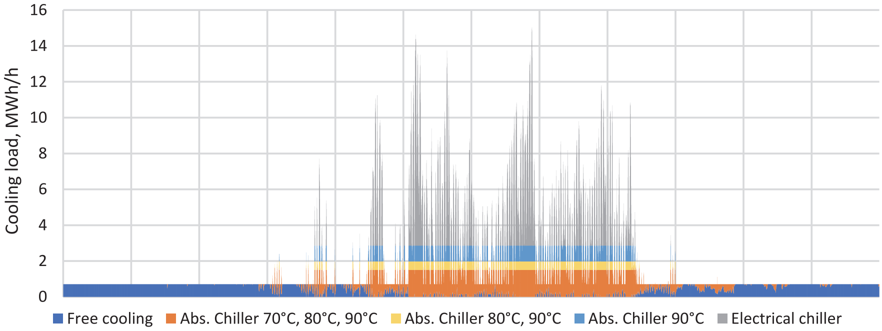


Fig. 3. Cooling supply of various units. For the absorption chiller, three scenarios are shown (70 °C scenario in orange, 80 °C scenario in orange and yellow, and 90 °C scenario in orange, yellow and blue). The remaining peak load for each scenario is supplied by the electric chiller. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 3 shows how the cooling load is supplied by various production plants throughout the year for the three scenarios. As shown, free cooling is used to supply base load when the outside air temperature is low enough. The absorption chiller is also partially used in the shoulder seasons. The difference in the cooling load covered by the absorption chiller for the three scenarios is indicated in different colours. The absorption chiller for each scenario provides cooling equivalent to the orange portion, while for the 80 °C scenario and 90 °C scenario the yellow portion can also be supplied due to the increase in capacity. The light blue portion is only supplied by the absorption chiller in the 90 °C scenario. The remaining cooling load in each scenario is supplied by an electric chiller.

4. Conclusions

Using excess heat to supply DC via absorption chillers is a promising option because the demand for cooling is high in summer and the demand for heat is low. Due to the current legislation, large amounts of surplus heat are not used in Estonia. If the CHP is located within long distance from the DC plant and there is no separate direct line between the CHP and the cooling plant, additional heat loss must be taken into account for the entire DH network. On the other hand, this heat is currently rejected to the ambient air, so no additional fuel is used to generate it.

Absorption chillers perform better when the temperature of the heating carrier is 90 °C compared to lower temperature scenarios. In this case, the EER as well as the cooling capacity of the absorption chiller are higher. The use of absorption chillers results in lower electricity consumption. The higher the DH supply temperature, the larger the share of cooling supplied by the absorption chiller. Reducing electricity consumption is particularly important from an environmental point of view in Estonia, as the current CO_2 emissions from electricity generation are very high.

This study presented an analysis of a solution that enables the provision of district cooling as a by-product of an existing DH network service. District heating, together with a district cooling service, results in a complete district energy service. The business model is to produce DH and DC with maximum efficiency, using as much renewable energy as possible, and provide consumers with green district energy.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This research project received funding from the Mobilitas Pluss Postdoctoral Researcher Grant, Estonia. Project title: 'Optimal dimensioning and annual operation of district cooling systems in cold climates with existing district heating'. Project number: MOBJD472

References

[1] European Commission. Heating and cooling. 2021.
[2] International Energy Agency (IEA). The Future of Cooling: Opportunities for energy-efficient air conditioning. In: Futur cool oppor energy-efficient air cond. 2018, p. 92.
[3] Gudmundsson O, Olsen PK, Thorsen JE. The role of district energy in future energy systems. Eng Tomorrow 2020;16:22–47. http://dx.doi.org/10.1080/10668680109508938.
[4] Inayat A, Raza M. District cooling system via renewable energy sources: A review. Renew Sustain Energy Rev 2019;107:360–73. http://dx.doi.org/10.1016/j.rser.2019.03.023.
[5] Pieper H, Ommen T, Elmegaard B, Volkova A, Brix Markussen W. Optimal design and dispatch of electrically driven heat pumps and Chillers for a New Development Area. Environ Clim Technol 2020;24:470–82. http://dx.doi.org/10.2478/rtuect-2020-0117.
[6] Anderson A, Rezaie B, Rosen MA. An innovative approach to enhance sustainability of a district cooling system by adjusting cold thermal storage and chiller operation. Energy 2021;214:118949. http://dx.doi.org/10.1016/j.energy.2020.118949.
[7] Sameti M, Haghighat F. Hybrid solar and heat-driven district cooling system: Optimal integration and control strategy. Sol Energy 2019;183:260–75. http://dx.doi.org/10.1016/j.solener.2019.03.034.
[8] Jangsten M, Filipsson P, Lindholm T, Dalenbäck JO. High temperature district cooling: Challenges and possibilities based on an existing district cooling system and its connected buildings. Energy 2020;199. http://dx.doi.org/10.1016/j.energy.2020.117407.
[9] Fabricius M, Tarp DØ, Rasmussen TW, Arabkoohsar A. Utilization of excess production of waste-fired chp plants for district cooling supply, an effective solution for a serious challenge. Energies 2020;13. http://dx.doi.org/10.3390/en13133319.
[10] Lepiksaar K, Mašatin V, Latõšov E, Siirde A, Volkova A. Improving CHP flexibility by integrating thermal energy storage and power-to-heat technologies into the energy system. Smart Energy 2021;2. http://dx.doi.org/10.1016/j.segy.2021.100022.
[11] Lazzeroni Paolo. Design of a polygeneration system with optimal management for a dhc network. Int J Sustain Energy Plan Manag 2019;22:81–94.
[12] Volkova A, Latõšov E, Mašatin V, Siirde A. Development of a user-friendly mobile app for the national level promotion of the 4th generation district heating. Int J Sustain Energy Plan Manag 2019;20. http://dx.doi.org/10.5278/ijsepm.2019.20.3.
[13] Krupenski I. District cooling system operation in cold climates with existing district heating networks. 2020.
[14] Volkova A, Latosov E, Siirde A. Heat storage combined with biomass CHP under the national support policy. A case study of Estonia. Environ Clim Technol 2020;24:171–84. http://dx.doi.org/10.2478/rtuect-2020-0011.
[15] European Environment Agency. Greenhouse gas emission intensity of electricity generation. 2020.

Appendix 5

Publication V

Pieper, H., Lepiksaar, K., & Volkova, A. (2022). GIS-based approach to identifying potential heat sources for heat pumps and chillers providing district heating and cooling. *International Journal of Sustainable Energy Planning and Management*, 34, 29–44. https://doi.org/10.54337/ijsepm.7021

International Journal of Sustainable Energy Planning and Management Vol. 34 2022 29–44

International Journal of
Sustainable Energy Planning and Management

GIS-based Approach to Identifying Potential Heat Sources for Heat Pumps and Chillers Providing District Heating and Cooling

Henrik Pieper[a], Kertu Lepiksaar[b], Anna Volkova[b*]

[a] HIR Hamburg Institut Research gGmbH, Paul-Nevermann-Platz 5, 22765 Hamburg, Germany
[b] Department of Energy Technology, Tallinn University of Technology, Ehitajate tee 5, 19086 Tallinn, Estonia

ABSTRACT

Geographic information system (GIS) software has been essential for visualising and determining heating and cooling requirements, sources of industrial excess heat, natural bodies of water, and municipalities. Policymakers highly encourage the use of GIS software at all administrative levels. It is expected that the heating and cooling demand will continue to increase. For a reliable heat and cooling supply, we must identify heat sources that can be used to provide heat or for removing surplus heat. We propose a method for identifying possible heat sources for large heat pumps and chillers that combines geospatial data from administrative units, industrial facilities, and natural bodies of water. Temperatures, capacities, heat source availability, as well as their proximity to areas with high demand density for heating and cooling were considered. This method was used for Estonia, Latvia and Lithuania. Excess heat from heat generation plants and industries, sewage water treatment plants, and natural heat sources such as rivers, lakes and seawater were included. The study's findings provide an overview of possible industrial and natural heat sources, as well as their characteristics. The potential of the heat sources was analysed, quantified, and then compared to the areas of heating and cooling demand..

Keywords

District heating and cooling;
Energy planning;
ESPON;
Heat sources;
Large-scale heat pumps;

http://doi.org/10.54337/ijsepm.7021

1. Introduction

In the EU, heating and cooling are responsible for half of the final energy consumption, 75% of which was produced using fossil fuels in 2012 [1]. Even though district heating (DH) accounts for only 12% of the heat supplied to EU residents, the proportion is highly dependent on the country. Countries in the North have particularly high proportions of DH. The proportion of DH in Denmark, Sweden, Finland, Poland, and the Baltics was about 50% or more in 2012 [2]. The transformation of the DH sector is not only important for these regions, but it could also aid in achieving ambitious climate goals. Mathiesen et al. [3] highlighted that an increased DH and district cooling (DC) share will support reaching the EU climate objectives in a cost-effective manner.

Geographic information system (GIS) tools have often been used to visualise and determine heating and cooling needs [4,5], as well as visualise and identify industrial excess heat sources [6], municipalities [7], natural bodies of water [8], solar energy potential [9], and densely populated areas [10]. Policymakers and experts strongly recommend using GIS tools at various administrative levels. There is a wide variety of such tools available, for example, in the ESPON Toolbox Database [11], such as ESPON's SDGs benchmarking tool [12], which shows indicators that measure and

---

*Corresponding author – e-mail: anna.volkova@taltech.ee

Abbreviations

CHP	Combined heat and power plant
DC	District cooling
DH	District heating
GIS	Geographic information system
HPs	Heat pumps
PEC	Primary energy consumption
RES	Renewable energy sources

monitor the 17 Sustainable Development Goals of the United Nations across Europe at country or regional level. For example, it can be used to show the share of renewable energy in heating and cooling of buildings as an indicator for Goal 7: Affordable and clean energy. Furthermore, this tool can be used to identify the benchmark for certain indicators or regions that are at the same level as the own in terms of the indicator under investigation or other similarities like similar rural/urban areas.

For the energy sector, energy need densities, resource availabilities and resource potentials have been visualised for various projects. Within the *Hotmaps* project [4], an online tool has been developed, which displays among others building related content such as heat and cooling demand densities, gross floor areas, and building volumes among the EU28 member states. Furthermore, industrial sites, emissions, sectors, and potential excess heat are displayed, as well as other parts related to the potential of renewable energy sources (RES), such as sewage water treatment plants or the potential of solar thermal and wind power. The information is complemented by climate data like average temperatures, wind speed and solar radiation.

With the *Heat Roadmap Europe* project, an online tool has been developed called Pan-European Thermal Atlas (Peta), version 4.3 [13]. A newer version, called Peta 5.1, is based on the *sEEnergies* project [14]. In Peta 4.1 [13], a GIS map with similar information as in the *Hotmaps* project [4] is provided for 14 countries of the EU. Information is also available for the quantities of annual available excess heat from metro stations, power plants and sewage water treatment plants, biomass resources, DH distribution costs, and others. In Peta 5.1 [14], information is provided for all EU member states and a new features were included to show e.g. the area of existing DH infrastructure.

Another relevant online GIS and planning tool for the energy sector is based on the Thermal Energy Resource Modelling and Optimisation System (THERMOS) project [15]. It can be used to plan and map the expansion of existing DH and DC infrastructure, to identify synergies and an optimal network path between local demands and known energy sources, to perform an assessment of potential DH and DC networks.

It should be mentioned that many of the mapped results of the above-mentioned projects are based on a top-down approach and several assumptions and general basic calculations in order to achieve approximate values for each country and to use the same approach for each country. Furthermore, a variety of RES were identified and mapped, while other sources are still missing that can become particularly relevant for large-scale heat pumps (HPs) and chillers, such as rivers and lakes [16,17]. Large-scale HPs and chillers are seen as a very efficient technology to utilize RES, to integrate the power and thermal energy sector and thereby help balancing the power generation from fluctuating RES. HPs allow the use of heat at ambient temperature from e.g. seawater, rivers, lakes, or sewage water for DH, which would reduce the proportion of fossil fuel-based heat [18,19]. Similarly, these sources can be used by chillers as a heat sink to supply DC. Connolly et al. [20] show the relevance of large-scale HPs for European DH systems, which are expected to produce 520TWh/a in the EU by 2050, thus providing 25% to 30% of the total DH production.

Therefore, the aim of this study is to perform a geospatial analysis and to develop a GIS map with the focus on providing detailed information about available sources that can be used particularly for large-scale HPs and/or chillers. Thereby, the potential of implementing large-scale HPs and chillers for DH and DC can be identified and barriers be lowered, if geospatial analysis based on advanced GIS software is used to provide detailed information and an overview of suitable locations of heat sources and sinks near DH and/or DC regions. This would be an added value to GIS maps by focusing (and adding) heat sources particularly relevant for large-scale HPs and to quantify their potential usage. So far identified heat sources in GIS were not considered for this purpose.

Estonia, Latvia and Lithuania were used to apply the methodology of a geospatial analysis of heat sources for large-scale HPs. The results of the ESPON *COMPASS* project [21] show how well spatial planning is integrated in sectoral policy. In terms of the Baltic states, it is noted that the influence of spatial planning on energy policy is very strong in Estonia and Lithuania, and less significant in Latvia. Therefore, the Baltic was considered as very suitable for such analysis, also in terms of a potential implementation of obtained results.

2. Method

According to the ESPON *FUTURES* project [22], the energy needs (space heating, domestic hot water, and cooling) of residential buildings in the Baltics are among the highest in Europe. In order to identify sustainable ways of supplying these large energy needs, the following methodology was applied:

- Geospatial analysis was used to locate possible high- and low-temperature heat sources for large-scale HPs and chillers in the Baltic countries.
- DH areas were visualised using geospatial data from settlement units or densely populated areas by filtering these general data sets according to information about the DH supply in cities.
- Heat source potential was calculated based on the data gathered and the proximity to established DH areas.
- The GIS data used to visualise the DH areas was compared to the data on the heat demand density areas from the *Hotmaps* project [4]. Likewise, potential DC areas were compared to the cooling demand density areas from the same project.

Industrial excess heat and flue gas from heat generation plants can be used as high-temperature heat sources to supply DH via HPs. Industrial excess heat is heat discharged into the atmosphere as a result of an industrial process. The exhaust gas that is discharged into the atmosphere as a result of the combustion process (e.g. at a DH plant) is flue gas. A heat exchanger and extra pipes can be used to deliver excess heat beyond the supply temperature of DH (for example, 90°C) straight into the DH network. Excess heat below the DH supply temperature necessitates the use of an electric boiler or HP in order to get the excess heat temperature up to the DH supply temperature. We considered the following high-temperature heat sources: boilers, combined heat and power plants (CHPs) (flue gas), and industrial processes like wood, dairy, cement, and food processing (industrial excess heat).

Low-temperature heat sources were only considered in the case of utilising HPs to provide DH when the temperature of the heat source is near the ambient temperature. These sources are mostly based on natural sources. Seawater, lake and river water, and treated sewage water from cleaning facilities were among the considered low-temperature heat sources. The low-temperature heat sources mentioned above can also be utilised as heat sinks to discharge excess heat from DC consumers.

We used ArcGIS Pro [23] to evaluate the potential of heat sources based on the sources located within the specified DH areas and up to 1km away. The 1km cut-off criterion was selected because anything over 1km would result in overly expensive investments in pipelines. Based on the heat source, this may not be reasonable. The cut-off criterion proposed by Bühler [24] is based on the maximum cost of connection, which varies depending on the heat capacity and the heat source. He discovered that distances of over 200m lead to a rapid increase in connection costs, while distances of 1km or more are still viable for larger heat sources.

The *Hotmaps* project [4] has created heat and cooling demand density maps for all EU countries. In order to display heat and cooling demand density maps at NUTS 3 level, they used the approach presented in the *LOCATE* project [25]. Before, energy consumption data of different end use sectors was not available at NUTS 3 level. However, within the *LOCATE* project [25], they scaled the useful energy demand and final energy consumption from level NUTS 0, NUTS 1 or NUTS 2 to level NUTS 3 based on own developed regional conversion matrices, depending on the kind of energy used (heating, cooling) and data availability. For example, detailed final energy consumption data of heating and cooling distinguished by the system and building categories at level NUTS 0 was broken down to level NUTS 3 using building stock data at NUTS 3 level. More information about this method and data availability at which NUTS level can be found in the *LOCATE* project [25].

2.1. District heating areas

In the Baltics, the majority of the residents get their heat via DH (62% in EE, 65% in LV, and 58% in LT), which is significantly higher than the EU average (26%) [26,27]. In 2018, the Baltic states had a far higher share of RES in the heating and cooling sector (54% in EE, 56% in LV, and 46% in LT) than the EU average of 29% [28]. Data was gathered from 184 (EE), 111 (LV), and 56 (LT) DH areas.

Datasets created for other uses were taken and used to visualise the DH areas. These areas were then compared to the data on the existing DH areas obtained from a variety of reports and databases, including regional and national development plans, as well as DH competition authorities [29–36]. It must be noted that the data used was collected for other purposes, so it does not reflect the accurate location and/or boundaries of the DH networks.

GIS data [7] containing administrative and settlement units was used to visualise DH areas in Estonia by means of processing it using data obtained on the DH areas and comparing the results to a similar online map of these areas [37]. In Latvia, the dissemination of datasets concerning territorial units and their borders is currently prohibited [38]. As a result, a dataset of densely populated areas had to be used [10] and then filtered based on the DH area data. A dataset of settlements and population was used for Lithuania, and it was filtered to display only areas with more than 4000 residents [39].

2.2. District cooling areas

DC is not very common in the Baltics. In Estonia, there are only a handful DC networks that are in operation. The available information on the planned and existing DC areas in Tartu and Tallinn was compared with the cooling demand density areas from the *Hotmaps* project [4].

Tartu's DC network is the first of its kind in the Baltics, with a cooling capacity of 13MW and a length of 1.3km. Fortum constructed it in 2016 and further expanded it in 2017, adding an extra 1.3km of pipes and 5.4MW of cooling capacity. Chillers, DC HPs, free coolers that utilise river water, and a cooling tower make up the two DC plants' equipment [40]. Large shopping malls, office complexes, and municipal buildings are the primary customers.

Tallinn has master plans for three different DC areas [41]. The first DC network is currently being built. The cooling demand of existing buildings in the region is 7.3MW, and the heat demand is 8.1MW. In the future, it is anticipated that extra cooling (23.6MW) and heating (26.2MW) capacity will be needed [41].

In addition, each Baltic country is expected to construct several more DC networks. This means that DC is still in its early stages of development. More DC networks could be implemented in the future due to their higher efficiency compared to individual cooling systems. At the same time, cooling demand is expected to rise rapidly in the future due to changing customer needs and a rise in the annual Cooling Degree Day (CDD) Index affected by climate change.

2.3. High-temperature heat sources

2.3.1. Industrial excess heat

Industrial excess heat typically produces higher temperatures of up to several hundred degrees than other natural or artificial heat sources. Bühler et al. [6] used Denmark data to analyse it and provide a detailed description. They measured the potential for using excess heat in a variety of industrial sectors, as well as the amount of excess heat that could be generated, and the temperatures at which it is usually produced. It was discovered that industrial excess heat derived from thermal processes would cover 5% of the current heat demand. In comparison to other regions, it is more likely to be used in industrial areas where it can be incorporated into a local DH network. Industrial excess heat is expected to provide a total of 1.36TWh per year, with HPs being needed for 36% of that to increase the temperature to the required level. Agreements between DH companies and companies from the industry are needed to allow and distribute investments, as well as to ensure long-term planning [42]. Bühler [24] provides a lot more detail on the matter.

2.3.2. Flue gas

Flue gas, which is generated as a result of fuel combustion at the plant for the production of heat or power, can reach temperatures ranging from 120°C to 180°C [43]. Therefore, flue gas can be condensed to heat the DH return line to temperatures of 40-60°C before it even reaches the plant. With the aid of HPs, the temperature of the flue gas can be decreased even more until it reaches an ambient temperature of 20°C or so. As a result, the DH network's return temperature rises even higher, increasing the plant's efficiency. The small temperature difference between the heat source and heat supply must be compensated for by HPs that use flue gas as a heat source. HPs that use flue gas need a separate plant to burn fuel, limiting their cost-cutting capacity [42].

2.3.3. Assumptions and data gathering

The data from A and B air pollution permits was gathered for a variety of high-temperature heat sources available in Estonia [44], [31], Latvia [45], [33] and Lithuania [46]. Since the investments necessary for a smaller heat source would likely not be economically, only units with an installed capacity over 10MW were considered. Data on the industrial sector, installed capacity, fuel consumption, and fuel type was gathered for 174 (EE), 106 (LV), and 99 (LT) possible high-temperature heat sources (industrial excess heat and flue gas from heat generation plants). Primary energy consumption (PEC) for each heat source was calculated using the obtained information. Then, based on the data from Bühler [24], sector-specific excess heat factors were applied, ranging from 0.08 for paper to 0.37 for metal production.

Since the temperature of the excess heat from industrial processes is often higher than the DH supply temperature, a heat exchanger could be used to integrate significant quantities of the available excess heat before introducing HPs. The proportion of used heat by the heat exchanger on the one hand and by the HP on the other hand depends on the excess heat temperature. This ratio changes for larger excess heat temperatures, since more heat can be used by a direct heat exchange, while the amount of heat used by the HP would remain constant according to the DH temperatures. Based on the measured PEC, shares of 67% for direct supply of heat and 33% for heat supplied via HPs were assumed based on excess heat temperatures of 150°C to estimate the excess heat potential for each part.

With an efficiency of 0.85 for biomass-fired plants, a flue gas factor of 0.05 was assumed for boilers, suggesting that a flue gas condenser should be installed first, which decreases the temperature of the flue gas from about 150°C to about 50°C (67% of the excess heat), and HPs should then cool the flue gas to around 20°C (33%). The same calculation method was used for CHP plants. Because not all excess heat is discharged as flue gas to the atmosphere, the excess heat factor has been reduced to 0.04. Water from the condenser accounts for up to 2/5 of excess heat discharged into the atmosphere [43].

2.4. Low-temperature heat sources

Possible heat sources and sinks include rivers, lakes, seawater, and treated sewage water. Groundwater, ambient air, and low-temperature excess heat generated as a result of cooling processes (e.g. supermarkets, DC networks) are among the other heat sources.

2.4.1. Seawater

Changes in environmental conditions, especially surface water, affect seawater. The less the environmental conditions affect the point of seawater extraction, the deeper it is located. Surface water can already begin to freeze in winter. As a result, extracting water from deeper points could be more lucrative. Big HPs in Oslo, Norway [47] and Stockholm, Sweden work in this manner [48]. Saltwater, minerals, and algae have a negative effect on the equipment, which requires special materials or coatings. The equipment must also be cleaned on a regular basis.

Because of the large volume of water, seawater is an ideal heat source for large-scale HPs. Seawater has also been used for cooling via free cooling and refrigeration plants, from which practical experience and knowledge can be gained. Seawater must be easily accessible and in close proximity.

2.4.2. River and lake water

The temperature properties of rivers and lakes are identical to those of seawater. Larger cities are often located near major rivers and lakes. Water from rivers and lakes usually has a lower capacity than seawater. In the case of lakes, the capacity is constraint by the water volume, and in the case of rivers, by the flow rate. Furthermore, the depth can be lower, compared to seawater. Debris, such as grass, algae, and other organic matter, can impair efficiency, so the equipment must be cleaned on a regular basis.

The source capacity can be assessed based on the river's volume flow rate and the lake's water volume. This data, combined with current regulatory requirements for return flow temperature, can aid in the identification of capacity constraints. Large lake-based HPs have been constructed in Lausanne, Switzerland, and several locations in Sweden [18]. Lake and river water can be used for cooling alongside seawater.

2.4.3. Sewage water

The sewage water temperature is usually higher than that of the surrounding air, and the volume flow rates are high. This means that sewage water is a suitable heat source. Since biological sewage water treatment is susceptible to temperature changes and should not be disrupted, treated sewage water is usually considered [49]. Moreover, using untreated water may demand extra care when passing through the HP evaporator, as it necessitates the use of cleaning equipment and heat exchanger design alterations. However, also cleaned sewage water contains a number of nutrients that encourage the growth of bacteria [50]. To ensure smooth operation, clean-in-place (CIP) equipment and filters may be necessary [51].

Sweden has implemented several large HPs that use sewage water, including one in Malmo that has a thermal capacity of 40MW [52]. Sewage treatment plant operators can provide data on sewage water temperatures and volume flow rates.

2.4.4. Measurement and geospatial data

As can be seen in Table 1, geospatial data and measurements of seawater, rivers, lakes, and sewage water treatment plants were collected from a variety of sources. Seawater, river, and lake temperatures were measured at 12, 17, and 7 different locations in Estonia, Latvia and Lithuania, respectively. In the case of rivers, the volume flow rate was also determined. One sewage water treatment plant provided temperature and flow measurements of sewage water.

3. Results

First, we present the overall results of the collected GIS data for all Baltic countries. Then the comparison of the considered data for the DH and DC areas with the heat and cooling demand density map from the *Hotmaps* project is provided [4]. Below are the results of the geospatial analysis, including information on high-temperature and low-temperature excess heat sources.

3.1. Overall GIS results

Figure 1 depicts an overview of all gathered data's geospatial information. The following elements are depicted: DH regions (in pink), sewage water treatment plants (red squares), high-temperature heat sources (green circles), rivers (black lines), lakes (blue areas), and seawater (light blue coastal areas). A link to an interactive online map can be found here.

Many of the high-temperature heat sources are localised inside or in close proximity to DH regions, as shown in the figure. Sewage water treatment plants are spread all over the Baltics. Most cities are situated near rivers, and a few are by the sea (especially in Estonia).

3.2. DH areas: comparison of GIS data and Hotmaps data

Figure 2 shows an example of current DH areas and accessible low- and high-temperature heat sources in the Pärnu region of Estonia. National GIS data is compared to the *Hotmaps* project's heat demand density map [4]. This demonstrates what GIS data was used, the data's consistency, how to use the GIS map, as well as how the data can be used further. The settlements of Pärnu, Sauga (North), Sindi (Northeast), and Paikuse (East) are encircled in blue, and the heat demand density is depicted as a colourmap, where the highest demand is shown in red, and the lowest in grey. The sewage water treatment plant is depicted as a red circle, while the nine high-temperature heat sources are shown as green circles, rivers in black, and seawater in light blue.

The annual heat demand of these settlements has been estimated at around 250GWh, the largest share of which belongs to Pärnu. It can be seen that settlements occupy a larger area than the heat demand density map. Depending on the settlement unit, this can have a significant impact, as is the case for Paikuse. Most of the settlement area is occupied by agricultural and forest land, while the residents of Paikuse are concentrated in only two places. The settlement units of Pärnu, Sauga, and Sindi are somewhat similar to the heat demand density maps. From this point of view, they can be used to pinpoint the approximate location of existing DH areas. It should be noted that the heat demand density map does not show the location of DH areas. However, since the existing DH areas are located in very densely populated areas, it can be assumed that this is the case.

Out of the nine high-temperature heat sources, one is located further away (pellet factory up North with 15.5GWh of potential excess heat). Despite the distance, constructing a pipeline to the DH network for excess heat sources of this scale could prove to be cost-effective. Paikuse also has a high-temperature heat source in

Table 1: Sources of GIS data and measurements (lakes, rivers, seawater, and sewage treatment plants)

Estonia	Latvia	Lithuania
Estonian Land Board: waterbodies [53]; Environmental Register [54]; Estonian Weather Service (available upon request) [102]	SIA Envirotech: Waterbodies, Watercourses, and Shoreline [55–57]; Latvian Environment, Geology and Meteorology Centre (available online) [78]	SE 'GIS-Centras': Annex I. Hydrography (INSPIRE dataset) [8]; MapCruzin.com: Waterways (based on the data from OpenStreetMap.org) [58]; Lithuanian Hydrometeorological Service, Hydrological Observations Division (available upon request) [103]
Seawater depth and distance from shore [59,60]		
The EU Urban Waste Water Treatment Directive [61]		

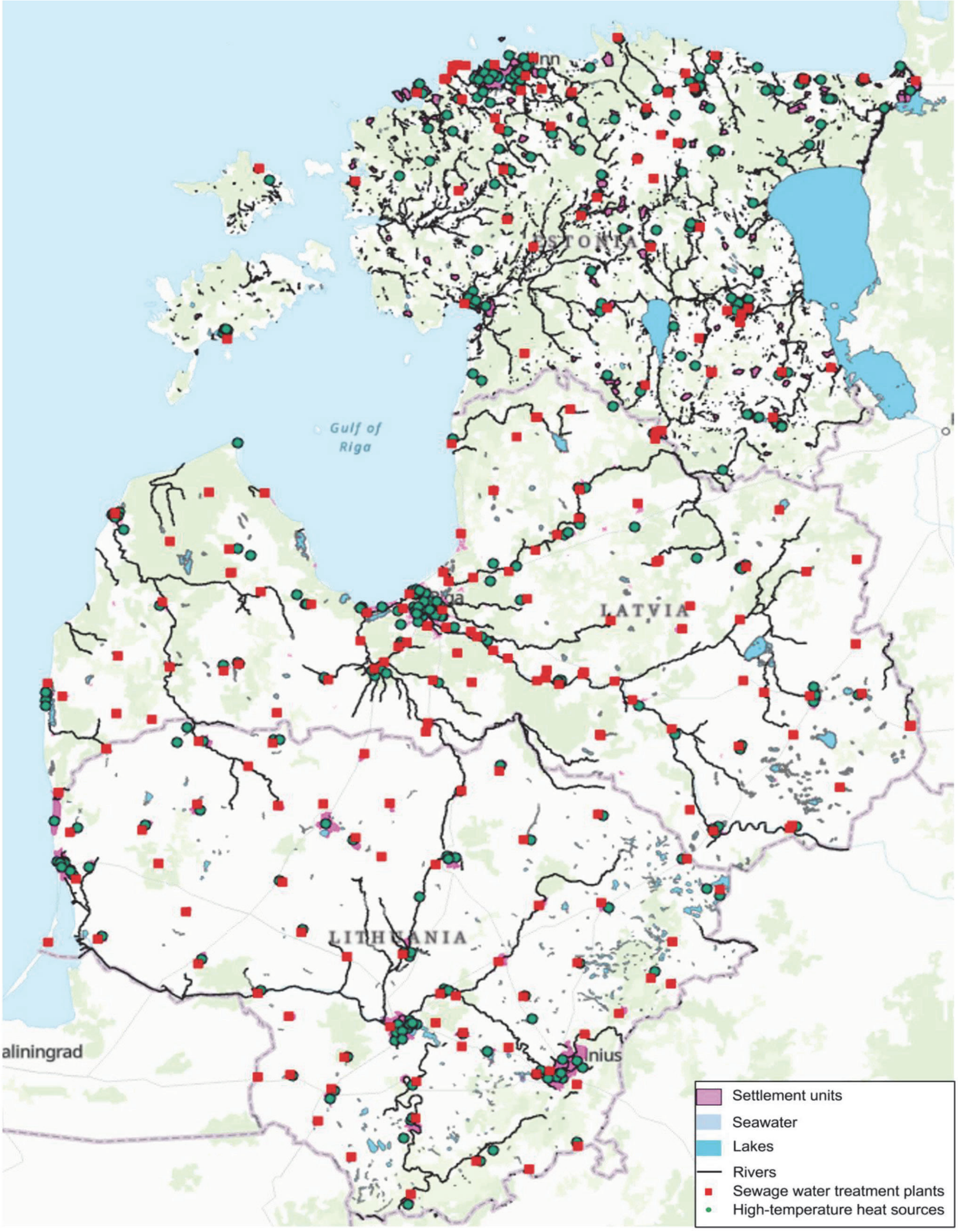


Figure 1: GIS results for the Baltics, displaying high- and low-temperature heat sources, as well as DH regions

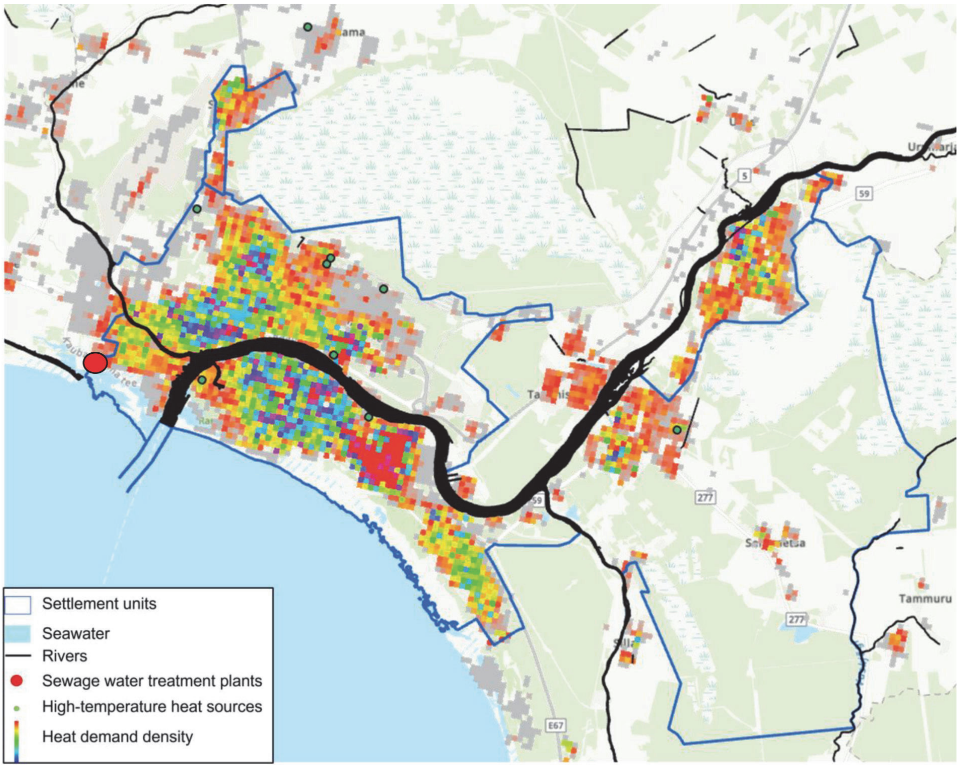


Figure 2: Municipalities, heat density areas, and accessible heat sources in the vicinity of Pärnu, Estonia

the form of a boiler house that can generate 9GWh of heat per year from flue gas. All other high-temperature heat sources are in Pärnu, including two sources located on the outskirts of the city: an asphalt plant (1.5GWh) and a CHP plant (33.5GWh flue gas). Two asphalt plants (0.8GWh and 1.7GWh), a fibreboard factory (19.3GWh), and two boiler houses (10.7GWh and 10.6GWh) make up the remaining five. Asphalt plants are often idle during the winter, making it more difficult to make use of such excess heat sources that have restricted availability during times of high demand for heat.

In addition, there are several low-temperature heat sources in and around Pärnu. The large Pärnu river flows through the city and can serve as both a heat source and a heat sink for Pärnu, Sindi, and Paikuse. Besides, Pärnu is located by the sea, so DH and/or DC can be supplied using sea or river water based on location. In particular, DC networks are usually smaller in size, so having a heat sink nearby becomes very important. Moreover, a sewage water treatment plant can serve as a potential heat source for large-scale HPs, since it maintains higher temperatures in winter, as opposed to sea and river water. As a result, a higher HP coefficient of performance (COP) can be achieved.

3.3. DC areas: comparison of GIS data and Hotmaps data

Figure 3 shows a comparison of Tartu's projected cooling demand based on the *Hotmaps* project [4] and the first DC network in the Baltics. It can be seen that the DC network was constructed in an area that the *Hotmaps* project described as having cooling needs.

Figure 4 shows another comparison, this time of the *Hotmaps* project results and Tallinn's cooling demand. Three DC regions with potential cooling demand of 60MW, 10MW, and 30MW have been discovered in Tallinn. As of today, the latter is considered a new development area with minimal cooling needs [41].

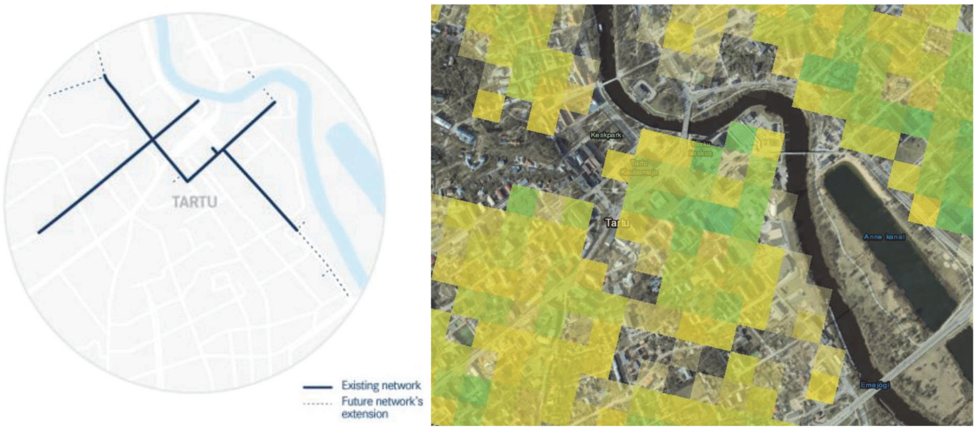


Figure 3: Tartu DC network (left) and for the same area the cooling demand resulting from the *Hotmaps* project (right) [62,63]

Since future cooling needs are not reflected in the project, the 30MW DC area could not be defined. The 60MW DC area is only partly defined, and the 10MW region is adjacent to the one shown. Instead, the project found other areas where there could be a higher cooling demand.

3.4. High-temperature heat sources

In the Baltics, 13 separate industrial sectors have been identified. Facilities unrelated to the identified sectors were categorised as ‘Other’. Table 2 provides an overview of the total PEC of high-temperature heat sources within each Baltic state. Estonia and Lithuania both have a high level of PEC in the industry. In terms of boilers and CHPs, Latvia has a fairly high PEC.

Estonia is dominated by the chemical, cement, refinery, and wood industries. They have a PEC of 16011GWh per year. With 63 (asphalt) and 10 (food) heat sources, the asphalt and food industries make up 1449GWh. Furthermore, since CHPs and boilers have an annual

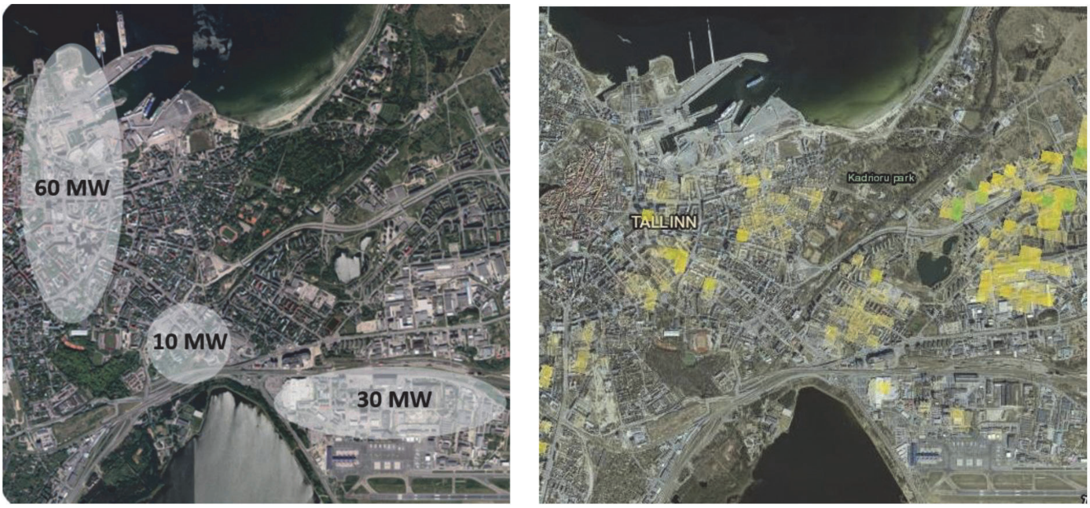


Figure 4: Tallinn DC potential (left) and for the same area the cooling demand resulting from the *Hotmaps* project (right) [41,63]

Table 2: Primary energy consumption in each country

Primary energy consumption, GWh	Estonia	Latvia	Lithuania
Industrial excess heat	18867	6257	15598
CHP plants and boilers	14029	22002	13654

PEC of 14029GWh, they provide extra capacity for excess heat from flue gas.

Cement and wood are the most prominent industrial sectors in Latvia, with a PEC of 3779GWh per year. Refineries, food, and pharmaceuticals have a PEC of 993GWh per year. At 22002GWh, the PEC for boilers and CHPs is very high.

With an annual PEC of 14064GWh, Lithuania is dominated by the chemical, cement, and paper industries. The food industry consumes 601GWh of energy per year. There are also many boilers in Lithuania, which consume a total of 10385GWh of primary energy per year. Compared to other countries, the CHP plants' excess heat potential is still very low. This could change once new CHP plants are introduced into the system.

3.4.1. Theoretical high-temperature excess heat potential

PEC, excess heat factors, and directly supplied heat or through HPs can all be used to calculate the theoretical potential of high-temperature excess heat sources, as can be seen in Figure 5. The possibility of the high-temperature excess heat source already providing excess heat to the DH network was not considered. Should the need arise, this should be evaluated separately for each source. Figure 5 does not reflect the chemical industry's potential. It is, however, significantly higher compared to other industries. In Estonia, the chemical industry has an excess heat potential of 1351GWh and in Lithuania, it has an excess heat potential of 1804GWh. Cement (EE, LV, LT), refineries (EE), wood (EE, LV), asphalt (EE), and food (EE, LV, LT), as well as boilers (EE, LV, LT) and CHP plants (EE, LV, LT) have a high excess heat potential.

Table 3 provides an overview of each country's total theoretical excess heat potential. The excess heat potential was split into two components: direct supply using a heat exchanger (2/3) and the supply by using HPs (1/3). In terms of CHPs and boilers, excess heat potential refers to flue gas after a flue gas condenser.

3.4.2. Practical high-temperature excess heat potential

Table 4 provides an overview of the potential excess heat and number of high-temperature heat sources and their accessibility in DH regions.

As can be seen, the DH regions have many industrial excess heat sources within their boundaries. However, a considerable portion, especially in Latvia, is concentrated in rural areas. This may be due to the kind of geospatial data used to represent the DH regions in this paper. In

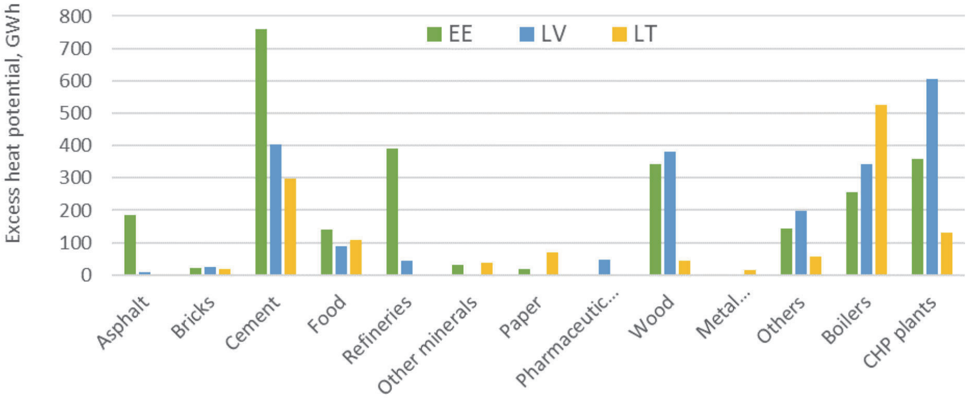


Figure 5: Theoretical excess heat potential of high-temperature heat sources in Estonia (EE), Latvia (LV), and Lithuania (LT)

Table 3: Theoretical excess heat potential of each country

Theoretical excess heat potential	**Estonia (GWh)**	**Latvia (GWh)**	**Lithuania (GWh)**
Industrial excess heat (total)	3370	1199	2490
Industrial excess heat (direct supply)	2247	799	1660
Industrial excess heat (HP supply)	1123	400	830
Boilers and CHPs (flue gas HPs)	590	949	650

Table 4: Practical excess heat potential of each country

Practical excess heat potential	**Distance (km)**	**Estonia (#, GWh)**		**Latvia (#, GWh)**		**Lithuania (#, GWh)**	
Industrial excess heat (direct supply and HPs)	0	44	2601	21	394	21	436
	<1	18	322	4	110	1	1730
CHPs and boilers (flue gas HPs)	0	46	445	54	901	63	413
	<1	1	66	1	5	1	0

Latvia, DH regions were defined in accordance with densely populated areas, while in Estonia and Lithuania, DH regions were defined on the basis of municipality borders. As a result, the areas in ArcGIS Pro that are considered to be the DH regions of the two countries may appear larger than they are, as can be seen in Figure 2. Therefore, the heat sources that must be considered for possible DH supply should be concentrated in these areas and not further out. The majority of boilers and CHPs are found in DH areas, which makes sense given that they supply DH. A separate evaluation should be carried out if any heat sources are further considered.

3.5. Low-temperature heat sources

Figure 6 provides an overview of water temperature measurements for various heat sources. As shown, sewage water retains higher temperatures throughout the colder months, when the heat demand is typically higher. Lake, river, and seawater temperatures are close to the freezing point in January and February. As a result, extracting extra heat from these sources during times of high demand of heat can be particularly difficult. Lakes, rivers, and the sea should be accessed from below the surface (≈10m), if possible, to prevent freezing. A steady temperature of 2-4°C can be reached this way, as demonstrated by the temperature of the lake water in Figure 6, which was measured at the lake's bottom (at the depth of 4m).

Crucial, but not the only selection criteria will play the heat source temperature. Other relevant criteria include distance to DH, available capacity, special equipment and/or investments, which may differ from heat source to heat source.

Table 5 provides an overview on which DH regions contain low-temperature heat sources or are within 1km

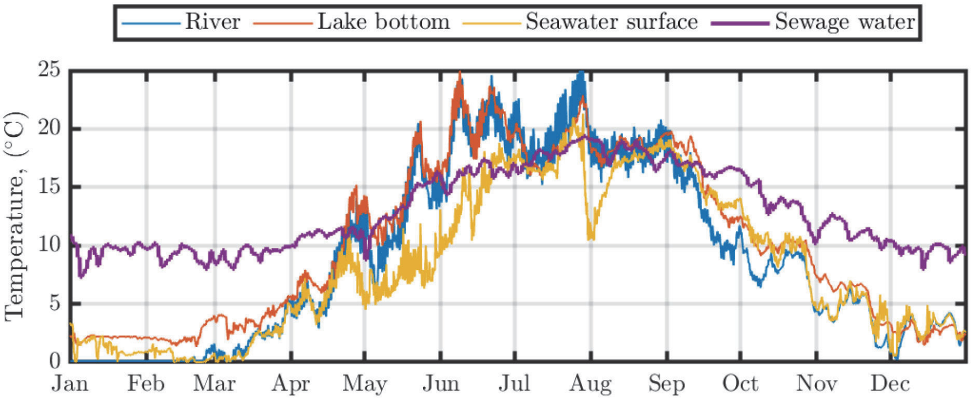


Figure 6: Heat source temperatures

Table 5: Potential of low-temperature heat sources of each country

Heat source potential	**Distance (km)**	**Estonia (#)**	**Latvia (#)**	**Lithuania (#)**
DH areas with access to seawater	0	18	9	3
	<1	4	0	0
DH areas with access to sewage water treatment plants	0	33	41	23
	<1	11	28	10
DH areas with access to large rivers	0	79	40	18
	<1	25	17	3
DH areas with access to large lakes	0	11	11	16
	<1	8	10	7

of them. As can be seen, the majority of DH regions with access to seawater are in Estonia, followed by nine in Latvia, and the city of Klaipėda, Klaipėda county, and the town of Palanga in Lithuania. Sewage water treatment plants are typically found in all major cities, although they are sometimes located outside of city limits. As a result, many DH regions have a sewage water treatment plant in the region or within 1km. Many DH regions with river access are in Estonia and Latvia, along with quite a few in Lithuania. The majority of DH regions with access to large lakes are in Lithuania, while a few are in Estonia and Latvia.

4. Discussion

As shown, existing GIS datasets can be used for a variety of purposes, including DH area visualisation. The limitations and uncertainties in describing the desired regions should be considered for future analysis. It has been shown that settlement units can represent densely populated areas; however, the unit itself is often a very large region in a rural area.

The *State of the European Territory* report [64] describes the impacts of climate change on the main biogeographic regions of Europe. It shows what potential changes to heat sources can be expected in the future, and which of them should be taken into account in terms of use and regional energy planning. The Baltics belong to the boreal region, in which a decrease in lake and river ice cover and an increase in precipitation and river flows can be expected, which may be relevant in terms of heat source usage.

The ESPON *FUTURES* project [22] shows how Europe could look like, if the entire energy system was based on 100% RES concerning the usage of regional RES, energy consumption and transport/mobility. Regarding the Baltics, for example a good wind energy potential per km^2 is shown compared to the rest of Europe. Once, this potential is used, HPs could use renewable electricity to provide also renewable heating.

Currently, all Baltic states have invested in biomass-based plants to provide heating and/or power. In 2018, Estonia, Latvia and Lithuania heat was produced by 47%, 61% and 80% using biomass, respectively [65–67]. In addition, biomass is also used for other purposes, such as construction inside the countries and as export product abroad. The ESPON HyperAtlas "REGICO" [68] was used to compare the share of forest area to the total land area (ha/ha) per country. In 2018 this ratio was 0.49, 0.39 and 0.31 in Estonia, Latvia and Lithuania, respectively. Estonia has the second highest share in Europe. Since the forest area ratio in Lithuania is much smaller, the biomass usage for different purposes, such as providing heating, should be carefully overseen.

To limit the biomass use and competition with other sectors for this resource, HPs, wind, hydropower and solar (PV, thermal) could be used more in the future to balance the sustainable usage of resources. The province Voralberg, Austria, can be used as an example of how the transition of the energy supply can be initiated. According to the ESPON *LOCATE* case study report of Rheintal [69], the share of oil and liquid gas on the energy use of households between 2003 and 2014 decreased from 45% to 29%. The biomass share has decreased from 21% to 16%, while the share of DH has almost doubled from 7% to 13% (93% biomass-based). However, the share of solar and HPs has increased enormously from 2% to 19% during the same period. Considering the generally high demand and use for biomass/wood for various purposes, its usage for the energy supply should be considered and a variety of RES be considered for the energy supply.

A high biomass usage was also reported in the case study report about Copenhagen, Denmark [70] of the

ESPON *LOCATE* project. Denmark managed to increase its production of renewable energy from 2000 until 2015 by 72%, from which biomass and wind power were the largest contributors. The consumption of renewable energy has increased by 249% during the same period, which shows that locally produced renewable energy could be used locally using e.g. the DH infrastructure. Advantageous for the biomass usage was the generally high share of heat supply by DH, which has increased from 34% to 64% from 1981 till 2015. Over the last decade, large-scale HPs have experienced an enormous growth in Denmark, because they are seen as the key technology to increase the share of RES in the energy consumption further. The growth can be explained by the regulatory framework, which has been changed in favour of large-scale HPs [71]. In the Baltic countries, a similar trend as in Denmark can be observed, namely a high share of citizens supplied by DH and a large share of biomass usage. If a similar pathway, as described in [70] for Denmark as a country and for Copenhagen as a major city, is continued, the Baltics may be on a good way for a sustainable supply of energy.

5. Conclusion

Geospatial data were applied to the Baltic states to identify DH areas, high-temperature heat sources for possible DH supply, and low-temperature heat sources that can be used for heating and cooling purposes. The available geographic data were compared with heat and cooling demand density maps. It was discovered that they contain similar information, but using settlement units as DH areas can overestimate the size of the region, especially in rural areas.

Over 350 high-temperature heat sources have been identified and their excess heat potential has been quantified. It was found that the industrial excess heat potential is 3370 GWh in Estonia, 1199 GWh in Latvia and 2490 GWh in Lithuania. From these quantities, 2601 GWh, 394 GWh and 436 GWh are located within existing DH areas in Estonia, Latvia and Lithuania, respectively. In addition, seawater, rivers, lakes, and sewage water treatment plants were considered as potential heat sources and sinks. It was found that sewage water treatment plants are located in the most major cities and that most cities, in particular in Estonia and Latvia, have access to either seawater or rivers, which all can serve as a suitable heat source for large-scale HPs. The proximity of over 350 DH areas has been analysed to identify synergy regions where excess heat or low-grade heat can be used for DH or natural heat sinks can be used for DC.

Acknowledgements

This research project received funding from the Mobilitas Pluss Postdoctoral Researcher Grant. Project title: “Optimal dimensioning and annual operation of district cooling systems in cold climates with existing district heating”. Project number: MOBJD472. This research project received funding from the Baltic-Nordic Energy Research programme. Project title: “Heat Pump Potential in the Baltic States”. Reference number: 40018 - A1H. The paper received funding from the ESPON 2020 Cooperation Programme within the framework of the initiative to support young researchers and dissemination of ESPON results among the scientific community. The authors would like to express appreciation to all the presenters, authors and the organisers of the 16th SDEWES conference (10-15 October 2021, Dubrovnik, Croatia), where the content of this paper was presented.

References

[1] European Commission. An EU Strategy on Heating and Cooling 2016. https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1575551754568&uri=CELEX:52016DC0051

[2] Colmenar-Santos A, Rosales-Asensio E, Borge-Diez D, Blanes-Peir?? JJ, Blanes-Peiró J-J. District heating and cogeneration in the EU-28: Current situation, potential and proposed energy strategy for its generalisation. Renew Sustain Energy Rev 2016;62:621–39. http://doi.org/10.1016/j.rser.2016.05.004

[3] Mathiesen BV, Bertelsen N, Schneider NCA, Garcia LS, Paardekooper S, Thellufsen JZ, et al. Towards a decarbonised heating and cooling sector in Europe: Unlocking the potential of energy efficiency and district energy. 2019. https://vbn.aau.dk/en/publications/towards-a-decarbonised-heating-and-cooling-sector-in-europe-unloc

[4] Hotmaps. Hotmaps: D2.3 WP2 Report – Open Data Set for the EU28 2019. https://www.hotmaps-project.eu/wp-content/uploads/2018/03/D2.3-Hotmaps_for-upload_revised-final_.pdf

[5] Miguel-Herrero FJ, Serna-González VI, Hernández-Moral G. Supporting tool for multi-scale energy planning through procedures of data enrichment. Int J Sustain Energy Plan Manag 2019;24:125–34. http://doi.org/10.5278/ijsepm.3345

[6] Bühler F, Petrovic S, Karlsson KB, Elmegaard B. Industrial excess heat for district heating in Denmark. Appl Energy 2017;205: 991–1001. http://doi.org/10.1016/j.apenergy.2017.08.032

[7] Estonian Land Board. Administrative and settlement units 2020. https://geoportaal.maaamet.ee/eng/Spatial-Data/Administrative-and-Settlement-Division-p312.html (accessed July 25, 2020)

[8] SE "GIS-Centras." Annex I. Hydrography (INSPIRE dataset) 2014. https://www.geoportal.lt/metadata-catalog/catalog/search/resource/details.page?uuid=%7B15DF8331-6D98-404F-A0B4-5660E613A790%7D (accessed October 22, 2020)

[9] Oloo F, Olang L, Strobl J. Spatial modelling of solar energy potential in Kenya. Int J Sustain Energy Plan Manag 2015;6: 17–30. http://doi.org/10.5278/ijsepm.2015.6.3

[10] Central Statistical Bureau of Latvia. Densely populated areas (experimental statistics) 2019. https://data.gov.lv/dati/eng/dataset/bat (accessed August 12, 2020)

[11] ESPON. ESPON toolbox overview 2013. https://www.espon.eu/tools-maps (accessed December 28, 2020)

[12] ESPON. ESPON's SDGs benchmarking tool 2021. https://sdg.espon.eu/homepage (accessed June 2, 2021)

[13] Heat Roadmap Europe. Pan-European Thermal Atlas 4.3 2018. https://heatroadmap.eu/peta4/

[14] sEEnergies. Pan-European Thermal Atlas 5.1 2021. https://euf.maps.arcgis.com/apps/webappviewer/index.html?id=8d51f3708ea54fb9b732ba0c94409133 (accessed April 22, 2021)

[15] THERMOS. THERMOS tool 2017. https://www.thermos-project.eu/home/ (accessed November 22, 2019)

[16] Trabert U, Jesper M, Bergstraesser W, Best I, Kusyy O, Orozaliev J, et al. Techno-economic evaluation of electricity price-driven heat production of a river water heat pump in a German district heating system. Int J Sustain Energy Plan Manag 2021;31:121–42. http://doi.org/10.5278/ijsepm.6291

[17] Pieper H, Mašatin V, Volkova A, Ommen T, Elmegaard B, Markussen WB. Modelling framework for integration of large-scale heat pumps in district heating using low-temperature heat sources: A case study of Tallinn, Estonia. Int J Sustain Energy Plan Manag 2019;20:67–86. http://doi.org/10.5278/ijsepm.2019.20.6

[18] David A, Mathiesen BV, Averfalk H, Werner S, Lund H. Heat Roadmap Europe: Large-Scale Electric Heat Pumps in District Heating Systems. Energies 2017;10. http://doi.org/10.3390/en10040578

[19] Leitner B, Widl E, Gawlik W, Hofmann R. A method for technical assessment of power-to-heat use cases to couple local district heating and electrical distribution grids. Energy 2019;182:729–38. http://doi.org/10.1016/j.energy.2019.06.016

[20] Connolly D, Mathiesen BV, Østergaard PA, Møller B, Nielsen S, Lund H, et al. Heat Roadmap Europe 2050 - Second Prestudy. Aalborg University; 2013. https://vbn.aau.dk/en/publications/heat-roadmap-europe-2-second-pre-study-for-the-eu27

[21] ESPON. COMPASS – Comparative Analysis of Territorial Governance and Spatial Planning Systems in Europe 2018. https://www.espon.eu/sites/default/files/attachments/2.Volume_1_Comparative_Tables.pdf

[22] ESPON. Possible European Territorial Futures 2018. https://www.espon.eu/sites/default/files/attachments/VOL E 2.pdf

[23] ESRI. ArcGIS Pro

[24] Bühler F. Energy efficiency in the industry: A study of the methods, potentials and interactions with the energy system. Technical University of Denmark, DCAMM Special Report No. S235, 2018

[25] ESPON. Territories and low-carbon economy (ESPON Locate) 2018. https://www.espon.eu/sites/default/files/attachments/Locate_final-scientific-report.pdf

[26] Euroheat and Power. District heating and cooling. Country by country 2015 survey 2015

[27] Sayegh MA, Jadwiszczak P, Axcell BP, Niemierka E, Bryś K, Jouhara H. Heat pump placement, connection and operational modes in European district heating. Energy Build 2018;166:122–44. http://doi.org/10.1016/j.enbuild.2018.02.006

[28] Eurostat. Statistics | Eurostat 2020

[29] Environmental Investment Center. Data system KIKAS. http://kik.ee/en/financed-projects

[30] Volkova A, Latõšov E, Lepiksaar K, Siirde A. Planning of district heating regions in Estonia. Int J Sustain Energy Plan Manag 2020;27:5–16. http://doi.org/10.5278/ijsepm.3490

[31] Estonian Competition Authority. Coordinated heat limit prices 2020

[32] Ekodoma. Data collection and analysis required for heat supply planning. District heating long-term tendencies till 2030. (in Latvian). 2015

[33] The Public Utilities Commission (PUC). https://www.sprk.gov.lv/

[34] Lithuanian National Energy Regulatory Council

[35] Lithuanian District Heating Association (LSTA). Lithuanian district heating sector overview in 2018 (Lithuanian), Lietuvos centralizuoto šilumos tiekimo sektoriaus 2018 metų apžvalga,

[36] Volkova A, Latõšov E, Mašatin V, Siirde A. Development of a user-friendly mobile app for the national level promotion of the 4 th generation district heating. Int J Sustain Energy Plan Manag 2019;20:21–36. http://doi.org/10.5278/ijsepm.2019.20.3

[37] Estonian Competition Authority 2020. https://www.csb.gov.lv/en/statistics/maps-and-spatial-data (accessed August 10, 2020)

[38] Central Statistical Bureau of Latvia. Maps and spatial data 2019

[39] Statistics Lithuania. Population (settlements) 2011 2015

[40] Fortum Tartu. Anne Soojus production plants 2018

[41] Krupenski I. District cooling system operation in cold climates with existing district heating networks 2020

[42] Danish Energy Agency. Guide for large-scale heat pump projects in district heating systems (in Danish) 2017

[43] Huang B, Bühler F, Müller Holm F. Industrial Energy Mapping: THERMCYC WP6. Tech Univ Denmark 2015

[44] Environmental information system KOTKAS. https://kotkas.envir.ee/

[45] The State Environmental Service of the Republic of Latvia. https://www.vvd.gov.lv/

[46] The Environmental Protection Agency (EPA). www.gamta.lt

[47] Ayub Z. World's Largest Ammonia Heat Pump (14 MWh) for District Heating in Norway—A Case Study. Heat Transf Eng 2016. http://doi.org/10.1080/01457632.2015.1052716

[48] Friotherm AG. Värtan Ropsten – The largest sea water heat pump facility worldwide , with 6 Unitop ® 50FY and 180 MW total capacity 2017. https://www.friotherm.com/wp-content/uploads/2017/11/vaertan_e008_uk.pdf

[49] AS Tallinna Vesi. Personal Communication with Mattias Müür 2018

[50] Danish Energy Agency. Drejebog til store varmepumpeprojekter i fjernvarmesystemet (English: Guide for large-scale heat pump projects in district heating systems) 2017

[51] Danish Energy Agency. Inspirationskatalog for store varmepumpeprojekter i fjernvarmesystemet (English: Inspiration catalogue for large-scale heat pump projects in district heating 2017

[52] Hoffman K. Large scale heat pumps for high efficiency district heating projects. IOR 2018

[53] Estonian Land Board. Waterbodies 2020

[54] Public Sercvice of the Environmental Register. Environmental Register 2020

[55] SIA Envirotech. Envirotech data: Shoreline 2016

[56] SIA Envirotech. Envirotech data: Water bodies 2016

[57] SIA Envirotech. Envirotech data: Watercourses 2016

[58] MapCruzin.com, OpenStreetMap.org. Lithuania Waterways 2020

[59] Ots S. Nautic map 2018. https://gis.ee/projektid/ (accessed September 1, 2020)

[60] Ministry of Environmental Protection and Regional Development of the Republic of Latvia. Marine Spatial Planning (MSP): A map of the depth of the sea 2013

[61] European Environment Agency. Urban Waste Water Treatment map 2019

[62] Euroheat & Power. Tartu: the first district cooling solution in the Baltics

[63] Hotmaps. Hotmaps online GIS-tool. https://www.hotmaps.eu/map (accessed January 3, 2021)

[64] ESPON. State of the European Territory: ESPON contribution to the debate on Cohesion Policy post 2020 2019. http://www.ccdr-lvt.pt/files/a56ad651cc65e16ef43864e843d281df73f51917.pdf

[65] Statistikaamet. KE023: Energiabilanss kütuse või energia liigi järgi (1999-2018) 2020

[66] Centralas Statistikas Parvaldes datubazes. Fuel consumption and heat produced in heat plants 2020

[67] Euroheat and Power. District Heating in Lithuania 2020

[68] ESPON. REGICO 2021. https://regico.espon.eu/ (accessed May 24, 2021)

[69] ESPON. Territories and low-carbon economy Rheintal, Austria 2017. https://www.espon.eu/sites/default/files/attachments/CS_Rheintal_0.pdf

[70] ESPON. Territories and low-carbon economy Greater Copenhagen, Denmark 2017. https://www.espon.eu/sites/default/files/attachments/CS_Copenhagen_0.pdf

[71] Ministry of Foreign Affairs of Denmark. New ambitious Danish energy agreement secured 2018. https://investindk.com/insights/new-ambitious-danish-energy-agreement (accessed November 1, 2019)

Appendix 6

Publication VI

Volkova A, Pakere I, Murauskaite L, Huang P, Lepiksaar K, Zhang X. 5th generation district heating and cooling (5GDHC) implementation potential in urban areas with existing district heating systems. *Energy Reports* 2022;8:10037–47. https://doi.org/10.1016/j.egyr.2022.07.162

Energy Reports 8 (2022) 10037–10047

Contents lists available at ScienceDirect

Energy Reports

journal homepage: www.elsevier.com/locate/egyr

Research paper

5th generation district heating and cooling (5GDHC) implementation potential in urban areas with existing district heating systems

Anna Volkova [a,*], Ieva Pakere [b], Lina Murauskaite [c], Pei Huang [d], Kertu Lepiksaar [a], Xinxing Zhang [d]

[a] *Tallinn University of Technology, Estonia*
[b] *Riga Technical University, Latvia*
[c] *Lithuanian Energy Institute, Lithuania*
[d] *Dalarna University, Sweden*

ARTICLE INFO

Article history:
Received 21 April 2022
Received in revised form 3 July 2022
Accepted 28 July 2022
Available online 12 August 2022

Keywords:
5GDHC
Urban waste heat
Excess heat
Heat pumps
Data centres
District cooling

ABSTRACT

The 5th Generation District Heating and Cooling (5GDHC) network has great advantages in terms of integration of low-temperature resources, bi-directional operation, decentralised energy flows, and possible energy sharing. One way to develop the idea and concept of 5GDHC is to identify potential agents, including residential buildings, office buildings, shopping malls, data centres, electrical transformers, and so on, in 5GDHC in each target context. The prospects for 5GDHC have been assessed in light of the conditions in the Baltics. The multi-criteria analysis method was used to quantify the main identified barriers and drivers behind the implementation of 5GDHC systems. It should be noted that new urban areas in the Baltic states are being actively developed with low-energy buildings, so 5GDHS can be integrated to supply heat to these areas. The highest score in the multi-criteria assessment was achieved by Lithuania due to support availability and open heating market conditions. When all applied criteria are weighted equally, Estonia has the most favourable conditions for 5GDHC systems due to widespread use of heat pumps and greater excess heat potential.

1. Introduction

District heating and cooling (DHC) technology has been widely recognised as a promising solution to reduce both primary energy consumption and local emissions (Rezaie and Rosen, 2012; International Energy Agency, 2014). The 5th generation district heating and cooling (5GDHC) network is the latest district heating/cooling concept, which is characterised by low temperature supply (i.e. close to ground temperature), bi-directional operation (i.e. it can provide heating and cooling simultaneously), decentralised energy flows (i.e. it allows multiple heat sources and heat sinks in the network), and heat sharing (i.e. it can recover waste heat and share it with different users) (Buffa et al., 2019). Unlike the 4th generation district heating (4GDH) technology, the 5GDHC technology is geared towards the consumer/prosumer. It only needs one thermal grid, but it serves multiple purposes for both heating and cooling distribution, including heat and cold storage, and thus provides flexibility in adopting local renewable energy and waste heat resources. As pointed out in Revesz et al. (2020), by integrating the low-grade heat with photovoltaic arrays, batteries, and vehicle-to-grid applications, 5GDHC systems also support the electrification of both the building and transportation sectors towards the broader concept of 'fifth generation smart energy networks'.

The distinction between 5GDHC and 4GDH has been studied in the past. For instance, Lund et al. (2021) performed a systematic comparison of 5GDHC and 4GDH in terms of goals and capabilities. According to their findings, 5GDHC has five of the same core capabilities as 4GDH: (i) the ability to supply different types of buildings, (ii) the ability to distribute heat with small grid losses, (iii) the ability to recycle heat from low-grade sources, (iv) the ability to be integrated into large smart energy systems, and (v) the ability to ensure proper planning and cost-effective investment. The main differences in 5GDHC are the strong emphasis on combined heating and cooling, as well as the use of a collective network close to ground temperature as a common heat source or sink for heat pumps (HP). After reviewing various literature, they also concluded that 5GDHC can be viewed as a technology with its own merits. It does not have to replace other 4GDH technologies. Instead, it can coexist with other 4GDH technologies. Ref. Gudmundsson et al. (2021) compared the levelised costs of heat from both 4GDH and 5GDHC in Denmark and the UK. The results of this study showed that, under current cost scenarios, 4GDH is more cost-effective compared to 5GDHC in both of these countries. This is due to three key factors: (1) economy of scale of central

---

[*] Corresponding author.
E-mail address: anna.volkova@taltech.ee (A. Volkova).

https://doi.org/10.1016/j.egyr.2022.07.162

Abbreviations

4GDH	4th Generation District Heating
5GDHC	5th Generation District Heating and Cooling
AHP	Analytic Hierarchy Process
DH	District Heating
DHC	District Heating and Cooling
HP	Heat pump
MILP	Mixed-integer linear program
MPC	Model predictive control
RES	Renewable energy sources
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution

HPs, (2) access to cheaper input energy, and (3) simpler building interface units. These factors can offset the additional cost of the insulated piping network and the associated distribution heat loss in 4GDH systems compared to 5GDHC. The key difference and barrier between 5GDHC and 4GDH is the HPs' reliance on the power supply system, as they must raise the temperature to fulfil the needs of the end users. Therefore, an increase in the electricity price will significantly increase the cost of 5GDHC.

Several studies have looked at 5GDHC technology from various perspectives. Grzegórska et al. (2021) reviewed the current status of district heating (DH) systems in terms of the application and solutions of novel approaches to smart asset management (i.e. maintenance approaches via control, prediction, optimisation, and selective refurbishment of assets with the aid of novel hardware and software solutions) for several countries of the Baltic region (Grzegórska et al., 2021). They compared the traditional maintenance system with smart asset management solutions for optimal design, operating conditions and management of the DH network. Their review concluded that integrating smart management tools into DH systems can solve issues in existing DH networks while also ensuring profitability for both heat providers and consumers. Buffa et al. (2019) conducted a comprehensive review of 40 thermal networks operating in Europe that can provide both heating and cooling to buildings. They conducted a drawback-benefit analysis to investigate the pros and cons of 5GDHC technology. They also explored the challenges associated with implementing 5GDHC technology, including the lack of guidelines for designers and planners, the lack of a local heat atlas, and the lack of new business models and tariff mechanisms. To improve the performance of energy transmission stations in a building, model predictive control (MPC) algorithms based on recurrent artificial neural networks were developed in Buffa et al. (2020). The results showed that MPC can effectively shift electricity consumption from energy transmission stations from peak to off-peak hours by up to 14%, and thus, the use of advanced control in 5GDHC can promote the coupling between the thermal and electric sectors. They also pointed out that the potential weaknesses of the 5GDHC technology mainly include complicated seasonal load balancing and increased complexity in both distribution network management and energy transmission stations at customer locations.

There are some studies related to the techno-economic analysis of the 5GDHC network. For example, Wirtz et al. (2021) developed a mixed-integer linear program (MILP) control method for short-term network temperature optimisation in 5GDHC systems that took into account the integration of both waste heat and free cooling. Their 5GDHC system includes a HP, a chiller and thermal storage in a central generation unit, as well as pumps, chillers, electric boilers and thermal storage in 17 agent buildings. The results showed that such temperature control can reduce the operating temperature of the network and cut operating costs by 10%–60%. Another study (Millar et al., 2021) provides an assessment framework for determining the economic, operational, and carbon benefits of HP-driven 5GDHC energy sharing networks for an urban centre. In particular, they created a load matrix to analyse which energy loads from various building types are suitable for energy sharing. Using the proposed assessment framework and load matrix, they conducted parametric studies of various scenarios for heat tariff, energy sharing, thermal storage, and carbon tax combinations. The results of the study showed that the financial benefits of 5GDHC are more dependent on factors such as the size of the thermal storage and time-of-use tariffs, while the carbon savings of 5GDHC are more dependent on system alternatives such as natural gas boilers. Energy sharing barely affects these metrics. A bibliographic analysis of the modelling and co-simulating of 5GDHC systems was published in Abugabbara et al. (2020). Their analysis concluded that the co-simulation between the district energy system and building energy models can help reduce oversized space heating and cooling systems, since proper advanced control strategies are still lacking for 5GDHC operation. They also stated that 5GDHC systems address two of the main challenges faced by the 4GDH, including (i) the need for separate pipes to provide both heating and cooling and (ii) centralised energy generation, which limits the expansion area of the network.

In the 5GDHC, different players can be considered as agents interacting with each other through pipes: consumers, suppliers, and prosumers. Consumers represent end users of heat and cold, such as residential buildings. Suppliers represent heat producers, such as the existing DH network, process excess heat, or solar thermal energy. Prosumers represent heat users that can sometimes produce heat, such as data centres and shopping malls. In 5GDHC, potential agents include office buildings, shopping malls, data centres, electrical transformers, etc., which can add low temperature heat to the network. The agents draw water at a temperature between 5-30 °C from the loop to cover their heating or cooling demand and re-inject the water back into the same loop. HPs can be utilised in a network to meet a variety of heating and cooling needs at various temperatures. HP can be powered with renewable energy from wind farms and photovoltaic (PV) farms. In this regard, the use of HPs by agents can also provide flexibility in balancing fluctuations in the power grid due to intermittent renewable energy sources (RES) (Fischer, 2014). Danfoss, as practitioners, emphasise that 5GDHC has a significant dwelling spatial impact, as well as medium dwelling noise levels due to the use of individual HP (Danfoss, 2021). There is a significant resident risk for the same reason that HP is used. Geothermal energy can also be integrated into 5GDHC as a potential agent (Boesten et al., 2019). The legal framework for shallow geothermal energy in 14 European countries is reviewed in detail in Tsagarakis et al. (2020). Their review showed that across European countries there are significant disparities in legal provisions, as well as in regulations, standards, and institutional support. These differences are barriers to the market's continued integration of geothermal energy into 5GDHC. 5GDHC is also subject to similar barriers, which prevent 5GDHC from being put into practice on a larger scale.

So far, there has not been a systematic study of potential agents that can be used in the 5GDHC, such as residential buildings, office buildings, shopping malls, data centres, electrical transformers, and so on. There is also no comprehensive review and analysis of the barriers and drivers for the implementation of 5GDHC. This may hinder the introduction of 5GDHC techniques on a large scale. Thus, this study provides a comprehensive review of potential agents that can be used as active heat sources or sinks in 5GDHC in the Baltic countries. This paper also explores the barriers and drivers for the implementation of 5GDHC in terms of economics, markets, technologies, policies, etc. Country-specific conditions such as heating tariffs, regulatory mechanisms, stakeholders, existing DH infrastructure, DH market and others are evaluated for the three Baltic states (Latvia, Estonia, and Lithuania). A preliminary evaluation is also conducted to explore possible implementation opportunities for the 5GDHC network in the Baltic states. This study can help to understand how different agents can be integrated into 5GDHC, and what waste heating or cooling potential they can bring to the 5GDHC network. This will provide a solid basis for the future 5GDHC modelling and techno-economic analyses. The identified barriers and drivers will pave the way for the implementation of the 5GHDC network in the future.

The structure of the paper is as follows. Section 2 reviews and analyses the barriers and drivers of 5GDHC. Section 3 presents the general research methodology. Section 4 presents waste heat potential results from a set of agents. The conclusions are provided in Section 5. A multi-criteria analysis is used to allow comparisons between countries.

2. Barriers and drivers of 5GDHC in the Baltic states

To identify the main barriers and drivers, it is necessary to assess the current situation. Due to the cold climate in the Baltic states, the heating sector plays a very important role. The majority of residents in the Baltic countries have their heat supplied via DH (62% in Estonia, 65% in Latvia, and 58% in Lithuania), which is well above the EU average of 26%. Despite the fact that the share of RES in the heating and cooling sector in the Baltic countries is rather high (52% in EE, 58% in LV, and 47% in LT (Eurostat, 2020a)), there is a potential to increase the share of renewable energy in this sector. The heat supply in these countries is mainly based on the combustion process, and the high share of renewable energy can be explained by the combustion of large amounts of wood chips in boiler houses and combined heat and power plants. It should be recognised that the share of energy from low-grade heat sources is minimal and can be significantly increased. The purpose of this section is to assess the possibilities for 5GDHC implementation in the Baltic states. The current situation was assessed and the main barriers to implementation were identified. Based on the 5GDHC definition, the following factors were analysed: stakeholders (DH operators and producers), regulatory mechanisms and DH tariffs, existing DH infrastructure, building stock, pilots, energy policy, and strategic DH energy goals.

2.1. Stakeholders

The main difference between DH stakeholders is ownership. In Estonia, DH operators are mostly private companies (Volkova et al., 2020), while in Latvia DH operators are mostly municipalities, but private companies also own some systems. There are both private and public DH operators in Lithuania.

Private DH companies are more experienced with specific DH operating issues and solutions, which is one of the key advantages when DH networks are operated or owned by private companies. Moreover, private entities as DH owners may be more interested in investing in improvements due to the profit orientation. In addition, private ownership of the DH network is less subservient because local municipalities do not need to buy services from private companies. The main disadvantages are that private companies are more profit-oriented and are not interested in less feasible DH networks (Egüez, 2021).

If the municipalities own DH, it is possible to implement complex heat supply renovation projects, including the improvement of heat supply and public buildings. For example, the municipality of Gulbene implemented the first small-scale low-temperature DH system in Latvia since it owned both the heat source and the buildings to which the heat was supplied. As a result, customer participation and agreements were not necessary. However, municipalities sometimes have limited access to adequate investment funds, modern management practices, and new technologies. In addition, municipal DH systems are subject to public and political control, which can slow down the adoption of innovative technological solutions.

Both private and municipal ownership are viable options for 5GDHC. Existing case studies show that private companies are more interested in developing the 5GDHC technology in parallel with 4GDH.

2.2. Regulatory mechanisms and district heating prices

The DH network in Estonia is regulated by the District Heating Act (Eesti Vabariigi Valitsus, 2017), while in Lithuania the DH sector is regulated by the Law on the Heat Sector. Only Latvia has no specific laws for the DH sector (The Cabinet of Ministers of the Republic of Latvia, 2008). However, the DH sector in Latvia is regulated by the Energy Law, which governs Latvia's energy sector, including heating as a sector of the economy that covers the extraction and use of energy resources. There is also a regulation on the Supply and Use of Thermal Energy, which establishes the procedure for the supply and use of thermal energy, as well as defines the obligations of the supplier and consumer of heat. In addition, the regulations on Energy Efficiency Requirements for Centralised Heating Supply Systems set out energy efficiency requirements for centralised heating systems, specifying the maximum heat loss in the DH network and the minimum requirements for the efficiency of heat production for various technologies.

All Baltic countries have DH price regulators. The main difference between the three countries is the market situation. In Estonia and Latvia, the DH monopoly exists, while heat production in Lithuania is based on heat producers competition (Volkova et al., 2020; Rušeljuk et al., 2020). In order to ensure competition between heat producers, NERC approves a set of conditions for the use of heat transmission networks, which are mandatory for all persons involved in energy activities in Lithuania's heating sector. Lithuania has a unique market mechanism for the DH sector. Each month, different DH suppliers compete in price level auctions. This competitive market model is the only one in European DH. Moreover, Lithuanian DH companies participate in the biomass market and the purchase of biomass is dependent on the market price. Independent heat producers have built about a third of biomass-based plants. Competition among heat producers is organised on the basis of monthly heat sale auctions. In Lithuania, there is a national biomass and heat energy exchange BALTPOOL, where all heat producers are obliged to buy biomass and sell heat in individual municipalities. The experience of the exchange is of interest to foreign politicians and officials. BALTPOOL is in the process of expanding its activities to other countries.

DH prices in the Baltic states are set in accordance with national legislation. The DH price limit in Estonia must be justified, cost-effective and enable the company to fulfil its legal obligations. Only justified sales volumes and profitability expenses may be taken into account when approving the heat energy price for the period of regulation. The validity of the costs included in the heat limit price and their cost-effectiveness are assessed. The maximum area price is set by the Competition Authority in accordance with technical indicators (Eesti Vabariigi

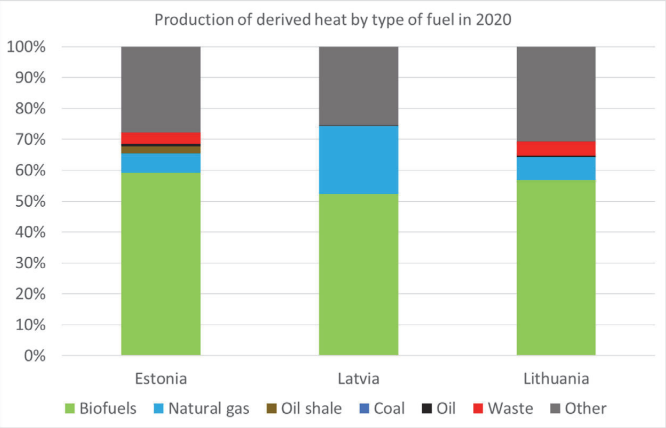


Fig. 1. Production of heat by fuel type in 2020 (based on Eurostat (2020b)).

Valitsus, 2017; Anon, 2020a). The Lithuanian National Energy Regulatory Council (NERC) sets the base price for heat. The municipal council determines the specific components of the heat price, submits documents to NERC for base price harmonisation, and provides feedback on the draft base price. The heat supplier, taking into account the established components of the price for heat, calculates the changed fuel prices and the changed prices for purchased heat, and publishes the final heat prices. Heating tariffs in Latvia depend on many factors, including the size of the system, the fuel used, the technical condition of the system, and even political considerations. Heat production, transmission and distribution are public services that are regulated by the Public Utilities Commission in Latvia. Small DH systems (up to 5000 MWh per annum) are not regulated (Latvian Public Utilities Commission, 2020).

For 5GDHC, strict regulation of DH may be a major disadvantage due to the inability to make a profit and pay banks for the investment necessary for a new low-temperature network.

2.3. Existing DH infrastructure

The DH infrastructure in the Baltic states is well-developed and widespread in many cities/towns. High-temperature DH is currently just in its third generation, but the heat generation sources are mostly renewable (Fig. 1).

Lithuania has a well-developed DH system. The share of DH in the overall heating sector has remained unchanged in recent years, on average, around 58% in the country and around 76% in cities. DH companies operate in all 60 municipalities of Lithuania. These entities are regulated by the NERC. Smaller heat supply companies are regulated by the municipalities. Municipalities own about 90% of DH companies and 10% have been leased to foreign and domestic investors. Private capital entered the Lithuanian DH market in 2000. Almost 70% of the heat is produced using RES (mainly biomass) and municipal waste in the Lithuanian DH sector (Eurostat, 2020a). The share of heat from natural gas in the fuel mix is less than 30%. Up until 2014, natural gas was the main fuel in the DH heat generation structure. The quick substitution of imported natural gas with local renewable biomass was beneficial to the local economy, created new jobs in the regions and expanded new industries. Penetration of biomass into the Lithuanian DH sector has been implemented by the use of EU support.

Historically, natural gas has been the dominant DH fuel in Latvia. Between 2014 and 2019, the share of heat produced using natural gas at cogeneration plants decreased from 75% to 53.5%, but in heat-only boiler houses, the share of natural gas-based heat decreased from 42.4% to 29.6%. This is mainly due to the support policy for switching to renewable fuels, particularly biomass fuels such as wood chips. Thus, biomass-based heat production increased from 19% in 2014 to 29% in 2019 at cogeneration plants and from 50% to 66% at heat-only boiler houses (Pakare et al., 2021).

The total length of heating networks in Latvia is about 2000 km, of which most of the heating pipelines are outdated and affected by large heat loss. However, there is a gradual renovation and optimisation of heating networks, and average heat loss has been on the decline since 2009, reaching 11% in 2020. The heat supply temperature in heating networks is around 80–90 °C during cold winter periods and around 70 °C during most of the season when the outdoor temperature is around 0 °C (Blumberga et al., 2020).

Oil shale is the main source of energy and the main fuel in Estonia's energy mix. On the one hand, the substantial use of oil shale as a domestic fuel guarantees energy security. Oil shale energy production, on the other hand, emits a substantial amount of greenhouse gases due to its high carbon intensity, which has a negative impact on the environment. As a result, the Estonian economy produces more than twice as much carbon dioxide (CO_2) as the EU average. The Estonian government is gradually decommissioning existing power plants and developing new technologies to drastically reduce CO_2 emissions and harmful environmental impact. Estonia exports electricity because its production slightly exceeds consumption. The total electricity output in Estonia in 2019 was 7.615 TWh, and while the total electricity demand was 8.257 TWh. Oil shale was used to generate more than half of all electricity (56%), followed by biomass (17%), wind power (9%), and renewable waste (1%) (Augutis et al., 2020).

There are over 200 DH networks in Estonia, with DH accounting for more than 60% of total heat production. Since 2014, with the EU's assistance, numerous small DH network boilers have been refurbished, and new biomass boilers have been deployed to replace ageing gas and oil-fired boilers. Oil and natural gas consumption in Estonia has been declining since 2010 (Statistics Estonia, 2020). In 2018, biomass accounted for 46.8% of the Estonian DH energy mix and natural gas for 25.6%. Oil shale (9.2%), municipal waste (6%), shale oil gas (6%), fuel oil (3%) and peat (2.8%) make up a small part of the DH energy mix in Estonia.

The main barrier to 5GDHC is the existing well-developed and widespread 3rd generation DH infrastructure in all three Baltic countries. As a result, 5GDHC development can be carried out primarily in newly built areas, in addition to the existing DH network.

2.4. Building stock

According to Statistics Estonia, there are 23,600 apartment buildings in Estonia. Most of these apartment buildings were built during the period of industrial construction between 1960 and 1990. Apartment buildings in Estonia are mainly heated by DH and have a single-pipe heating system with hydronic radiators and no thermostats. The indoor temperature is regulated only at heating substations (Kuusk and Kurnitski, 2019). The annual energy consumption of residential buildings remains relatively stable at 10 to 12 TWh. Heating accounts for about 85% of consumption (∼9 TWh) and electricity accounts for ∼15% (∼2 TWh). The share of electricity consumption in residential building energy consumption has grown steadily over the years. The final energy consumption of non-residential buildings has also increased. In 2004, non-residential buildings consumed 4 TWh of energy. By 2017, their consumption has increased by 50%, reaching 6 TWh. Around 50% of non-residential building consumption is for heat (∼3 TWh) and the remaining 50% is for electricity (∼3 TWh). A reduction in final energy consumption of about 7 TWh/y would be possible if the buildings were fully renovated. It would be possible to reduce heat consumption by up to 70% (∼6.4 TWh/y) and electricity consumption by up to 20% (∼0.5 TWh/y). The slight reduction in electricity consumption is due to buildings that do not have an appropriate indoor climate, but this can be achieved by installing appropriate utility systems that use electricity (Ministry of Economic Affairs and Communications (Estonia), 2014).

According to the Real Property Register, there are more than 41,000 apartment buildings in Lithuania. Most of these apartment buildings (90%) were constructed before 1992 with very low energy efficiency. Only 2% of buildings in Lithuania are owned by the state (state or municipal property), with private ownership accounting for 98% (individuals or legal entities). Therefore, the main obstacle to renovation is the persuasion of private owners of buildings. The annual consumption of thermal energy by the building stock is about 20 TWh for heating and 8.5 TWh for hot water supply. Residential buildings consume 17.5 TWh of thermal energy and only 1.7 TWh of electricity.

Data provided by the State Land Service show that there were 39,000 apartment buildings in Latvia in 2019. The total housing stock is 91.08 million m^2, and the total area of non-residential buildings is 115.50 million m^2 (Ministry of Economics of the Republic of Latvia, 2020). The total consumption for space heating in 2019 was 10.24 TWh. Most existing buildings have a high heat consumption and significantly lower thermal properties than can be provided by currently available technologies. The average rate of depreciation for residential buildings is 38.9%. The average energy consumption for space heating among all types of buildings is 138–139 kWh/m^2 per year. In recent years, however, step-by-step measures have been taken to improve energy efficiency, resulting in a reduction in specific heat consumption. In apartment buildings, for example, the decrease between 2016 and 2019 is 13.8 kWh/m^2.

5GDHC ultra-low temperature regime requires high energy efficiency in buildings. A large proportion of old buildings that consume large amounts of thermal energy are not suitable for 5GDHC implementation.

2.5. Pilots

DH operators mainly provide space heating and domestic hot water, while some also generate electricity in all three countries. The existing DH infrastructure is represented only by the 3rd generation (Volkova et al., 2018). The first steps to reduce the temperature are planned to be implemented in the Lithuanian capital Vilnius in 2022. A small low-temperature DH was also introduced in Latvia, in a parish of the Gulbene Municipality, which is more focused on the optimisation of the existing heating network in the village (Pakere et al., 2018). In Estonia, there are no implemented DH networks of the 4th generation. District cooling is implemented only in Estonia (Tallinn, Tartu and Pärnu) (Pieper et al., 2021; Volkova et al., 2022).

2.6. Energy policy

The electricity generation mix is diverse and unique in each of the Baltic countries. Estonia is the only country where more than 70% of oil shale is used to generate electricity. Latvia is the country where natural gas (50%) prevails over hydropower (33%). Since the shutdown of the Ignalina nuclear power plant in 2009, Lithuania has had a unique situation in the electricity market, with about 70% of electricity imported. The rest of Lithuania's electricity is generated primarily by wind (38%) and hydropower (24%), but hydropower generation in Lithuania is quite low compared to Latvia due to a substantial share of imported electricity. Electricity production can be seen in Fig. 2.

Latvia is one of the leading countries in terms of the achieved share of RES in the power generation mix due to a significant share of hydropower. However, Latvia has a limited installed capacity of RES variable energy from solar and wind energy, but this is likely to grow as the market develops and natural gas prices rise. Even if the general energy policy continues to prioritise the use of biomass and improving energy production and transmission efficiency, more widespread electrification is possible. The heating network is anticipated to become more open and accessible to various heat sources, increasing the diversity of DH systems. Since the first large-scale solar thermal field has been successfully launched, it is predicted that the share of solar heat in DH may increase in the coming years. It is also expected that large-scale solar plants will get a larger share in DH, and energy accumulation technologies will develop.

In early 2021, the new Estonian government introduced plans to achieve carbon neutrality by 2050 and drastically reduce the use of oil shale. Estonia has met its mandatory 2020 emission reduction and renewable energy targets. In 2030, for the first time, Estonia will have to reduce emissions and not just limit their growth. Because of the incentives granted by the Electricity Market Act, which apply to the generation of electricity using renewable sources, the share of renewable energy has climbed to 30% and will continue to grow.

Lithuania reached its 2020 renewable energy target (23%) back in 2014. More than a third of all local electricity production in Lithuania comes from wind power plants. The share of solar PV is the highest in Lithuania among the Baltic countries due to energy policy that is favourable for investment subsidies and energy prosumers, as well as renewable energy communities. The installed capacity of energy prosumers increased from 30 MW in 2019 to 138 MW in 2021. The amount of electricity supplied by energy prosumers increased by about 4 times (from 9 MWh in 2019 to 35 MWh in 2021). For 5GDHC, the electricity mix and the particularly low electricity price is a major factor in the low maintenance costs of such a system.

2.7. Strategic DH goals

The strategic DH goals of the Baltic states are ambitious in terms of the use of RES. According to the National Development Plan of the Energy Sector until 2030, 11 TWh of the total heat

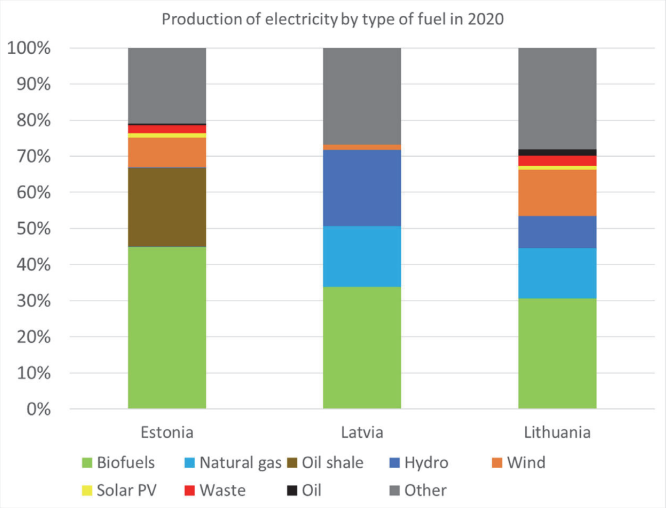


Fig. 2. Electricity generation by fuel type in 2019 (based on Eurostat (2020b)).

demand will be met by biomass in 2030, and 80% of DH in Estonia will be provided using renewable sources (Government of the Republic of Estonia, 2017). In 2020, RES already accounted for 71.5% of the total energy production in the DH networks in Lithuania. Furthermore, Lithuania has set a goal to increase this percentage to 90% by 2030 and bring it to 100% by 2050, which is the most ambitious goal among the Baltic states. According to the Latvian NECP 2021–2030, the share of RES in DH will increase by around 0.8–1.0 percentage points each year from 2020 to 2030, reaching 57.6% in 2030 (Ministry of Econonics of the Republic of Latvia, 2018).

5GDHC is not mentioned in any of the Baltic countries' strategic documents. In the DH sector, development is focused on renewable energy, primarily biomass. However, 5GDHC may have important infrastructure that can integrate different types of renewable energy technologies, especially in areas with new high-energy-efficiency buildings.

The main drivers behind the implementation of 5GDHC and barriers that limit its development in Europe are summarised in Table 1. The main aspect that distinguishes 5GDHC from 4GDH is the dependence on the electricity system. A new pipe system for the ultra-low temperature DH system, as well as a dedicated new infrastructure that incorporates both heating and cooling and renewable energy sources, demand substantial initial expenses. The country's ambitious energy and climate change targets can be major drivers. Other drivers include the possibility of recycling low-temperature waste heat not only from industry but also from other local sources, as well as the development of local economic value and the creation of jobs.

3. Methodology

The possibility for 5GDHC introduction in the Baltic states was assessed using a multi-criteria analysis. A qualitative comparison was made by discussing the barriers and drivers that each country faces, and a quantitative comparison was made by assigning numerical values to each criterion. The quantitative analysis was performed using a multi-criteria decision method to compare various aspects of a potential 5GDHC implementation. The result of the quantitative analysis is the ranking of the country for each aspect.

The obtained criteria values were evaluated using the method of multi-criteria analysis called the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) and the Analytic Hierarchy Process (AHP) method to determine the weight of each criterion. The TOPSIS method of multi-criteria analysis is widely used to compare different environmental strategies for sustainable development (Balioti et al., 2018; Laktuka et al., 2021), taking into account different points of view. The main purpose of TOPSIS is to allow users to compare and choose between multiple alternatives.

The evaluation criteria are shown in Table 2. The authors used 15 different criteria to quantify and compare barriers and drivers for 5GDHC implementation in the Baltic countries.

The assessment includes criteria related to the existing power system, since the operation of 5GDHC is highly dependent on the implementation of power-driven HPs. The authors compared the average final electricity price between the countries, expecting that lower electricity prices will encourage HP adoption. In addition, the share of power supplied by RES is included because the power for 5GDHC must primarily be produced in a climate-neutral way. Finally, the authors included two criteria related to electricity CO_2 emission factors: the existing CO_2 emission factor and the projected CO_2 emission factor for each country's future energy balance based on Elering (2014), European Commission (2016). Criteria related to the current status of HP installations in the country have also been included as they indicate whether the HP market is in a mature stage. This is important from the point of view of stakeholders such as HP resellers and users.

Since 5GDHC can be considered a competitor to traditional DH systems, the authors included several criteria that characterise the main parameters of the existing centralised heat supply system: the maximum and minimum heat tariffs and tax rates. The analysis suggested that the implementation of 5GDHC is preferable if the heat tariffs and taxes of existing DH systems are high. Two qualitative criteria have been introduced to describe the available support measures and the possibility of introducing innovative business models in each country. These criteria were evaluated using a three-point scale. The three points for available support measures apply if subsidies or other support policies for DH and individual heating solutions have been implemented in recent years with the possibility of introducing innovative

Table 1
5GDHC barriers and drivers.

BARRIERS	DRIVERS
Dependence on the electricity system	Climate change targets (low GHG emissions): e.g. stop using natural gas
High initial costs	Geopolitical implications of using imported natural gas
Specific new infrastructure is required	Ambitious energy transition targets of the country
Increase in the price of electricity	Reduced price volatility
Financial sources (lack of adequate funding and financing products)	Positive effect on health
Awareness (lack of skilled personnel)	Strengthening energy security
Institutional and administrative barriers	Creating local economic value and jobs
Market barriers	Increased access to affordable, reliable, and sustainable energy for heating and cooling
Lack of public acceptance	Ability to reuse waste heat
Regulatory and policy barriers	
Separate pipes are needed to provide both heating and cooling	
Centralised energy production, limiting network expansion area	
Dwelling spatial impact and dwelling noise	
High resident risk	

Table 2
Overview of criteria used.

Criteria	Unit	Source
1 Average final price of electricity	EUR/MWh	Eurostat (Eurostat, 2020b)
2 Share of RES energy	%	Eurostat (Eurostat, 2020b)
3 Share of heat supplied via HPs	Unit per 1000 households	
4 CO_2 emission factor for electricity	t CO_2/MWh	
5 Future CO_2 emission factor for electricity	t CO_2/MWh	
6 Maximum heat tariff	EUR/MWh	
7 Minimum heat tariff	EUR/MWh	
8 DH tax rates	%	
9 Available support measures for possible 5GDHC implementation	Evaluation scale	
10 Possibility to implement innovative business models	Evaluation scale	
11 Specific building heat consumption	kWh/m^2	Odysee–Muree (Anon, 2020b)
12 Share of new buildings	%	Odysee–Muree (Anon, 2020b)
13 Excess heat source potential from shopping malls	MWh	
14 Excess heat source potential from transformers	MWh	
15 Excess heat source potential from data centres	MWh	

technological solutions. If the legal framework allows for the establishment of different tariffs and discounts for thermal energy for consumers, as well as the affordable entry of various heat producers into the heat supply market, the greatest number of points is granted for innovative business models.

The heat supply of energy-efficient buildings with low heating demand is addressed by 5GDHC solutions. Therefore, two criteria were introduced that describe the existing consumer situation: the average specific heat consumption for space heating and the share of new buildings. Both criteria were taken from the Odyssee-Mure database describing the situation in the residential sector. The average heat consumption for space heating is expressed in kWh per m^2 of heating area and is normalised based on climatic conditions. The share of new buildings represents the total area of new buildings built over the past 10 years.

In addition, three criteria were created to assess the accessible potential of low temperature heat sources in each country, characterising the available heat from agents (shopping malls, transformers, and data centres). As mentioned above, it is crucial to identify 5GDHC agents. The identification of agents will allow the potential of their use in 5GDHC to be assessed. This potential is one of the most important criteria for evaluating the concept's implementation. The preliminary potential of the following agents has been determined: shopping malls, electrical transformers, and data centres. According to Buffa et al. (2019), supermarkets and warehouses can play a significant role in the development of new 5GDHC projects. Retail stores as potential sources of low-grade heat were evaluated in Persson et al. (2020). It was decided to collect locally available information on retail stores in the Baltic states, including the total area and the exact location of each store.

The list of retail stores and shopping malls in Estonia was compiled using the websites of major retail chain stores and additional information obtained from companies. When most retail stores were added, the year of construction of each store and its total area were taken from the Estonian Register of Buildings (Ministry of Economic Affairs and Communications (Estonia), 2021). For Latvia, data on the total area were collected from large retail chain stores and supplemented with additional information from the data distribution portal of the State Land Service of the Republic of Latvia (Anon, 2021). For Lithuania, most of the information was obtained from large retail chain stores. The list of collected retail store data was added as a GIS map layer. The next step was to sort out the stores that are located within the DH regions and can be connected to the DH system. It was possible to merge the GIS map layer with retail stores and the layer with DH regions. The calculation results from the ReUseHeat report (Persson et al., 2020) were used to determine the estimated relative

Table 3
Excess heat potential of 5GDHC agents.

	Estonia		Latvia		Lithuania	
	Total (MWh)	Within DH (MWh)	Total (MWh)	Within DH (MWh)	Total (MWh)	Within DH (MWh)
Retail stores	1,050,693	991,307	887,354	795,414	1,285,050	1,157,938
Electrical transformers	212,160	86,000	285,040	202,480	410,960	114,560
Data centres	107,081		53,271		30,903	

excess heat from retail stores in each country. Based on these results, the following average estimated excess heat amounts was determined: 0.555 MWh/m^2 for Estonia, 0.547 MWh/m^2 for Latvia and 0.469 MWh/m^2 for Lithuania. The results of possible excess heat amounts from retail stores in the DH region and beyond for the Baltic countries are presented in Table 3.

Electrical transformers can be considered as potential 5GDHC agents (Buffa et al., 2020). In Milan (Viale Gadio), there is a demo project consisting of a newly built low-temperature DH network that uses excess heat from an electrical transformer as a waste heat source. Excess heat from electrical transformers is available at 30 °C continuously throughout the year (Nathalie Fransson et al., 2021). To assess the excess heat potential of electrical transformers, a database of electrical substations has been created. Transformer location and voltage data were obtained from (Elektrilevi, 2021) for Estonia, (Sadales Tīkli, 2022) for Latvia, and (Regia:Regional Geoinformational Environmental service, 2021) for Lithuania. Locations of 330 kV and 110 kV substations were also obtained. Unfortunately, there was very limited information on transformers, so the substations were aggregated into two types: 110 kV and 330 kV. Based on previous studies on the potential of electrical transformers in Denmark (Petrović et al., 2019), it has been estimated that a 330 kV transformer can produce 18,400 MWh/y of excess heat and a 110 kV transformer can produce 560 MWh/y. Substations located in the DH regions were classified. Data centres are considered low-grade heat sources in the case of 4GDH and can be assessed as agents for 5GDHC systems. Public data on data centres were collected for each country. It was assumed that 65% of the total electricity consumption of the data centres can be considered as excess heat, as was done in Persson et al. (2020). All identified data centres are located in the DH regions.

The obtained criteria values were further normalised and weighted. The decision-making matrix and normalisation of the obtained criteria values were done using the TOPSIS method described by Loken (2007). Multi-criteria analysis' TOPSIS is often used to evaluate environmental strategies for sustainable development (Laktuka et al., 2021). The main purpose of TOPSIS is to allow for comparison and choice between several alternatives or, in this case, a comparison of barriers and drivers for the implementation of 5GDHC systems.

The ability to prioritise the analysed criteria is one of the most important aspects of using multi-criteria analysis. In this study, the AHP method was used to rank the identified criteria. In order to evaluate the problem using the AHP method, it is necessary to determine the priority criteria using pairwise comparison. The selected pairs of criteria were compared in terms of their importance on a scale from 1 (equally important) to 9 (absolutely more important). After comparing the criteria, it is necessary to check the obtained results by performing a consistency check. This check examines the evaluation of the criteria for inconsistencies. If there are inconsistencies, it is necessary to check whether the problem and the criteria are clearly defined, and to revise and re-evaluate the pairs of criteria. The criteria ranking results are shown in Fig. 3.

The authors believe that the ability to introduce an innovative business model and the availability of support for the implementation of the technology in accordance with criteria that describe the current situation in each country's energy sector are critical factors for the implementation of 5GHDC. The criterion is re-evaluated with equal weights to all options to identify the impact of the weights of the criteria set by the AHP on the evaluation of the criterion.

The final comparison between the Baltic countries was performed by multiplying the weight of the criterion by the corresponding normalised criterion value. An ideal positive decision and an ideal negative decision are calculated when constructing a normalised weighted decision matrix. The distance to the ideal solution and the distance to the non-ideal solution are calculated first (TOPSIS, 2013). The next step after determining the distance to the ideal and non-ideal solutions is to determine the ideal positive and ideal negative solutions. The relative proximity of the alternative to the ideal solution is calculated by determining which country has the most potential to introduce 5GDHC systems.

4. Results

The section presents the results of the quantitative assessment of several identified barriers and drivers for the implementation of the 5GDHC system in the Baltic countries. A summary of the obtained criteria values is provided in Table 4. The lowest final electricity price is in Estonia (0.12 EUR/kWh), but the prices in Lithuania and Latvia are almost the same. The highest share of renewable electricity is in Latvia due to the high share of hydropower. Lithuania relies heavily on imported energy. Therefore, its share of RES is low at 18.79%. However, the share of RES in Estonia is not much higher, at 22%.

The share of RES is directly related to the CO_2 emission factors for electricity from the grid. Due to the high penetration of imported energy, the CO_2 emission factor and local renewable energy generation for Lithuania is 0.02 t_{CO2}/MWh, which is relatively low compared to the values for Latvia (0.12 t_{CO2}/MWh) and Estonia (0.89 t_{CO2}/MWh). The authors also included projected CO_2 emission factors based on Elering (2014), European Commission (2016) as the implementation of 5GDHC systems is likely to be delayed and may start within the next decade. It is predicted that CO_2 emissions may decrease in Latvia and significantly so in Estonia. However, CO_2 emissions for electricity generation in Lithuania may increase.

The criteria analyses show that Estonia has a higher cumulative knowledge of HP usage, which is a closely related technology to 5GDHC. According to the report of the European Heat Pump Association, there are 29.3 HP units/1000 households in Estonia and 9 units/1000 households in Lithuania (European Heat Pump Association, 2018). Because the number of HP units utilised in Latvia is quite low, at just 1% (Ministry of Econonics of the Republic of Latvia, 2018), an estimate of one unit per 1000 households was chosen.

According to criteria used to evaluate existing DH systems, Estonia had the highest maximum heat tariff in 2019, whereas

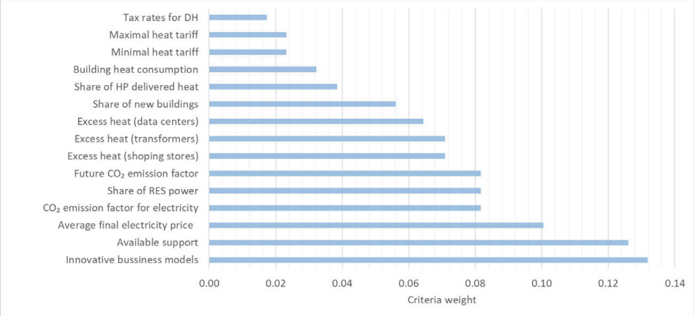


Fig. 3. Overview of the defined weight of each criterion.

Table 4
Summary of criteria results for the Baltic states.

Description	Latvia	Lithuania	Estonia
Average final electricity price, EUR/kWh	0.14	0.14	0.12
Share of RES energy, %	53.42	18.79	22.00
Number of individual HPs, unit/1000 households	1.00	9.00	29.30
CO_2 emission factor for electricity, t_{CO2}/MWh	0.12	0.02	0.89
Future CO_2 emission factor for electricity, t_{CO2}/MWh	0.08	0.06	0.22
Maximum heat tariff, EUR/MWh	69.98	79.63	86.96
Minimum heat tariff, EUR/MWh	35.45	32.57	35.33
DH tax rates, %	21	9	20
Available support measures for possible 5GDHC implementation	2.00	2.00	1.00
Possibility to implement innovative business models	1.00	2.00	1.00
Specific building heat consumption, kWh/m^2	159.7	131.3	142.8
Share of new buildings, %	5	6	2
Excess heat source potential from shopping malls, %	10%	13%	16%
Excess heat source potential from transformers, %	3%	1%	1%
Excess heat source potential from data centres, %	1%	0%	2%

Latvia had the highest minimum heat tariff. Latvia and Estonia have the same tax rates, whereas Lithuania has a lower rate. As previously stated, if the heat tariffs of existing DH systems are high, the 5GDHC system is presumed to be better.

Based on previously implemented support programmes for local and district heating systems, the qualitative assessment criteria indicate probable support for 5GDHC systems in Lithuania and Latvia. Furthermore, due to the open heating market conditions in Lithuania, innovative business models that are crucial for 5GDHC systems are more likely to be implemented. However, existing market regulations do not allow introducing different heating tariffs in Latvia and Estonia. Therefore, the criteria score is lower.

In terms of building stock, Lithuania has the best conditions due to lower specific heat consumption (131.3 kWh/m^2) and a higher proportion of new building area (6%). Latvia has the most inefficient buildings (159.7 kWh/m^2), but Estonia has the lowest proportion of new buildings (2%).

Finally, the determined low-temperature heat source agents described in the previous section have been identified and allocated to the national total heat supply. The results show that Estonia has the largest share of excess heat obtained from shopping malls (16% of total heat consumption), but Latvia has the highest share of excess heat obtained from electrical transformers (3%). The identified share of excess heat from data centres is relatively low in all three countries, peaking at 2% in Estonia.

In accordance with the methodology described above, the values of the identified criteria from Table 4 were normalised and weighted to determine the proximity to the ideal solution for each country. The results in Fig. 4 show different values for similar and prioritised criteria values. When the identified criteria are prioritised by assigning higher weight values for the possibility of introducing an innovative business model and available support for technology implementation, followed by criteria describing the existing situation in each country's energy sector, Lithuania has the highest score due to support availability and open heating market conditions. However, when equal criteria weights are assigned, the highest evaluation rank belongs to Estonia due to the wider use of HPs and higher excess heat potential.

5. Conclusion

This study conducted a comprehensive review of potential agents that could be used as active heat sources or sinks in 5GDHC in the Baltic states. The barriers and drivers for the implementation of 5GDHC were also systematically investigated in terms of economics, markets, technology, policies, etc. Country-specific conditions such as heating tariffs, regulatory mechanisms, stakeholders, existing DH infrastructure, DH market and others were evaluated for the three Baltic states (Latvia, Estonia, and Lithuania). The main barrier to the development of 5GDHC in the Baltic countries is the well-maintained and widespread 3rd generation DH in all three countries. More than half of the population in each country is already connected to DH systems not only in major cities but also in smaller towns. Another major hurdle is the high initial costs of the new 5GDHC pipeline system for ultra-low heating and cooling temperatures and renewable energy sources. The main drivers for the development of 5GDHC in the Baltic countries are the countries' ambitious energy and climate change goals. Furthermore, the possibility of recycling low-temperature waste heat not only from industry but also from other local sources, as well as the development of local economic value and jobs are among the drivers.

The multi-criteria analysis method was used to quantify the main identified barriers and drivers behind the implementation of

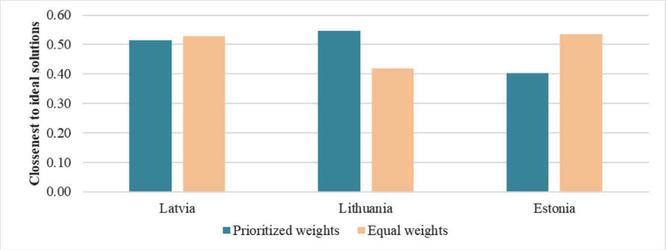


Fig. 4. Results of multi-criteria assessment with prioritised criteria weights and equal criteria weights.

5GDHC systems. The authors examined the three Baltic countries from a variety of angles, including possible competition with existing DH systems, power market sustainability, excess heat potential from different sources, and potential support policies. Although Latvia, Lithuania, and Estonia have similar conditions, there are some differences. For example, different fuel mixes are used for power generation; stricter heating market regulations exist in Latvia and Estonia; and Estonia has more experience with HPs use, while there are almost no installed HPs in Latvia. The highest score in the multi-criteria assessment was achieved by Lithuania due to support availability and open heating market conditions. When all applied criteria are weighted equally, Estonia has the most favourable conditions for 5GDHC systems due to widespread use of HPs and greater excess heat potential.

This study can help to understand how different agents can be integrated into 5GDHC and what waste heating or cooling potential they can contribute to the 5GDHC network. The findings of this study provide a solid foundation for the future 5GDHC modelling and feasibility studies. The identified barriers and drivers also indicate directions for future efforts to implement the 5GHDC network.

It should be emphasised that 5GDHC is a niche solution and, according to experts, will not replace 4GDH in the future, but in certain cases it may become the most effective technical solution for heat supply. Theoretical excess heat potential from 5GDHC agents was calculated, and the results indicated that the proportion of excess heat obtained would only make up a small portion of the district heating supply (15% for Latvia, 14% for Lithuania, and 19% for Estonia). Even though the actual potential for excess heat from 5GDHC agents is even lower, this technical solution may be implemented in certain areas in the future. The technical and economic aspects of 5GDHC implementation prospects need to be investigated further based on country-specific case studies.

The present geopolitical situation has significant impact on the imported energy prices, and this will further affect the electricity and natural gas prices in different countries. The countries with large electricity import (e.g., Lithuania) could be more sensitive to the geopolitical issues for the 5GDHC development. But in the long term, with more integration of renewable energy into the energy mix (corresponding to the climate targets in each country), the impact of geopolitical situation is expected to be decreased. The findings from this study are still valid in a long-term perspective.

CRediT authorship contribution statement

Anna Volkova: Conceptualization, Methodology. **Ieva Pakere:** Methodology, Software, Writing – original draft. **Lina Murauskaite:** Investigation, Writing – review & editing. **Pei Huang:** Methodology, Validation. **Kertu Lepiksaar:** Data curation, Visualization. **Xinxing Zhang:** Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Anna Volkova reports financial support was provided by Nordic Energy Research. Ieva Pakere reports financial support was provided by Nordic Energy Research. Lina Murauskaite reports financial support was provided by Nordic Energy Research. Pei Huang reports financial support was provided by Nordic Energy Research. Kertu Lepiksaar reports financial support was provided by Nordic Energy Research. Xingxing Zhang reports financial support was provided by Nordic Energy Research.

Data availability

Data will be made available on request.

Acknowledgements

The results presented in this paper were made possible thanks to the funding from the Nordic Energy Research, Norway as part of the joint Baltic-Nordic Energy Research Program Project no.: 106840 – Agent-GIS-5GDHC 'Techno-economic performance and feasibility study of the 5GDHC technology using agent-based modelling and GIS' project.

References

Abugabbara, M., Javed, S., Bagge, H., Johansson, D., 2020. Bibliographic analysis of the recent advancements in modeling and co-simulating the fifth-generation district heating and cooling systems. Energy Build 224. http://dx.doi.org/10.1016/j.enbuild.2020.110260.

Anon, 2020a. Estonian competition authority. https://www.konkurentsiamet.ee/.

Anon, 2020b. Odyssee-mure database.

Anon, 2021. Data distribution portal of state land service of the Republic of Latvia.

Augutis, J., Krikštolaitis, R., Martišauskas, L., Urboniene, S., Urbonas, R., Ušpuriene, A.B., 2020. Analysis of energy security level in the baltic states based on indicator approach. Energy 199. http://dx.doi.org/10.1016/j.energy.2020.117427.

Balioti, V., Tzimopoulos, C., Evangelides, C., 2018. Multi-criteria decision making using TOPSIS method under fuzzy environment. Appl. Spillway Sel. Proc. 2, 637. http://dx.doi.org/10.3390/proceedings2110637.

Blumberga, D., Veidenbergs, I., Lauka, D., Kirsanovs, V., Pakere, I., Gravelsins, A., et al., 2020. Development of heat supply and cooling systems in Latvia (in Latvian). Available online: n.d.

Boesten, S., Ivens, W., Dekker, S.C., Eijdems, H., 2019. 5Th generation district heating and cooling systems as a solution for renewable urban thermal energy supply. Adv. Geosci. 49, 129–136. http://dx.doi.org/10.5194/adgeo-49-129-2019.

Buffa, S., Cozzini, M., D'Antoni, M., Baratieri, M., Fedrizzi, R., 2019. 5Th generation district heating and cooling systems: A review of existing cases in Europe. Renew. Sustain. Energy Rev. 104. http://dx.doi.org/10.1016/j.rser.2018.12.059.

Buffa, S., Soppelsa, A., Pipiciello, M., Henze, G., Fedrizzi, R., 2020. Fifth-generation district heating and cooling substations: Demand response with artificial neural network-based model predictive control. Energies 13, 4339. http://dx.doi.org/10.3390/en13174339.

Danfoss, 2021. District Energy Academy Economic comparison of 4th and 5th generation district heating systems.

Eesti Vabariigi Valitsus, 2017. Kaugkütteseadus.

Egüez, A., 2021. District heating network ownership and prices: The case of an unregulated natural monopoly. Util. Policy 72. http://dx.doi.org/10.1016/j.jup.2021.101252.

Elektrilevi, 2021. Spare capacities. https://www.elektrilevi.ee/en/vabad-voimsused.

Elering, 2014. Estonian long-term power scenarios.

European Commission, 2016. EU reference scenario 2016 energy. In: Transport and GHG Emissions Trends to 2050.

European Heat Pump Association, 2018. European heat pump market and statistics report.

Eurostat, 2020a. Share of energy from renewable sources.

Eurostat, 2020b. Production of electricity and derived heat by type of fuel, Code:nrg_bal_peh.

Fischer, David, 2014. Potential for balancing wind and solar power using heat pump heating and cooling systems.

Government of the Republic of Estonia, 2017. National development plan of the energy sector until 2030. pp. 1–124.

Grzegórska, A., Rybarczyk, P., Lukoševičius, V., Sobczak, J., Rogala, A., 2021. Smart asset management for district heating systems in the Baltic Sea Region. Energies 14, 314. http://dx.doi.org/10.3390/en14020314.

Gudmundsson, O., Dyrelund, A., Thorsen, J.E., 2021. Comparison of 4th and 5th generation district heating systems. E3S Web Conf. 246, 09004. http://dx.doi.org/10.1051/e3sconf/202124609004.

International Energy Agency, 2014. Linking heat and electricity systems.

Kuusk, K., Kurnitski, J., 2019. State-subsidised refurbishment of socialist apartment buildings in Estonia. pp. 339–355. http://dx.doi.org/10.1007/978-3-030-23392-1_16.

Laktuka, K., Pakere, I., Lauka, D., Blumberga, D., Volkova, A., 2021. Long-term policy recommendations for improving the efficiency of heating and cooling. Environ. Clim. Technol. 25, 382–391. http://dx.doi.org/10.2478/rtuect-2021-0029.

Latvian Public Utilities Commission, 2020. Tariffs for heat supply services in Latvia.

Loken, E., 2007. Use of multicriteria decision analysis methods for energy planning problems. Renew. Sustain. Energy Rev. 11, 1584–1595. http://dx.doi.org/10.1016/j.rser.2005.11.005.

Lund, H., Østergaard, P.A., Nielsen, T.B., Werner, S., Thorsen, J.E., Gudmundsson, O., et al., 2021. Perspectives on fourth and fifth generation district heating. Energy 227. http://dx.doi.org/10.1016/j.energy.2021.120520.

Millar, M.-A., Yu, Z., Burnside, N., Jones, G., Elrick, B., 2021. Identification of key performance indicators and complimentary load profiles for 5th generation district energy networks. Appl. Energy 291, 116672. http://dx.doi.org/10.1016/j.apenergy.2021.116672.

Ministry of Economic Affairs and Communications (Estonia), 2014. Long-term strategy for building renovation. p. 69.

Ministry of Economic Affairs and Communications (Estonia), 2021. Estonian register of buildings.

Ministry of Economics of the Republic of Latvia, 2020. Long-term strategy on the renovation of buildings, available online: http://tap.mk.gov.lv/mk/tap/?pid40487380No (in Latvian).

Ministry of Econonics of the Republic of Latvia, 2018. National energy and climate plan of Latvia 2021–2030.

Nathalie Fransson, Tobias Popovic, Giorgio Bonvicini, Roberto Fedrizzi, 2021. D3.2 - Customers' perspective on REWARDHeat solutions n.d.

Pakare, I., Gravelsins, A., Lauka, D., Blumberga, D., 2021. Estimating energy efficiency increase in national district heating network. Energy Rep. 7, 401–409. http://dx.doi.org/10.1016/j.egyr.2021.08.088.

Pakere, I., Romagnoli, F., Blumberga, D., 2018. Introduction of small-scale 4th generation district heating system. Methodology approach. Energy Procedia 149, 549–554. http://dx.doi.org/10.1016/j.egypro.2018.08.219.

Persson, U., Averfalk, H., Nielsen, S., Moreno, D., 2020. Accessible urban waste heat. p. 168.

Petrović, S., Bühler, F., Radoman, U., 2019. Power transformers as excess heat source. In: Proc. ECOS 2019 32nd Int. Conf. Effic. Cost, Optim. Simul. Environ. Impact Energy Syst.

Pieper, H., Kirs, T., Krupenski, I., Ledvanov, A., Lepiksaar, K., Volkova, A., 2021. Efficient use of heat from CHP distributed by district heating system in district cooling networks. Energy Rep. 7, 47–54. http://dx.doi.org/10.1016/j.egyr.2021.09.041.

Regia:Regional Geoinformational Environmental service, 2021. Maps of Electric power networks.

Revesz, A., Jones, P., Dunham, C., Davies, G., Marques, C., Matabuena, R., et al., 2020. Developing novel 5th generation district energy networks. Energy 201, 117389. http://dx.doi.org/10.1016/j.energy.2020.117389.

Rezaie, B., Rosen, M.A., 2012. District heating and cooling: Review of technology and potential enhancements. Appl. Energy 93, 2–10. http://dx.doi.org/10.1016/j.apenergy.2011.04.020.

Rušeljuk, P., Volkova, A., Lukić, N., Lepiksaar, K., Nikolić, N., Nešović, A., et al., 2020. Factors affecting the improvement of district heating. Case studies of estonia and Serbia. Environ. Clim. Technol. 24. http://dx.doi.org/10.2478/rtuect-2020-0121.

Sadales Tīkli, A.S., 2022. Data from distribution operator. Not publicly available.

Statistics Estonia, 2020. KE023: Energy balance sheet by type of fuel or energy(1999–2018).

The Cabinet of Ministers of the Republic of Latvia, 2008. Regulations regarding the supply and use of thermal energy.

TOPSIS, 2013. Multi-Criteria Decis. Anal. John Wiley & Sons Ltd, Chichester, UK, pp. 213–221. http://dx.doi.org/10.1002/9781118644898.ch8.

Tsagarakis, K.P., Efthymiou, L., Michopoulos, A., Mavragani, A., Anđelković, AS, Antolini, F., et al., 2020. A review of the legal framework in shallow geothermal energy in selected European countries: Need for guidelines. Renew. Energy 147, 2556–2571. http://dx.doi.org/10.1016/j.renene.2018.10.007.

Volkova, A., Hlebnikov, A., Ledvanov, A., Kirs, T., Raudsepp, U., Latõšov, E., 2022. District cooling network planning. a case study of Tallinn. Int. J. Sustain. Energy Plan. Manag. 34, 63–78. http://dx.doi.org/10.54337/ijsepm.7011.

Volkova, A., Latõšov, E., Lepiksaar, K., Siirde, A., 2020. Planning of district heating regions in Estonia. Int. J. Sustain. Energy Plan. Manag. 27, 5–16. http://dx.doi.org/10.5278/ijsepm.3490.

Volkova, A., Mašatin, V., Siirde, A., 2018. Methodology for evaluating the transition process dynamics towards 4th generation district heating networks. Energy 150, 253–261. http://dx.doi.org/10.1016/j.energy.2018.02.123.

Wirtz, M., Neumaier, L., Remmen, P., Müller, D., 2021. Temperature control in 5th generation district heating and cooling networks: An MILP-based operation optimization. Appl. Energy 288, 116608. http://dx.doi.org/10.1016/j.apenergy.2021.116608.

Appendix 7

Publication VII

Lepiksaar, K., Kalme, K., Siirde, A., & Volkova, A. (2021). Heat Pump Use in Rural District Heating Networks in Estonia. *Environmental and Climate Technologies*, 25(1), 786–802. https://doi.org/10.2478/rtuect-2021-0059

Environmental and Climate Technologies
2021, vol. 25, no. 1, pp. 786–802
https://doi.org/10.2478/rtuect-2021-0059
https://content.sciendo.com

Heat Pump Use in Rural District Heating Networks in Estonia

Kertu LEPIKSAAR[1*], Kiur KALME[2], Andres SIIRDE[3], Anna VOLKOVA[4]

[1,3,4]*Tallinn University of Technology, Ehitajate tee 5, 19086 Tallinn, Estonia*
[2]*Elering AS, Kadaka tee 42, 12915 Tallinn, Estonia*

Abstract **– District heating has proven to be an efficient way of providing space heating and domestic hot water in populated areas. It has also proven to be an excellent way to integrate various renewable energy sources (RES) into the energy system. In Estonia, biomass covers most of the heat demand, but carbon-intensive fuels are still used to cover peaks and lows. Heat pumps can be a good solution for rural areas, as there is usually plenty of land available for heat pump facilities. In addition, heat pumps require low-grade heat sources such as ambient air, groundwater, lakes, rivers, sea, sewage water, and industrial waste heat. One of the downsides of heat pumps is the need for large investments compared to boilers fired by natural gas and biomass, and electric boilers. This study examines the impact of heat pump use on consumer prices for district heating in rural district heating networks in Estonia.**

Keywords **– Consumer prices; district heating; heat pumps; low-temperature heat sources; rural areas**

Nomenclature

AHD	annual heat demand	MWh
AP	allowable profit	EUR
CC	capital costs	EUR
CHP	combined heat and power plant	–
COP	coefficient of performance	–
DH	district heating	–
hl	heat loss	%
HP	heat pump	–
OM	operation and maintenance costs	EUR
Pr_{max}	maximum heat price	EUR/MWh
RES	renewable energy sources	–
WACC	weighted average cost of capital	EUR
VC	variable costs	EUR

---

[*] Corresponding author.
E-mail address: kertu.lepiksaar@taltech.ee

1. INTRODUCTION

There has been a growing interest in the utilisation of electrical solutions in the heating sector in recent years. The wide range of low-grade heat sources available along with advanced and highly efficient heat pump (HP) technology has generated widespread interest in the use of large-scale heat pumps in district heating systems. District heating (DH) has proven to be an efficient way of providing space heating and domestic hot water in populated areas [1]. It has also proven to be an excellent way to integrate various renewable energy sources (RES) into the energy system [2]–[4]. However, viability and feasibility are often critical issues for rural district heating networks because consumption density tends to be low and consumption often dwindles due to declining rural populations [5], improved energy efficiency in buildings [5], and warming climate conditions [6]–[8].

Recent research on power-to-heat technologies [9] has focused on the effects of wind energy penetration into electricity markets on the optimal power-to-heat capacity in local district heating systems. The effects of power-to-heat technologies on Germany's energy system were explored in [10], and it was discovered that the interaction between the heating and electricity sectors will make both sectors flexible when dealing with short-term fluctuations in wind and solar energy production. When biomass is limited, utilising power-to-heat solutions in systems with an ever-increasing share of renewable energy will also help to incorporate even more RES into the heating sector, according to [10]. A comparison between different methods for the best design of distributed power systems was made in [11], where heat pumps were considered as a power-to-heat solution. A risk assessment for integrated heat and electricity systems was conducted in [12], which determined that the use of power-to-heat solutions (electric boilers and heat pumps) leads to reduced risks when a greater proportion of renewable energy sources is incorporated into the system [13].

As per the European Commission's EU Energy System Integration Strategy, sector coupling will massively boost electricity consumption, increasing generation of renewable energy, and propagating RES technologies [14]. According to [15], heat pumps (as power-to-heat solutions) play a significant part in the coupling of RES and the heating sector, and the amount of heat obtained from RES is highly dependent on the type of strategy; the largest number of RES can be incorporated into a system using a wind energy generation-based strategy. It is mentioned in [16], that when the heating and electricity sectors are interconnected, residential heating load has considerable potential to maximise the utilisation of wind power while minimising carbon emissions.

DH is very important for Estonia [17]. In [18], Estonian DH regions are discussed, and five different scenarios for all types of Estonian DH regions are investigated. In [18], it is concluded that it is necessary to consider all possible changes in the DH network when planning a DH region. Therefore, we propose an algorithm based on 146 Estonian DH networks of different sizes, lengths, capacities and primary energy structures to help predict possible changes in DH networks.

This study was designed to assess the impact of heat pump use in rural DH networks in Estonia on DH consumer prices. Heat pumps can be a good solution for rural areas, as there is usually plenty of land available for heat pump facilities. In addition, heat pumps require low-grade heat sources such as ambient air, groundwater, lakes, rivers, sea, sewage water, and industrial waste heat [19], [20]. One of the downsides of heat pumps is the need for large investments compared to boilers fired by natural gas and biomass, and electric boilers [21].

First and foremost, various aspects must be taken into account when considering the possibilities of using heat pumps in DH networks. In order to maintain balance in the electricity grid, it is important to assess how the addition of a large number of electricity consumers, such as heat pumps, would affect the balance and the electricity market. Electricity market options for heat pumps in rural DH networks are described in [22] for the integration of heat pumps into rural DH networks in Austria. Since heat pumps can play an important role in balancing the electricity market, [22] shows how heat pumps can be used as regulators in the electricity market.

Oil shale is the primary energy source in Estonia, as well as an essential source of fuel and the major component in the energy mix. On the one hand, using oil shale as the main source of fuel guarantees a significant degree of energy security. However, it is an extremely carbon-intensive fuel. Consequently, the production of energy from oil shale results in a significant amount of greenhouse gases that affect the climate. Because of this, the Estonian economy has twice the amount of carbon dioxide (CO_2) than is usual in the EU. This is rapidly changing as the Estonian government continues to dismantle old energy plants and the number of innovations aimed at reducing CO_2 emissions and their negative impact is increasing. The amount of power generated in Estonia is more than its consumption, so the state trades electricity.

The total power generated in Estonia in 2019 was 7.615 TWh, while the demand for it was 8.257 TWh. In 2020, the amounts were 4.398 TWh and 7.954 TWh, respectively. More than half of the electricity was generated using oil shale (56 %), as well as biomass (17 %), wind (9 %), and sustainable waste (1 %) power plants. Latvia (76 %) and Finland (24 %) received 2.704 TWh of the electricity generated [23].

All three Baltic states are attempting to separate from the Russian power grid and join the Western European grid, which is due to be completed by 2025. Another important goal – climate neutrality – must be achieved by 2050. To achieve this goal, the Baltic countries must increase their renewable energy source (RES) capacities [23].

The largest RES in Estonia is the 48 MW wind power plant in Aulepa, the largest of its kind in the Baltics. Wind power plants (303 MW in total) are located inland in the north-east, north-west and west of Estonia. There are currently no offshore wind parks in Estonia. The largest combined heat and power plants (CHP) are Tartu CHP and Tallinn CHP with a capacity of 25 MW each. Biofuel plants are CHPs and therefore have to be spread throughout Estonia, close to urban settlements that use heat. It is known that 102 MW of biomass-powered, 17 MW of waste-powered, and 11 MW of biogas-powered plants are connected to the network [24].

There are three small DH systems in Estonia that use HPs as innovative heat generation technologies. They are located in Palamuse, Kaarepere, and Kiikla. Palamuse has two small, isolated DH systems where the demand for heat is supplied by ground source HPs. The DH network consists of the Palamuse School and its auxiliary buildings. The other network supplies DH to private structures (7 buildings). These HPs were commissioned in 2013. The annual DH consumption of the Palamuse School is 830 MWh and the private building network's annual consumption is 750 MWh. The annual *COP* of the HPs averages 2.6 [25]. Similarly, HPs are used in the DH network in Kaarepere, near Palamuse. As in the previous case, Kaarepere also uses ground source HPs. The consumers of the network are 6 private buildings and a kindergarten. Their annual heat consumption is 730 MWh. The annual *COP* of the pumps is usually 2.3. HPs were introduced in 2013, same as in Palamuse [25]. The heat demand is covered by a 400 Kw HP in the DH network of Kiikla village. It uses water from a nearby mine as a heat source. The HP was introduced in 2012, and according to its manufacturer, its *COP* should be 4.1 (on average). The annual heat consumption of the Kiikla DH network is 530 MWh [26].

Three seawater HPs are used for heating and cooling of the Seaplane Harbour historic centre in Tallinn. The introduced heating capacity of the facility is 395 kW, the cooling capacity is 250 kW, and the power capacity is 180 kW [27].

The use of heat pumps in DH also has a positive effect on air quality since heat pumps do not require combustion to generate heat and therefore no fine particles or acid-oxides (NO_x and SO_x) are emitted. Biomass boilers are widely used because they are considered CO_2-neutral and because biomass is widely available in Estonia. However, the downside to using biomass is that it can be a source of air pollution. The impact of biomass boilers on the atmosphere has been studied in [27]–[29]. Emissions from biomass boilers depend on combustion methods. It is stated in [30], that NO_x and SO_x emissions are lower than the environmentally harmful amounts, and CO_2 emissions do not exceed the amount consumed by plant growth. This makes biomass an environmentally friendly fuel. On the other hand, it was found in [28] that fine particle emissions from biomass combustion can be harmful to health if flue gas cleaning equipment is not used.

When considering HPs as a source for space heating, it should be borne in mind that the use of heat pumps to generate heat instead of combustion boilers has an overall positive effect on the atmosphere only if the electricity used for HPs is also produced in accordance with the clean production principles and from renewable energy sources. Fine particle and acid oxide emissions in the event of combustion can be reduced by using air treatment equipment such as flue gas condensers, electric precipitators and various kinds of filters. Such equipment can be expensive and not all boiler houses have it installed. According to Directive 2015/2193 of the European Parliament and of the Council of 25 November 2015 on the limitation of emissions of certain pollutants into the air from medium combustion plants, the maximum amount of fine particles (dust, fly ash) for medium-sized biomass boilers is 20 mg/Nm^3 [31]. Emissions of fine particles are also regulated by Directive 2016/2284 of the European Parliament and of the Council of 14 December 2016 on the reduction of national emissions of certain air pollutants, which established an emission reduction strategy [32].

There are about 230 district heating networks in Estonia, and 95 % of them use woodchips as their primary fuel, while shale oil or natural gas is used to cover peak loads. In other DH networks, the main fuel is natural gas or shale oil. Most biomass boilers were installed after 2014 with the support of the European Cohesion Fund [33]. As the European Union's goal is to become climate neutral by 2050 [34], all fossil fuel-fired boilers must be replaced with RES, which means that it is necessary to find a sustainable solution to cover peak loads. Replacing old biomass boilers with HPs is a solution that should be discussed.

Price is the most important factor for consumers. The Estonian DH market is regulated by the District Heating Act and the Competition Act, and the Competition Authority approves the maximum prices charged in the network regions. At the beginning of 2020, the weighted average of the maximum DH prices was EUR 60/MWh; the lowest price was EUR 35/MWh (excluding VAT 20 %) and the highest price was EUR 86/MWh [35]. Typically, the actual selling price is very close to the maximum price indicated. In rural areas, where heat demand density is usually quite low, the costs of boiler house and network operations and maintenance are relatively high. This results in a high DH consumer price. When DH is produced using heat pumps, the price of heat is directly related to the price of electricity. This study provides a thorough analysis of how the use of HPs in rural DH networks will affect the consumer price of DH and, as a result, it will determine the areas where the use of HPs for DH can be cost-effective and have a positive impact on the DH consumer price. At the same time, suitable HP capacities are estimated for DH networks of different sizes, resulting in two types of solutions: those that use HPs for covering only peaks and troughs and fully HP-based solutions.

2. METHODOLOGY

Since this study is focused on rural areas, only DH networks with an annual consumption of less than 16 GWh are considered. There are about 140 DH networks in Estonia that meet this criterion. This limit was chosen because all DH regions with an annual heat consumption below it can be considered a rural area in Estonia. The average population in these areas is anywhere from 165 to 5000 residents, and the number of DH consumers ranges from 3 to 70. In this study, all these networks are divided into seven groups according to annual consumption. The criterion for division was to maintain minimum fluctuations in annual heat consumption within a group. It was significant to include all groups, but special focus was on small district heating networks, because heat pump integration is especially important in the case of small DH networks. That is why there are 3 groups for district heating networks below 5000 MWh. The main characteristics of these groups are presented in Table 1. Annual consumption figures are given for a 'normalised' year. The input data in Table 1 are taken from the heat management and development plans of the DH networks considered. In most cases, DH is also used for domestic hot water.

TABLE 1. MAIN CHARACTERISTICS OF DH GROUPS

Group no.	Average annual heat consumption, MWh/year	Average number of consumers in the DH network	Average DH price, EUR/MWh	Average DH supply temperature, °C	Number of such DH networks in Estonia
1	681	3	70.3	80	23
2	1914	6	67.4	80	58
3	3956	15	64.5	80	24
4	6235	25	61.7	85	8
5	7812	37	56.7	90	8
6	10 393	52	64.4	100	9
7	14 192	70	57.1	110	5

For all network groups, annual heat demand profiles have been generated using *EnergyPro* software, based on the annual heat demand, DH network temperatures and ambient temperatures. Base and peak loads that are important for estimating the required HP thermal capacity were determined using the generated heat demand profiles. Since the average ambient temperature for continental Estonia has been chosen (islands are excluded due to the milder climate), the shape of the heat demand profile is thus the same for all groups, and the groups with higher annual consumption lead to higher base and peak loads. Heat demand profiles for all groups are shown in Fig. 1.

Depending on the heat demand profile, different options were proposed for each group. This study presents two different options. The first option is to use a biomass boiler for base load and HP for summer loads and partly during the heating season. The criterion for selecting the base load boiler is to obtain the maximum amount of heat from the base load boiler. It is also assumed that the minimum load for the boiler is 50 % of its nominal capacity and the maximum load is 110 % of its nominal capacity. The second option is that all demand is covered by HPs.

When selecting HPs, it is important to know which heat sources are located nearby, as the temperature level of the heat source determines the coefficient of performance (*COP*) of the HP.

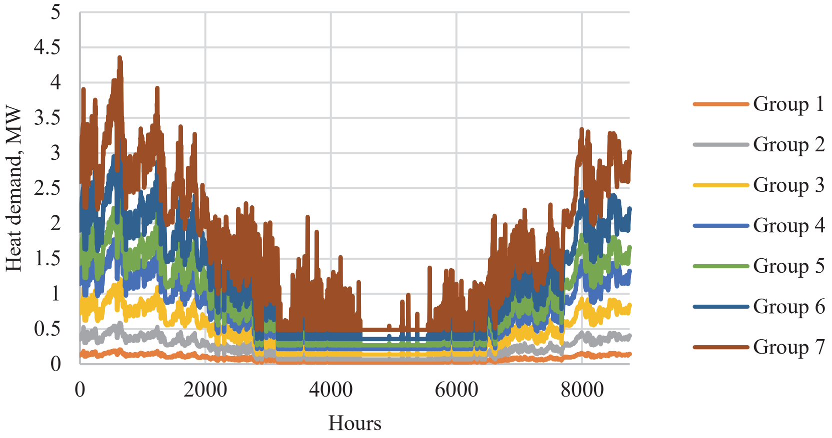


Fig. 1. Heat demand profiles for each group.

In this study, the *COP* for each possible heat source is estimated considering the temperature levels of possible local low-temperature heat sources and the temperature levels in rural DH networks. Possible heat sources discussed in this study are ground, seawater, lakes and rivers, and sewage water. This study obtained the necessary heat source temperatures for every hour using data from the Estonian National Weather Service [36]. For sewage water, the data given in [20] are used.

To estimate the *COP* of HPs, the Carnot equation for heat pump efficiency was used (Eq. (1)) with efficiency coefficient ε = 1:

$$COP = \varepsilon \frac{T_{\text{supply}}}{T_{\text{supply}} - T_{\text{source}}}, \quad (1)$$

where T_{supply} (K) is the DH supply temperature and T_{source} (K) is the heat source temperature.

The average *COP*s of all mentioned HP heat sources for each hour, considering heat source temperatures, are shown in Fig. 2. *COP* estimation also takes the DH supply temperature for each group into account.

To estimate the necessary electric capacity of HPs for each group for both options, the minimum *COP* value is used. This ensures the necessary electric capacity under all conditions. The higher the ambient temperature, the higher the *COP*.

The required electric capacities for option 1 (HP and biomass boiler) and option 2 (HP only) for each group and for different heat sources are shown in Table 2.

The proposed options and the existing solution are compared by the DH consumer price calculated using the Estonian Competition Authority's Method for DH maximum price [37]. In order to calculate the prices, the required investments, annual fuel costs, and operations and maintenance costs were estimated.

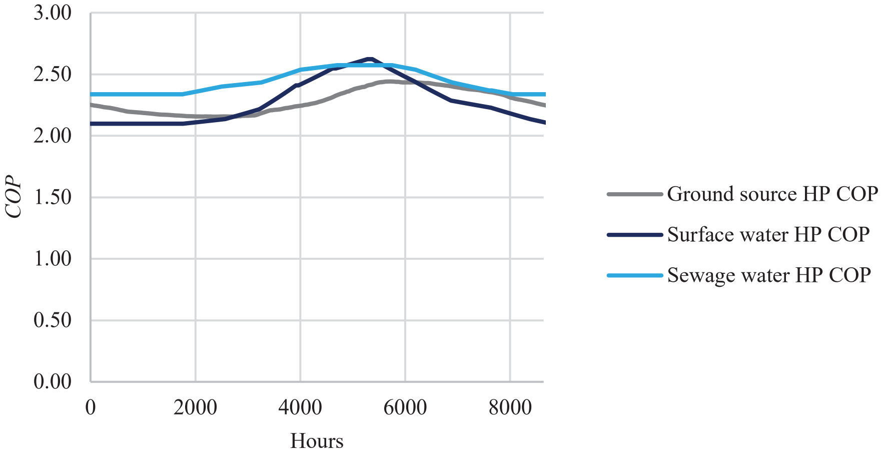


Fig. 2. Average *COP* for ground source, hydrothermal and sewage water HPs.

TABLE 2. HP ELECTRIC CAPACITIES FOR BOTH OPTIONS

Group no.	**Option 1 – HP electric capacity, MW_{el}**			**Option 2 – HP electric capacity, MW_{el}**		
	Ground source	**Surface water**	**Sewage water**	**Ground source**	**Surface water**	**Sewage water**
1	0.033	0.033	0.031	0.088	0.093	0.084
2	0.081	0.085	0.077	0.247	0.26	0.234
3	0.164	0.164	0.155	0.509	0.509	0.482
4	0.273	0.287	0.259	0.845	0.888	0.803
5	0.357	0.375	0.319	1.11	1.164	0.992
6	0.511	0.534	0.490	1.608	1.608	1.541
7	0.755	0.784	0.726	2.366	2.459	2.277

According to the Estonian Competition Authority's heat price calculation method, the maximum heat price depends on the allowable profit and sales capacity since the annual sales capacity of a heat producer is equal to the annual heat demand plus heat losses. The method of the Estonian Competition Authority has also set a limit for the allowable heat loss, which is 15 %. The maximum heat price Pr_{max} (EUR/MWh) according to the method of the Estonian Competition Authority can be calculated using Eq. (2):

$$Pr_{max} = \frac{AP}{AHD \cdot (1 + hl)}, \tag{2}$$

where AP (EUR) is the allowable profit, AHD (MWh) is the annual heat demand and hl (%) is the heat loss. Allowable profit consists of several other components: variable costs, operating costs, capital costs, and weighted average cost of capital ($WACC$). The $WACC$ is determined by the Estonian Competition Authority and for heat producers the $WACC$ is 5.76 %. To determine the possible heat price for both proposed solutions, it is necessary to estimate the variable costs, operating costs and capital costs, since the allowable profit is calculated as follows: (Eq. (3)).

$$AP = VC + OM + CC + WACC \tag{3}$$

Variable costs VC (EUR) consist of fuel costs (both biomass and electricity), environmental fees and water and sewerage services. For an annual estimate of variable costs, biomass and electricity prices are needed. The 2020 NordPool prices for Estonia are used for both electricity and biomass prices. The biomass price has been quite stable in recent years and in 2020 the price was EUR 16.42/MWh, which was also used in this study. Since biomass combustion emits fine particles, all biomass boiler houses must also pay environmental fees for fine particle emissions. The fine particle emission fee for particles smaller than 2.5 μm is EUR 1000/t [38]. In the case of this study, it is assumed that flue gas treatment equipment is not used, because flue gas condensers are usually installed in bigger boiler houses with a base load of 7 MW and more. This is mainly due to the fact that investments in this type of equipment are quite high and it is more economical for smaller boiler houses to pay environmental fees for particle emissions than to install flue gas condensers.

Water and sewerage services are also considered variable costs. Water and sewerage services are necessary for DH as water preparation and water use from local water utilities is necessary. The cost of water and sewerage services is not related to the heat source and depend only on the heat demand. Based on information from various regional heat management development plans in Estonia, the cost of the service is approximately EUR 17.8/MWh. This provides the same result for both options.

Operations costs OM (EUR) are the costs for boiler and HP services that must also be considered. Capital costs CC (EUR) are the investments divided by the expected technical useful life of the equipment. It is expected that service life for both biomass boilers [39] and HPs [40] is 20 years. The operations and maintenance (*OM*) costs for a biomass boiler are assumed to be EUR 9.5/MWh, according to the data given in several Estonian regional heat management development plans. To estimate the costs of HP operation and maintenance, the data from [41] were used (EUR 14/kWh). The value is the same for ground source, surface water and sewage HPs.

The main assumptions used in this study are listed below:

- The base load boiler was selected based on the maximum number of hours of use at full load;
- HP *COP* was estimated using the Carnot equation for HP efficiency;
- To estimate HP *COP*, the annual heat source temperature graphs and DH supply temperature were used;
- The minimum *COP* value was used for the required HP electric capacity;
- For DH consumer prices, the Estonian Competition Authorities Method was used;
- To estimate fuel costs, 2020 prices (electricity and woodchips) were used;
- Flue gas treatment equipment was not considered;
- Water and sewerage services are the same for both options.

3. RESULTS

Estimates of DH heat source capacity based on the heat demand profiles and previously described assumptions are shown in Fig. 3.

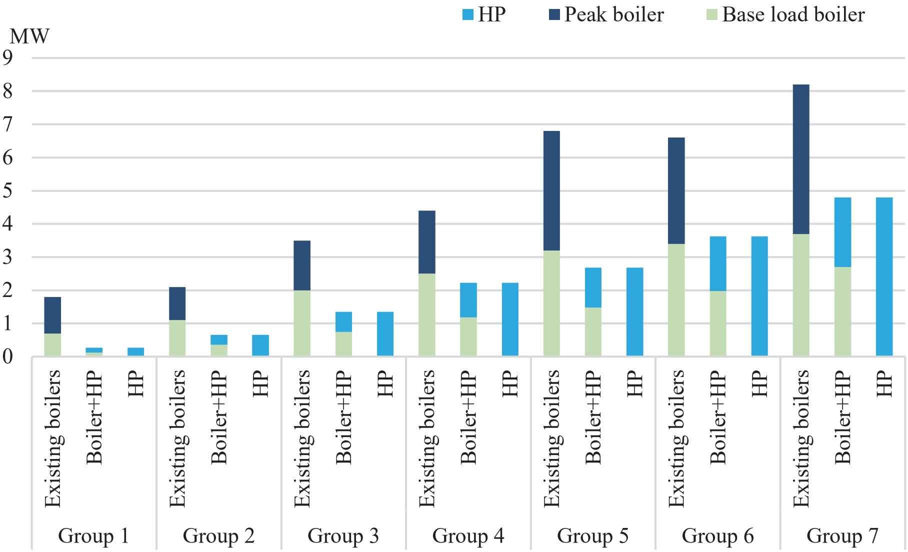


Fig. 3. Existing boiler capacities and capacity estimates for each group.

The results also showed that the maximum share of the total heat that can be delivered by base load boilers is 78 %, and peak boilers or HPs can cover the rest, i.e., 22 %. In addition, the existing base load boiler capacities are significantly higher than those proposed in this study. For smaller DH networks (groups 1, 2 and 3), this may be associated with high losses in the network caused by the low heat demand density.

Since HPs are also electricity consumers, when they are used for heat production in DH, they can significantly increase the demand for electricity in the power grid. Therefore, it is necessary to estimate the annual HP power consumption to determine the total extra power consumption that is caused by DH HPs.

The total number of electricity consumers to be added to the electricity grid for both options is shown in Table 3.

TABLE 3. ADDITIONAL ELECTRICITY CONSUMERS FOR BOTH OPTIONS

Group no.	**Option 1 – HP electric capacity, MW$_{el}$**			**Option 2 – HP electric capacity, MW$_{el}$**		
	Ground source	**Surface water**	**Sewage water**	**Ground source**	**Surface water**	**Sewage water**
1	0.76	0.76	0.71	2.02	2.14	1.93
2	1.86	1.96	1.77	5.68	5.98	5.38
3	3.77	3.77	3.57	11.71	11.71	11.09
4	6.28	6.60	5.96	19.44	20.42	18.50
5	8.21	8.63	7.34	25.53	26.77	22.82
6	11.75	12.28	11.27	36.98	36.98	35.44
7	17.37	18.03	16.70	54.42	56.56	52.37
Total	50.00	52.03	47.31	155.78	160.56	147.50

Table 3 shows that applying Option 1 to all rural DH networks will result in an additional consumption of around 50 MW in the electric grid. If all considered rural DH networks choose to cover the heat demand using HPs, the additional consumption will amount to 160 MW. The peak consumption in the Estonian electric grid is usually around 1500–1600 MW, therefore, the consumption of HPs in rural areas will amount to a maximum of about 10 % extra consumption.

Annual electricity consumption is also necessary to estimate annual fuel costs since electricity is considered a fuel for HPs.

Fig. 4 shows the annual fuel costs for Option 1 and Option 2 in the case of ground source, surface water and sewage water HPs.

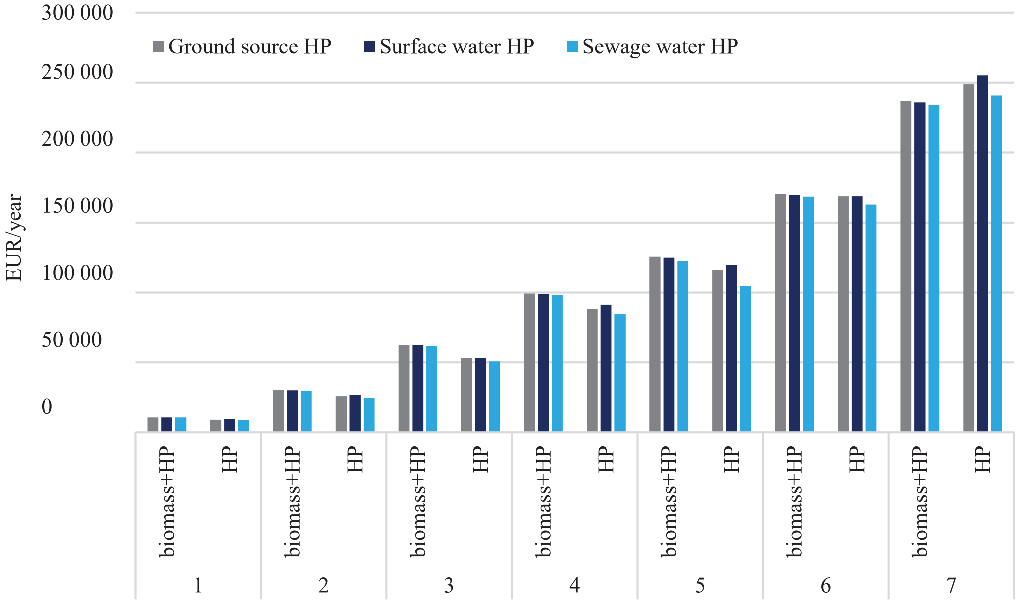


Fig. 4. Annual fuel costs for each option.

TABLE 1. ANNUAL PARTICLE EMISSIONS AND ENVIRONMENTAL FEES FOR OPTION 1

Group no.	**Particle emissions for Option 1 biomass boiler, t/year**	**Annual fee for fine particle emissions, EUR/year**
1	0.350	350
2	0.977	977
3	2.013	2013
4	3.174	3174
5	3.976	3976
6	5.282	5282
7	7.216	7216

It can be seen that sewage water HPs have slightly lower annual fuel costs than other types of HPs, which can be explained by higher heat source temperatures. It can be also seen that the option where only HPs are used as the DH heat source has lower fuel costs, which can be explained by the fact that the average electricity price is lower than the price of woodchips.

Table 4 shows the average annual amount of emitted fine particles for each group and the corresponding fee that can be accounted for as part of the variable costs.

The results in Table 4 show that in any case, the environmental fees for fine particle emissions are not significant compared to other variable costs. Still, the results in Table 4 show how much fine particles would not be emitted when HPs are used instead of biomass boilers.

Operations and maintenance costs (*OM*) for both options are given in Table 5.

TABLE 5. ANNUAL OPERATIONS AND MAINTENANCE COSTS FOR BOTH OPTIONS

Group no.	**Total annual operations and maintenance costs for Option 1, EUR/year**	**Total annual operations and maintenance costs for Option 2, EUR/year**
1	8574	3 780
2	22 387	9 240
3	45 987	18 900
4	73 932	31 220
5	91 014	37 520
6	121 829	50 820
7	164 226	67 200

It can be seen in Table 5 that the *OM* costs are reduced by more than half in the case of Option 2, where only HPs are used. This is because Option 1 also includes two different types of heat sources that require maintenance, while Option 2 only requires one type of maintenance service. Option 1 has lower HP *OM* service costs, but there are additional *OM* costs for the biomass boiler, making the final *OM* cost higher than that of Option 2.

The necessary investments for each group in Option 1 (heat pump and biomass boiler) and Option 2 (HP only) are shown in Fig. 5. Information on average biomass boiler investments was obtained from public announcements of the Estonian Environmental Investments Centre [42]. For HP investments, the data from [43] were used.

The actual investment requirements depend on whether the existing base load boiler is new or needs to be replaced. If a new biomass boiler has been installed within the past 10 years, then it should not be replaced and probably only investment in a peak load boiler will be required. If the existing boiler is old or uses carbon-intensive fuels, larger investments are necessary to achieve climate policy goals.

Capital costs (*CC*) are estimated using investment data provided in Fig. 5 and previously stated technical lifetimes. Once all costs have been estimated, the *WACC* can be calculated and added to the costs. The final consumer price can be calculated using Eq. (2); it is shown divided by costs in Fig. 6. Fig. 6 shows the final DH consumer price for both solutions for average HP costs and for the existing DH consumer price.

Fig. 6 illustrates well that the DH consumer price can be reduced by using HPs as a heat source in rural DH networks, since for all DH groups except group 1, the estimated consumer price is lower than the existing DH price. It should also be noted that the existing price has already been reduced through investment support in many cases, but the calculated data in Fig. 6 does not include investment support, which means that the DH consumer price could be even lower. For group 1, the higher calculated price can be attributed to very low annual heat consumption, which results in lower annual profit, making the estimated consumer price higher.

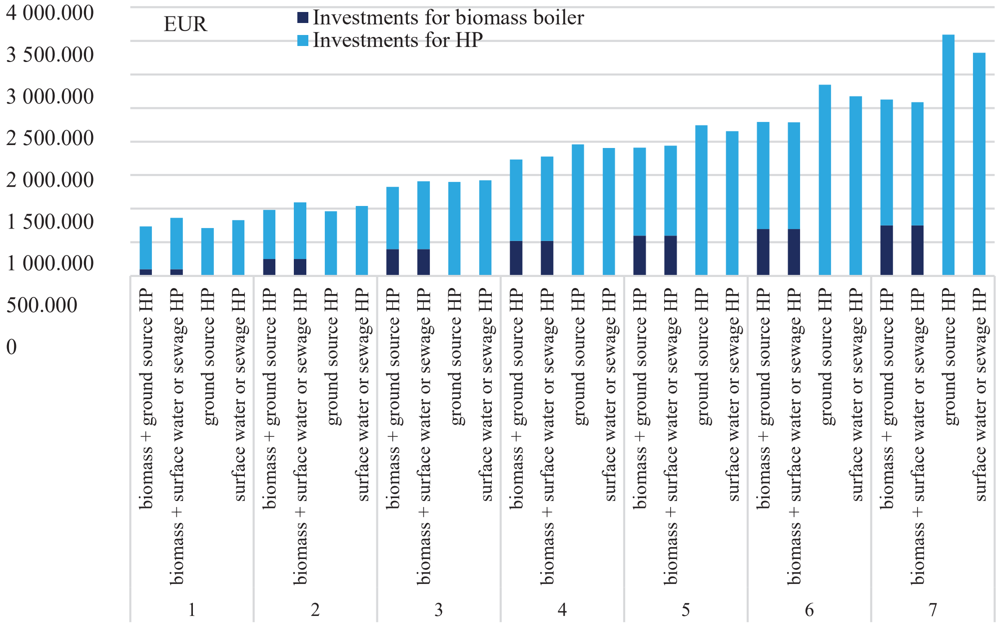


Fig. 5. Required investments for each group for both options.

Fig. 6 also shows that, in all cases, Option 2 results in a lower consumer price than Option 1, the main reason for this is the higher *OM* costs in the case of Option 1.

There is also a remarkable relationship between annual consumption and annual DH network consumption, indicating a major problem for small rural DH networks. Since there are very few consumers in the network, the annual heat consumption is also very low, resulting in a small profit from heat sales. The relationship is also evident in this study and is presented in Fig. 7, which shows the relationship between annual heat consumption and the estimated consumer price of DH.

Fig. 7 illustrates this relationship well: the higher the annual heat consumption, the smaller the consumer price. However, it can be seen that the consumer price increases exponentially when heat consumption decreases. This leads to the conclusion that for very small DH networks such as groups 1 and 2, finding new consumers for the DH network is crucial to maintaining the viability and feasibility of the DH network.

DH consumer prices for both options for different HP types are also provided in Table 6.

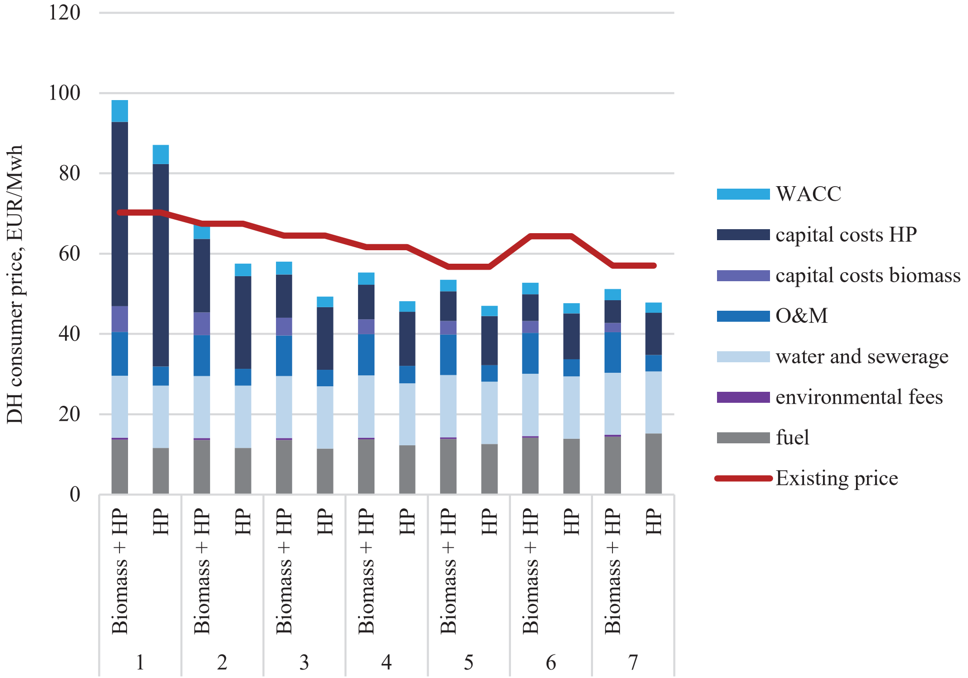


Fig. 6. DH consumer price divided by costs for both solutions and existing consumer price.

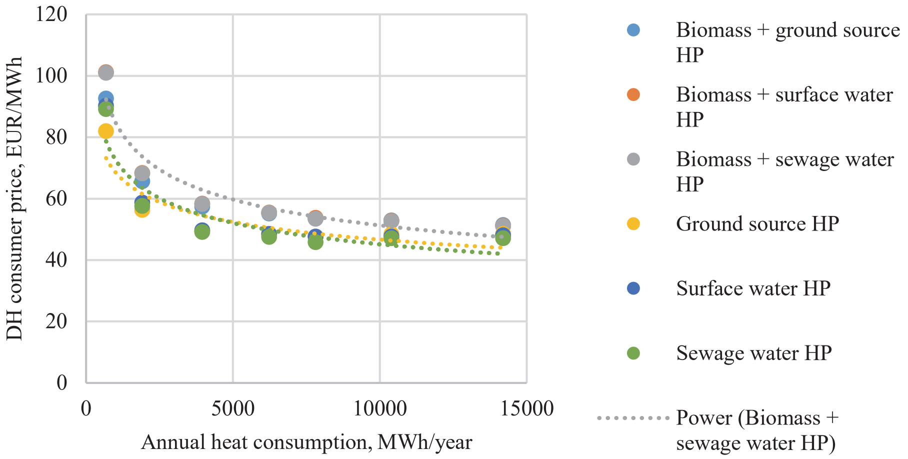


Fig. 7. DH consumer price relationship to DH annual heat consumption.

TABLE 2. DH CONSUMER PRICES FOR BOTH SOLUTIONS FOR DIFFERENT TYPES OF HEAT SOURCES

Group no.	**Consumer price for Option 1, EUR/MWh**			**Consumer price for Option 2, EUR/MWh**		
	Ground source HP	**Surface water HP**	**Sewage water HP**	**Ground source HP**	**Surface water HP**	**Sewage water HP**
1	92.61	101.14	100.97	81.90	90.15	89.15
2	65.66	68.32	68.20	56.25	58.64	57.64
3	57.38	58.38	58.21	49.38	49.62	49.07
4	55.14	55.42	55.31	48.43	48.48	47.50
5	53.55	53.69	53.39	47.66	47.57	45.76
6	52.83	52.75	52.64	48.38	47.63	47.11
7	51.34	51.14	51.04	48.47	48.02	47.10

Investment costs can be significantly reduced through investment support. According to national plans, new renewable heating solutions are going to be installed, including heat pumps with a capacity of more than 20 MW [44]. When support mechanisms are used, this can reduce the capital costs by 50 % and lead to lower DH consumer prices. DH consumer prices with 50 % investment support are given in Table 7.

TABLE 3. DH CONSUMER PRICES WITH 50 % INVESTMENT SUPPORT

Group no.	**Consumer price with 50 % investment support for Option 1, EUR/MWh**			**Consumer price with 50 % investment support for Option 2, EUR/MWh**		
	Ground source HP	**Surface water HP**	**Sewage water HP**	**Ground source HP**	**Surface water HP**	**Sewage water HP**
1	67.77	72.04	71.87	57.85	62.20	61.20
2	53.87	55.16	55.05	44.70	46.11	45.11
3	49.69	50.19	50.01	41.24	41.36	40.81
4	48.76	48.87	48.75	41.20	41.45	40.47
5	47.94	47.98	47.68	41.05	41.23	39.42
6	47.76	47.69	47.58	42.09	41.71	41.19
7	47.08	46.96	46.85	42.66	42.64	41.72

Comparison of the results in Tables 6 and 7 shows that investment support has a greater impact on consumer prices in smaller DH networks (groups 1, 2 and 3). Through investment support, consumer prices can be reduced by up to 31 % (group 1, sewage HP); the reduction is the smallest in group 7 for Option 1 at only 8 %. With investment support, consumer prices will be lower than the existing DH prices in every single case.

4. DISCUSSION AND CONCLUSIONS

The main purpose of this study is to find solutions that will make DH feasible and lower consumer prices for rural DH networks in Estonia. In this study, two different options were considered and compared in terms of the estimated consumer price: biomass boiler plus HP and HP only. Various types of HPs were considered in order to determine which type of heat source is most feasible.

The results show that for smaller DH networks (groups 1, 2 and 3), ground source HPs will be more cost effective than hydrothermal HPs or sewage water HPs. For larger DH networks (groups 4, 5, 6 and 7), the difference between HP types is not very significant. In any case, from a consumer price point of view, using HPs to cover total demand is the best solution. However, this is only applicable if existing boilers need to be replaced. DH consumer prices are lower for all heat sources when the total demand is covered by HPs. The average difference between the consumer price of Options 1 and 2 is 13 %, the difference is more significant for smaller DH networks (groups 1–5) and less for larger DH networks (groups 6 and 7).

The impact on power consumption was also assessed, leading to the fact that even when all rural DH networks use HPs as heat sources, power consumption in the Estonian electricity grid will increase by about 10 % (160 MW) in case of peak consumption.

The results also show the importance of investment support, which can significantly reduce the consumer price. For smaller DH networks the investment support can reduce the consumer price by up to 31 %, while for larger DH networks the effects of investment support are not so noticeable.

The situation for very small DH networks (groups 1, 2 and 3) is difficult anyway, as heat demand density is very low and DH is often not viable. One possible solution for these networks is to give up DH and use individual solutions. This will make it possible to save on heat distribution losses that tend to be high in these DH network groups. If these areas still want to continue using DH, the only possible solution is to increase the annual heat demand by adding new consumers to the network.

In conclusion, it should be noted that using HPs in rural DH networks is a solution that is worth considering. This solution can reduce the DH consumer price and is a good alternative to carbon-intensive peak boilers. It can also integrate RES into the heating sector and help to couple the heating and electricity sectors.

REFERENCES

[1] Sorknæs P., *et al.* The benefits of 4th generation district heating in a 100 % renewable energy system. *Energy* 2020:213:119030. https://doi.org/10.1016/j.energy.2020.119030
[2] Trabert U., *et al.* Decarbonizing building stock with renewable district heating - A case study for a rural area in Germany. *Proceeding of ISES Solar World Congress 2019. IEA SHC International Conference on Solar Heating and Cooling for Building Industry 2019* 2020:470–481. https://doi.org/10.18086/swc.2019.11.02
[3] Polikarpova I., *et al.* Multi-Criteria Analysis to Select Renewable Energy Solution for District Heating System. *Environmental and Climate Technologies* 2019:23(3):101–109. https://doi.org/10.2478/rtuect-2019-0082
[4] Gravelsins A., *et al.* Solar power in district heating. P2H flexibility concept. *Energy* 2019:181:1023–1035. https://doi.org/10.1016/j.energy.2019.05.224
[5] Servinski M., *et al.* Rahvastiku paiknemine ja rahvaarv (Population location and population). Statistikaamet 2012:9. (in Estonian)
[6] Chervenkov H., *et al.* Degree-day climatology over central and southeast Europe for the period 1961-2018 - Evaluation in high resolution. *Cybernetics and Information Technologies* 2020:20:166–174. https://doi.org/10.2478/cait-2020-0070
[7] Grygierek K., *et al.* Energy and environmental analysis of single-family houses located in Poland. *Energies* 2020:13(11):2740. https://doi.org/10.3390/en13112740
[8] Kozarcanin S., *et al.* Impact of climate change on the cost-optimal mix of decentralised heat pump and gas boiler technologies in Europe. *Energy Policy* 2020:140:111386. https://doi.org/10.1016/j.enpol.2020.111386
[9] Dorotić H., *et al.* Impact of wind penetration in electricity markets on optimal power-to-heat capacities in a local district heating system. *Renewable and Sustainable Energy Reviews* 2020:132:110095. https://doi.org/10.1016/j.rser.2020.110095
[10] Bloess A. Impacts of heat sector transformation on Germany's power system through increased use of power-to-heat. *Applied Energy* 2019:239:560–580. https://doi.org/10.1016/j.apenergy.2019.01.101
[11] Karmellos M., Georgiou P. N., Mavrotas G. A comparison of methods for the optimal design of Distributed Energy Systems under uncertainty. *Energy* 2019:178:318–333. https://doi.org/10.1016/j.energy.2019.04.153
[12] Wang C., *et al.* Risk assessment of integrated electricity and heat system with independent energy operators based on Stackelberg game. *Energy* 2020:198:117349. https://doi.org/10.1016/j.energy.2020.117349
[13] Lepiksaar K., *et al.* Improving CHP flexibility by integrating thermal energy storage and power-to-heat technologies into the energy system. *Smart Energy* 2021:2:100022. https://doi.org/10.1016/j.segy.2021.100022

[14] European Commission. COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS Powering a climate-neutral economy: An EU Strategy for Energy System Integration. Brussels: European Commission, 2020.

[15] Arabzadeh V., Pilpola S., Lund P. D. Coupling variable renewable electricity production to the heating sector through curtailment and power-to-heat strategies for accelerated emission reduction. *Future Cities and Environment* 2019:5(1):1–10. http://doi.org/10.5334/fce.58

[16] Bashir A. A., *et al.* Minimizing Wind Power Curtailment and Carbon Emissions by Power to Heat Sector Coupling - A Stackelberg Game Approach. *IEEE Access* 2020:8:211892–211911. https://doi.org/10.1109/ACCESS.2020.3039041

[17] Rušeljuk P., *et al.* Factors Affecting the Improvement of District Heating. Case Studies of Estonia and Serbia. *Environmental and Climate Technologies* 2021:24:521–533. https://doi.org/10.2478/rtuect-2020-0121

[18] Volkova A., *et al.* Planning of district heating regions in Estonia. *International Journal of Sustainable Energy Planning and Management* 2020:27:5–15. https://doi.org/10.5278/ijsepm.3490

[19] Pieper H., *et al.* Assessment of a combination of three heat sources for heat pumps to supply district heating. *Energy* 2019:176:156–170. https://doi.org/10.1016/j.energy.2019.03.165

[20] Pieper H., *et al.* Modelling framework for integration of large-scale heat pumps in district heating using low-temperature heat sources: A case study of Tallinn, Estonia. *International Journal of Sustainable Energy Planning and Management* 2019:20:67–86. https://doi.org/10.5278/ijsepm.2019.20.6

[21] Volkova A., *et al.* Small low-temperature district heating network development prospects. *Energy* 2019:178:714–722. https://doi.org/10.1016/j.energy.2019.04.083

[22] Terreros O., *et al.* Electricity market options for heat pumps in rural district heating networks in Austria. *Energy* 2020:196:116875. https://doi.org/10.1016/j.energy.2019.116875

[23] Augutis J., *et al.* Analysis of energy security level in the Baltic States based on indicator approach. *Energy* 2020:199:117427. https://doi.org/10.1016/j.energy.2020.117427

[24] Litgrid, AST, Elering. Review of RES perspective in Baltic countries till 2030. 2015.

[25] Rummel L. Kaarepere küla ja Luua küla soojusmajanduse arengukava aastateks 2017-2027 (Approval of the heat management development plan of Palamuse small town, Kaarepere village and Luua village for 2017–2027.). Palamuse: Palamuse Vallavolikogu, 2017. (in Estonian)

[26] Rummel L. Mäetaguse valla Mäetaguse aleviku ja Kiikla küla soojusmajanduse arengukava aastateks 2017-2030 (Mäetaguse rural municipality Mäetaguse small town and Kiikla village heat management development plan for 2017–2030). Mäetaguse: Mäetaguse Vallavolikogu, 2017. (in Estonian)

[27] Sweco, Port of Tallinn. Cruise Terminal of Old City Harbour. Sustainable energetic solutions for cruise terminal buildings in Northern Climate. Tallin: Sweco, 2017.

[28] Woolley K. E., *et al.* Effectiveness of interventions to reduce household air pollution from solid biomass fuels and improve maternal and child health outcomes in low- and middle-income countries: a systematic review protocol. *Systematic Reviews* 2021:10(33):1–7. https://doi.org/10.1186/s13643-021-01590-z

[29] Cheng W., *et al.* Mitigation of ultrafine particulate matter emission from agricultural biomass pellet combustion by the additive of phosphoric acid modified kaolin. *Renewable Energy* 2021:172:177–187. https://doi.org/10.1016/j.renene.2021.03.041

[30] Kažimírová V., Opáth R. Biomass combustion emissions. *Research in Agricultural Engineering* 2016:62:S61–S65. https://doi.org/10.17221/69/2015-RAE

[31] Directive (EU) 2015/2193 of the European Parliament and of the Council of 25 November 2015 on the limitation of emissions of certain pollutants into the air from medium combustion plants. *Official Journal of the European Union* 2015:L 313/1.

[32] European Parliament and Council. DIRECTIVE (EU) 2016/2284 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 14 December 2016 on on the reduction of national emissions of certain atmospheric pollutants, amending Directive 2003/35/EC and repealing Directive 2001/81/EC. *Official Journal of the European Union* 2016:L 344:1.

[33] European Commission. Operational Programme for Cohesion Policy Funding 2014-2020. Estonia 2014 [Online]. [Accessed 15.03.2021]. Available: https://ec.europa.eu/regional_policy/en/atlas/programmes/2014-2020/estonia/2014ee16m3op001

[34] European Commission. 2050 long-term strategy [Online]. [Accessed 15.03.2021]. Availabe: https://ec.europa.eu/clima/policies/strategies/2050_en

[35] Eesti Konkurentsiamet. Kooskõlastatud soojuse piirhinnad (Coordinated marginal heat prices) [Online]. [Accessed 15.03.2021]. Available: https://www.konkurentsiamet.ee/et/vesi-soojus/soojus/kooskolastatud-soojuse-piirhinnad (in Estonian)

[36] National Weather Service. Observation data [Online]. [Accessed 14.03.2021]. Available: https://www.ilmateenistus.ee/ilm/ilmavaatlused/vaatlusandmed/ (in Estonian)

[37] Konkurentsiamet. Soojuse piirhinna kooskõlastamise põhimõtted (03.05.2013 käskkiri nr 1.1-2/13-012) (Principles of approval of the maximum heat price (Directive No. 1.1-2 / 13-012 of 03.05.2013.). Tallin: Estonian Competiton Authority, 2020. (in Estonian)

[38] Keskkonnaministeerium. Keskkonnatasude Raamkava Aastateks 2016-2025 (Environmental Charges Framework Plan for 2016–2025.). Tallin: Ministry of the Environment, 2014. (in Estonian)

[39] PHS Engineers. Biomass (Wood-Pellet) Boiler VS Conventional Gas Boiler - Pros & Cons [Online]. [Accessed 15.03.2021]. Available: https://phsengineersltd.co.uk/biomass-wood-pellet-boiler/

[40] Danish Energy Agency. Drejebog til store varmepumpeprojekter i fjernvarmesystemet (Guide for large-scale heat pump projects in district heating systems.). Kolding: DEA, 2017.

[41] Knobloch F., *et al.* A technical analysis of FTT:Heat - A simulation model for technological change in the residential heating sector. Technical Study on the Macroeconomics of Energy and Climate Policies. Brussels: European Commission, 2017.

[42] Environmental Investment Center. Funded applications [Online]. [Accessed 08.01.2021]. Available: https://www.kik.ee/et/rahastatud-projektid (in Estonian)

[43] Pieper H., *et al.* Allocation of investment costs for large-scale heat pumps supplying district heating. *Energy Procedia* 2018:147:358–367. https://doi.org/10.1016/j.egypro.2018.07.104

[44] Majandus- ja kommunikatsiooni Ministeerium, Vaks R. Open public discussion about European Union support on topics 'Greener Estonia' in 'Energy efficient consumption'. 2020

Curriculum vitae

Personal data

Name: Kertu Lepiksaar
Date of birth: 18. October 1991
Place of birth: Tallinn, Estonia
Citizenship: Estonian

Contact data

E-mail: kertu.lepiksaar@taltech.ee

Education

2020–2024	Tallinn University of Technology – Mechanotechnics, major field: thermal power engineering, PhD
2018–2020	Tallinn University of Technology – Energy technology and thermal power engineering, MSc
2011–2018	Tallinn University – Physics, minor field: Geoecology, BSc
1998–2010	Keila School

Language competence

Estonian	Native language
English	Fluent

Professional employment

2020–…	Tallinn University of Technology, junior researcher
2018–2020	Tallinn University of Technology, laboratory assistant
2018	Elering AS, regime planner
2017–2018	Metrosert AS, measurements technician

Elulookirjeldus

Isikuandmed

Nimi: Kertu Lepiksaar
Sünniaeg: 18. oktoober 1991
Sünnikoht: Tallinn, Eesti
Kodakondsus: eesti

Kontaktandmed

E-post: kertu.lepiksaar@taltech.ee

Hariduskäik

2020–2024	Tallinna Tehnikaülikool – Mehhanotehnika, peaeriala: Soojusenergeetika, PhD
2018–2020	Tallinna Tehnikaülikool – Energiatehnoloogia ja soojusenergeetika, MSc
2011–2018	Tallinna ülikool – Füüsika, kõrvaleriala: Geoökoloogia, BSC
1998–2010	Keila Kool

Keelteoskus

Eesti keel	emakeel
Inglise keel	kõrgtase

Teenistuskäik

2020–…	Tallinna Tehnikaülikool, doktorant-nooremteadur
2018–2020	Tallinna Tehnikaülikool, laborant
2018	Elering AS, püsitalitluse režiimiplaneerija
2017–2018	Metrosert AS, mõõtetehnik

ISSN 2585-6901 (PDF)
ISBN 978-9916-80-143-7 (PDF)