DOCTORAL THESIS

Decarbonisation of Fossil-Fuel CHP Based District Heating System

Pavel Ruševljuk

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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.

Pavel Ruševljuk

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Fossiilkütustel põhineva CHP kaugküttesüsteemi dekarboniseerimine

PAVEL RUŠELJUK

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Contents

List of Publications

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

I Rušeljuk, P.; Volkova, A.; Lukić, N.; Lepiksaar, K.; Nikolić, N.; Nešović, A.; Siirde, A. Factors Affecting the Improvement of District Heating. Case Studies of Estonia and Serbia Clim. Technol. 2021, 24, 521–533, https://doi.org/10.2478/rtuect-2020-0121

II Rušeljuk, P.; Lepiksaar, K.; Siirde, A.; Volkova, A. 2021. Economic Dispatch of CHP Units through District Heating Network's Demand-Side Management, Energies 14, no. 15: 4553, https://doi.org/10.3390/en14154553

III Rušeljuk, P.; Dedov, A.; Hlebnikov, A.; Lepiksaar, K.; Volkova, A. Comparison of District Heating Supply Options for Different CHP Configurations, Energies 2023, 16, 603. https://doi.org/10.3390/en16020603

List of Publications Not Included in this Thesis

IV Lepiksaar, K.; Volkova, A.; Rušeljuk, P.; Siirde A. The effect of the District heating return temperature reduction on flue gas condenser efficiency. Environ Clim Technol 2020; https://sciendo.com/downloadpdf/journals/rtuect/24/3/article-p23.xml

Author’s Contribution to the Publications

The author’s contributions to the papers in this thesis are as follows:

I The author served as the main author of the paper and was responsible for developing the paper’s concept and methodology. Additionally, the author conducted data collection and processing and performed the techno-economic analysis of the Narva district heating system. The author identified system-level factors influencing district heating and compared the factors affecting district heating in Estonia and Serbia. Based on these analyses, the author provided recommendations to improve DH systems in Serbia, which can make a significant contribution to increasing the share of renewable energy sources and reducing CO_2 emissions in the Serbian energy sector.

II The author developed a method for determining the energy efficiency of CHP units. This method allows for making decisions and selecting the optimal load for the operating CHP unit while systematically changing dispatch schedules for the supply of heat and electricity throughout the day. This method has allowed for the resolution of two critical challenges. Firstly, it enables the optimal distribution of heat and electric energy, thereby optimising overall energy efficiency. Secondly, it addresses operational and short-term predictive planning issues for a wide range of electrical and thermal energy generation within the load control range. These solutions are applicable to the load modes of the CHP unit, considering the implementation of electricity supply schedules in the wholesale electricity market for diverse modes of heat and electricity generation. Moreover, the method permits continuous data adjustment, considering the actual consumption of thermal energy, further enhancing its effectiveness.

III The author conducted a comparative analysis to assess the efficiency of different configurations of thermal power plants. The study estimated the fuel efficiency coefficient, exergy efficiency, and specific fuel consumption for the total production of electrical and thermal energy, assuming an equal production of thermal energy across these configurations. Additionally, the author presented a comparative analysis of various heat supply sources, leading to the conclusion that steam turbine CHP plants are more favourable for producing electrical and thermal energy. However, it is crucial to note that this path cannot be considered promising for the further development of heat supply due to the preservation of all shortcomings inherent in the existing district heating system. Consequently, to advance heat supply systems, it becomes imperative to introduce alternative sources and low-temperature heat supply technologies.

Introduction

The European Commission has proposed the European Green Deal [1] as a means to establish a modern, climate-neutral, resource-efficient, and competitive economy. The core principles of this initiative encompass the adoption of clean energy, combating climate change, and mitigating environmental pollution, among others. To achieve the EU's 2050 climate neutrality target, the majority of EU nations must phase out fossil fuels, the primary contributors to global emissions, by 2030. Human activities, particularly the burning of fossil fuels, release greenhouse gases that drive climate change and currently dominate global energy consumption [1], despite their finite nature [2]. Transitioning to pure renewable energy [3-5], and enhancing primary energy conservation through improved production, distribution, and consumption efficiency are essential strategies for addressing these challenges [6-8].

In this context, district heating (DH) represents a critical area where innovative technologies can make a substantial contribution to the pursuit of these objectives by reducing heat loss in DH networks and optimising the operation of heat generation units. However, it is crucial to acknowledge that, compared to the power generation sector, the research and implementation of new technologies in DH networks have been relatively limited. Therefore, exploring and investigating this domain is of paramount importance, and its significance should not be underestimated.

Research Topicality

Today, combined heat and power (CHP) is one of the most widely used technologies at power plants, aimed at conserving fuel and consequently reducing CO_2 emissions.

Furthermore, the following steps can be taken to decarbonise DH systems:

- reconstruction of DH systems;
- demand-side management;
- replacement of fossil fuels with biomass;
- utilisation of waste heat from power plants and industrial processes;
- integration of non-fuel sources such as heat pumps (HP).

All of the alternatives listed should be considered when determining the true potential for decarbonisation and efficiency improvements in a specific DH system.

Hypothesis

It is postulated that implementing diverse technical solutions within existing fossil-fuel-based DH systems can lead to a significant reduction in CO_2 emissions. These solutions are centred around distinct components of the DH infrastructure.

The initial phase of analysing the feasibility of integrating a HP into CHP systems involves evaluating potential low-grade heat sources while considering the operational characteristics of the installations. The exploration and assessment of the potential and temperature profiles of these sources rely on statistical data and nominal characteristics. This approach identifies the advantages and disadvantages associated with each low-grade heat source.

A combination of mathematical modelling, thermodynamic analysis of HP cycles, and techno-economic assessment was proposed to determine the effectiveness of HP integration into CHPs. A comparative analysis of key technical and economic indicators with and without HPs is necessary to assess the impact of HP integration on CHP operating modes. Changes in these indicators are also evaluated to establish nominal CHP operating modes as well as modes involving partial heat and power outputs.

Selecting a HP with optimal potential for incorporation into a CHP system is a critical step in enabling the efficient utilisation of low-grade waste heat for heating purposes. The investigation delves into how the thermal loads of the CHP system impact the efficiency of the HP integration within the thermal scheme.

Further analysis entails scrutinising the correlations between enhanced technical and economic indicators of a CHP system when integrating a HP across a range of heat loads.

Aims and Objectives

The overarching aim of this thesis is to assess various technical options that can effectively reduce CO_2 emissions within operational, fossil fuel-based CHP-centred DH systems:

- the object of the study is a CHP with a HP included in the equipment;
- the subject of the study is the thermal processes occurring during the operation of the main and auxiliary equipment of the CHP.

Research Tasks

- Identifying Factors Influencing District Heating Improvement:
  - investigate factors impacting DH at both national and system levels.
- Optimisation of CHP Operation through Demand-Side Management:
  - optimise CHP operational strategies using demand-side management techniques to minimise CO_2 emissions.
- Solving the Economic Dispatch Problem:
  - address the economic dispatch problem to determine the optimal load distribution for CHP units while considering CO_2 reduction.
- Energy and Exergy Balances for District Heating Systems:
  - maintain energy and exergy balances for DH systems to understand energy flows and efficiencies.
- Analysis and Comparison of Different CHP Turbine Configurations:
  - analyse various CHP turbine configurations to evaluate their impact on reducing CO_2 emissions.
- Evaluation of Biomass Substitution for Fossil Fuels:
  - assess the feasibility of substituting fossil fuels with biomass and its potential contribution to CO_2 reduction.
- Analysis of Non-Fuel Heat Integration into District Heating:
  - examine the integration of non-fuel heat sources into DH systems and their influence on CO_2 reduction.

By accomplishing these research tasks, this study aims to shed light on effective strategies for mitigating CO_2 emissions within existing fossil fuel-based CHP DH systems.

The thesis structure is illustrated in Figure 0.1.:

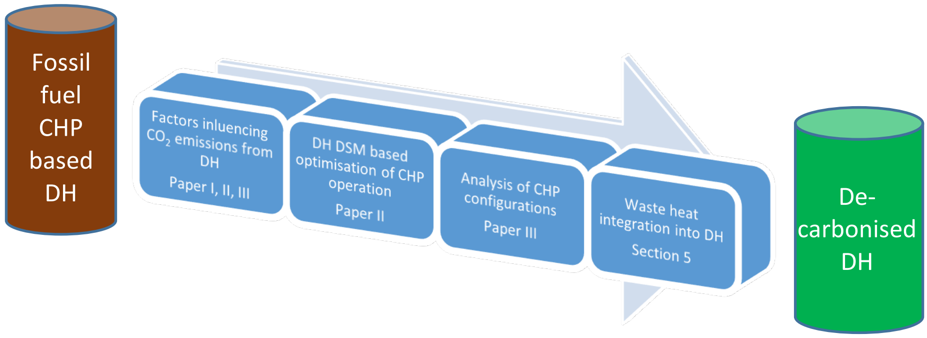

Figure 0.1. Thesis structure.

According to this Structure

The initial step involves identifying and assessing various factors at both national and system levels, encompassing legislative, economic, geographical, technical, and other considerations (Paper I). This allows us to identify the potential for DH improvement and decarbonisation. Using remotely obtained hourly heat demand data to optimise CHP operations is a crucial option for improving DH, as discussed in Paper II, which assesses the extent to which this optimisation can lead to lower CO_2 emissions. The research also delves into the configuration of CHP turbines and examines the feasibility of partially replacing fossil fuels with biomass, assessing the maximum potential for CO_2 reduction (Paper III).

Furthermore, this thesis investigates the integration of non-fuel heat energy sources (Section 5) and their impact on DH decarbonisation.

The examination of DH improvements is discussed in Paper I, which considers factors such as geographical and climate variables, along with economic and legal considerations. This analysis is complemented by evaluating key technical and economic parameters associated with DH networks.

In Paper II, a simulation of a real CHP unit coupled with a DH network illustrates how demand-side management enhances the CHP unit's economic efficiency and extends its operating range in the electricity spot market. The paper addresses the optimisation of the CHP unit's operating mode, determining the optimal increase in the unit's electrical load under specific consumer heat load conditions, leading to enhanced CHP efficiency.

The objective of Paper III is to scrutinise various turbine modifications for existing CHPs, aiming to identify the most favourable scenario. The paper undertakes primary comparisons of scenario characteristics and performance indicators, calculating ratios of thermal load fuel consumption and fuel savings for different scenarios.

The practical significance of this paper lies in applying methodological guidelines for selecting rational options in CHP unit renovation. This enhances the efficiency of heat supply system sources and assists in identifying optimal transformation directions.

To reach this goal, the following research questions must be addressed:

- What are the factors at both local and national levels that exert an influence on DH efficiency and the specific CO_2 emissions associated with it?
- To what extent can the optimisation of CHP operations through a demand-side management model contribute to the reduction of CO_2 emissions linked to DH?
- How does the configuration of a CHP system impact turbine efficiency, and subsequently, how does it influence CO_2 emissions related to DH?
- What is the potential reduction in CO_2 emissions achievable by substituting fossil fuels with biomass in various configurations?
- What is the effect of integrating waste heat into high-temperature DH systems on CO_2 emissions reduction?
- How can the methodology for assessing the energy efficiency of heat supply systems featuring HPs be comprehensively studied?
- How can the economic and mathematical models for evaluating optimal configurations, parameters, and the economic viability of HPs in CHP systems be systematically investigated?

Methodology

The methodology used in the thesis facilitates the assessment of decarbonisation possibilities within fossil-fuel-based CHP-oriented DH systems by integrating diverse technical solutions. Various methods were employed to attain this objective. The rationale behind method selection, as well as a comprehensive description of each approach, has been expounded in the papers.

Initially, a review of published articles was conducted as part of this study of energy efficiency opportunities. This then led to the development of a number of broad research questions for further investigation. Table 0.1 illustrates the research methodology used in this dissertation. The array of methods used to achieve the goal and address the research questions is shown in Table 0.1.

Table 0.1. Research methodology and research questions.

	Factors Affecting the Improvement of District Heating. Case Studies of Estonia and Serbia	Economic Dispatch of CHP Units through District Heating Network's Demand-Side Management	Comparison of District Heating Supply Options for Different CHP Configurations	Thesis: Utilization of low-grade waste heat from CHP cooling water using a HP
Literature and legislation review	•	•	•	•
Key performance indicators	•	•	•	•
Techno-economic analysis	•	•	•	•
Regression analysis		•		
Periodic autoregressive algorithm		•		•
Non-linear optimisation		•		•
Efficiency analysis		•	•	•

The dissertation encompasses a range of methodologies, including the study of scholarly sources, analysis and evaluation of existing heat supply methods employing economic dispatching, exploration of diverse CHP configurations, and integration of HPs into CHP structures. Experimental studies were conducted, coupled with mathematical modelling and result analysis through numerical and analytical approaches to solving differential equations. Furthermore, assessments were conducted to justify the implementation of these developments, considering the prevailing technical and economic contexts. The thesis thoroughly examines existing information on technical methods for improving DH efficiency. This includes optimising heat supply systems, using consumption data to assist CHP dispatching, comparing various CHP configuration schemes, and utilising CHP waste heat using HPs. The development of an optimisation methodology validates the theoretical possibility of using these options as technological solutions.

The solution of the problem of improving the efficiency of the CHP is accompanied by the consideration of technical and economic factors. These include the features of the technological scheme of the CHP, the condition of the equipment in operation, the operating modes of the CHP, the climatological characteristics of the facility. The actual modes of operation of the equipment affect the efficiency of the use of HP, which necessitates their accounting.

The purpose of the study is to evaluate the effectiveness of the use of HPs in the technological schemes of CHP, taking into account the operating modes of the equipment. To achieve this goal, it is necessary to solve the following tasks:

- perform an analysis of the potential capabilities of the CHP, taking into account its technological scheme, equipment operating modes;
- to develop a methodology for analyzing the possibility of introducing HP into the technological scheme, taking into account the operating modes of the CHP;
- to propose solutions that increase the efficiency of the cogeneration process at CHPs, to determine options for using the heat received from the CHP to improve the operating modes of the CHP;
- to assess the economic efficiency of energy-saving measures implemented with the help of HP.

Theoretical Novelty

The theoretical significance of this study resides in the exploration of the incorporation of HP installations as a means to capitalise on waste heat from the cooling system of CHP. The analysis and optimisation of this combined approach involve the cogeneration of a heat and power system coupled with a HP. This arrangement employs the low-grade heat from the cooling circulating water to elevate the temperature of the return network water within the cogeneration unit. The ultimate aim is to satisfy consumer heat load requirements and enhance the overall efficiency of CHP generation. This paper assesses the comprehensive impact of this solution on the entire system.

The study identifies the most promising avenue for integrating HPs into existing district heating systems, particularly for effective synergy with CHP. The objective is to bolster the energy efficiency of district heating systems by devising a cost-effective strategy for HP implementation. This approach also paves the way for the further advancement of CHP and HP combination technologies. To achieve this goal, the following tasks were established: determine the viability and optimal integration points for HP utilisation within CHP; develop an efficient heat supply methodology with HPs; thereby mitigating any negative effects on CHP efficiency; and develop a methodology for assessing the technical and economic parameters of a CHP, accounting for changes in heat supply modes resulting from integration with HP:

- a methodology has been developed for analyzing the possibility of introducing HP into the technological scheme, taking into account the operating modes of the CHP;
- an analysis of the impact of the inclusion of HP on the technical and economic indicators of the CHP for the characteristic operating modes of the stations was carried out;
- a comparative assessment of the effectiveness of the use of heat from the HP for additional heat supply to the consumer from the CHP was carried out.

Scientific Novelty

The scientific novelty of the dissertation encompasses the following contributions:

- Methodological Approaches: Novel methodological approaches have been devised for the examination of heat supply systems. These approaches involve establishing interrelationships among the intricate components of the system, leading to the derivation of novel outcomes.
- Thermal Efficiency Assessment Methodology: A distinctive methodology has been developed for evaluating the thermal efficiency of heat supply systems featuring HPs. This methodology is based on the criterion of relative fuel savings and associated fuel expenditures.
- Mathematical Models: Mathematical models have been formulated to facilitate the selection of economically optimal configurations, source parameters, and network setups while accounting for pertinent system factors.
- Rational Application Recommendations: The research offers recommendations concerning the rational application domains of HPs and the assessment of the fuel and economic efficiency of heat supply systems.

In addition, innovative thermal schemes have been proposed to enhance the thermal efficiency of CHP’s, specifically a scheme for harnessing the heat from cooling water. Analytical relationships have been introduced to ascertain the boundary conditions for the implementation of HPs. Further analytical dependencies have been devised to explore alterations in the fuel heat utilisation factor and the specific electricity generation pertaining to the CHP's heat consumption. These analyses are conducted with the incorporation of HPs into the technological scheme. Moreover, the proposed analytical dependencies assist in selecting the optimal approach for the utilisation of low-grade heat.

Practical Novelty

A noteworthy practical contribution of this study is the integration and development of a methodological framework for calculating the energy efficiency of an integrated solution. This methodology takes into account the intricate aspects of seasonal heat consumption, contingent on the temperature schedule of the heat supply system, the temperature of the low-grade heat source, and the pertinent climate parameters of the given season (with a focus on weather conditions in Estonia). Furthermore, the research endeavours to optimise efficiency by redistributing the annual heating load among the heat sources within the CHP unit, maximising the utilisation of the most economical among them. As a result, a substantial portion of inter-heating heat consumption is met through efficient solution.

The proposed and substantiated technical solutions hold the potential to significantly enhance the thermal efficiency of CHPs while simultaneously curbing their environmental impact. The outcomes of this study offer practical utility in devising low-grade heat utilisation schemes incorporating HPs, not only in the design of new facilities but also in the modernisation of existing CHPs.

The research findings have practical value since they may be used to select perfect schemes, determine suitable parameters, and identify logical utilisation avenues for HPs in heat supply systems. The overall efficiency of heat supply systems can be increased by including these methodological breakthroughs, recommendations, and circuit solutions into design procedures.

The practical significance of this project manifests through the resolution of several critical and pressing issues:

- identification of a promising refrigerant (circulated cooling water) for HP installations, facilitating efficient utilisation of low-potential waste heat and concurrently minimising environmental pollution;
- determination of key conditions and directions for heat supply system enhancements via alternative solutions;
- assessment of the resource pool of heat supply system to facilitate HP operation utilising residual heat from the CHP unit's circulating water;
- development of an alternative solution schematic and a methodology for gauging efficiency enhancements in this alternative scheme;
- comprehensive study and analysis of technical and economic efficiency indicators associated with the developed scheme, including optimisation and financial assessments;
- enhancement of the energy efficiency of the existing CHP system by incorporating a combined heat source;
- development of combined circuit solutions for the CHP unit;
- devising a methodology for quantifying efficiency improvements within the combined scheme;
- extensive research and analysis of the technical and economic efficiency indicators related to the combined scheme;
- conducting optimisation studies for the combined circuit solutions;
- performing a thorough investigation and analysis of the financial and economic indicators pertinent to the combined scheme.

The practical significance of the work lies in the fact that the developed methodology for analyzing the possibility of introducing HP into the technological scheme, taking into account the operating modes of CHP, can be used by operating and project organizations when implementing HP schemes in the design processes of new and modernization of existing CHPs. It is also of interest to all existing heat supply facilities and industrial enterprises that have secondary sources of low-grade heat.

The practical value of this work is supported by experimental calculations based on the CHP unit of the Balti Power Plant (BPP), confirming the real-world applicability of the presented approaches. A significant emphasis is placed on DH companies, where the proposed methodology assists in the implementation of new pilot projects in heat transmission and generation. Improved DH performance indicators allow for more accurate detection of energy efficiency initiatives and subsequent optimisation efforts. This helps with long-term heat supply development planning.

Approbation of the Research Results

I Rušeljuk, P.; Volkova, A.; Lukić, N.; Lepiksaar, K.; Nikolić, N.; Nešović, A.; Siirde, A. Factors Affecting the Improvement of District Heating. Case Stud. Est. Serb. Clim. Technol. 2021, 24, 521–533, https://doi.org/10.2478/rtuect-2020-0121

II Rušeljuk P., Lepiksaar k., Siirde A., Volkova A., 2021. Economic Dispatch of CHP Units through District Heating Network's Demand-Side Management. Energies 14, no. 15: 4553, https://doi.org/10.3390/en14154553

III Ruseljuk, P.; Dedov, A.; Hlebnikov, A.; Lepiksaar, K.; Volkova, A. Comparison of District Heating Supply Options for Different CHP Configurations. Energies 2023, 16, 603. https://doi.org/10.3390/en16020603

Reports at Scientific Conferences

I Nebojsa Lukic, Novak Nikolic, Aleksandar Nesovic, Pavel Rušeljuk, Anna Volkova, Kertu Lepiksaar, Andres Siirde Factors affecting the improvement of district heating. Case studies of Estonia and Serbia, CONECT 2020, 13–15 May 2020, Riga, Latvia.

II Kertu Lepiksaar, Anna Volkova, Andres Siirde, Pavel Rušeljuk: The effect of the District heating return temperature reduction on flue gas condenser efficiency, CONECT 2020, 13−15 May 2020, Riga, Latvia.

III Pavel Rušeljuk: Economic Dispatch of District Heating Networks via Consumption Based Management, The 6th International Conference on Smart Energy Systems, 6–7 October 2020, Aalborg, Denmark.

IV Pavel Rušeljuk, Kertu Lepiksaar, Anna Volkova, Optimal Heat Supply Solution for Combined Heat and Power Production with Climate-Neutral District Heating in Narva, The 18th Conference for Sustainable Development of Energy, Water and Environment Systems (SDEWES), 23–25 September, 2022, Paphos, Cypros.

Abbreviations

CHP	Combined Heat and Power
BPP	Balti Power Plant
Capex	Capital Expenditures
CHP	Combined Heat and Power
COP	Coefficient of Perfomance
CO_2	Carbon dioxide
DH	District Heating
DHA	District Heating Act
DHW	District Heating Water
DPP	Discounted Payback Period
ECA	Estonian Competition Authority
EED	Energy Efficiency Directive
ENMAK	Energy Economy Development Plan / Energiamajanduse arengukava
EREA	Estonian Renewable Energy Association
EU	European Union
GHG	Greenhouse Gas
FESR	Fuel Energy-Savings Ratio
HP	Heat Pump
IRR	Internal Rate of Return
LCOE	Levelized Costs of Energy
LCOH	Levelized Costs of Heat
NPV	Net Present Value
Opex	Operational Expenditures
PEF	Primary Energy Factors
PI	Profitability Index
PP	Payback Period
PV	Photovoltaics
RES	Renewable Energy Source
SCOP	Seasonal Ccoefficient of Performance
STC	Solar Thermal Collectors
WACC	Weighted Average Cost of Capital

Symbols

B_f	fuel consumption
B_{CHP}^{e}	consumption fuel per CHP for the generation of electrical energy
B_{CHP}^{h}	consumption fuel per CHP for the generation of heat energy
B_{CHP}^{ov}	overall consumption fuel per CHP for the generation of heat and power energy
B_{re}^{h}	fuel consumption at the thermal unit that replaces the heat load
B_{re}^{e}	fuel consumption for the replacement of electricity for the HP
B_{CHP}^{h}	B_{CHP}^{h}- electricity generation in the initial scenario
ΔB_i	primary energy savings from the introduction of the HP for the i-th mode of operation of the HP
Capex	capital expenditures (CHP heat part, HP initial investment)
E_{HP}	the energy needed to operate the HP
E_{CHP-HP}^{a}	electricity generation in the proposed scenario with a HP
E(t)	amount of electrical energy produced in year t
$E_{HP}(t)$	annual power consumption for HP in year t
Fuel(t)	fuel cost (CHP electrical/heat) in year t
H(t)	amount of heat energy produced in year t
k_{CO2}	specific CO_2 emission factor
L_{DHw}	useful work of DH network water
n	total number of hours
N_{CHP}^{e}	electric power of CHP
N_{CHP}^{h}	heat power of CHP
N_E	electrical power of turbine
Opex(t)	operating cost (CHP electrical/heat, HP heat pump) in year t
$Price_{el}^{CHP}$	price of CHP electricity
Q_{DH}^{a}	annual heat generation for DH
Q_H	thermal energy of district heating
Q_{HP}	heat supplied by the HP
Q_{LHV}	low calorific value of the fuel
Q_{LHV}^{re}	Low calorific value of the fuel of the replacement source
r	discount rate
R_t	net cash flow (inflow minus outflow) at period t
s_{bio}	share of biomass
w	specific power generation per heat consumption
W_{CHP}^{a}	annual consumption of primary energy by the CHP
W_{HP}^{a}	annual consumption of primary energy for the generation of electricity consumed by the HP
y	unit lifetime, years

Greek Symbols

η_{CHPi}	energy efficiency of the i heat load
η_e	efficiencies for the production of electricity
η_{Ei}	efficiency of electricity production of the CHP unit at hour *i*
η_h	efficiencies for the production of heat
η_{Hi}	heat production efficiency of the CHP unit at hour *i*
η^{HP}	average CHP efficiency for the generation of thermal and electrical energy with HP
$\eta_{overall}$	overall efficiency of the CHP unit
η_{re}^{e}	efficiency of the power generation for HP
τ_a	annual duration work of HP
τ_i	duration of the i-th mode of operation of the HP

1 Literature Review

1.1 Overview of Factors Affecting DH Improvement

Many studies have analysed the elements affecting DH system efficiency improvements; hence, in [9], a number of technical and economic factors have been discussed: energy sources, design considerations, environmental impact, performance analysis, and energy policy. A different approach was proposed in [10], which split the key technical and economic factors into three major groups: fuel-related factors, network factors, and energy production factors. Fuel-related factors include fuel cost, environmental concerns, existing fuel supply infrastructure, transportation and storage logistics, energy density, and fuel quality [10]. A method for assessing the current state of the DH system and its development potential was proposed in [11]. According to [11], the most important factor is the heating load. Technical factors affecting the potential for DH improvement are described in [12]. Along with technical and economic factors, energy policy also has a significant impact on the DH sector. Energy policy measures such as the tariff system and support policies also affect DH. The economic feasibility of several development scenarios was examined in [13], and it was determined that the DH tariff cannot be reduced in order for DH prosumers to continue investing in future advancements. An appropriate tariff system can encourage DH prosumers to increase efficiency and utilise renewable energy sources [14]. Legislation is also important for preserving DH viability [15]. Primary energy factors (PEF) on building energy efficiency [16, 17] also have an impact on DH, as they suggest that the number of nearly zero-energy buildings must increase in order to achieve this. A methodology for calculating PEF for energy-efficient DH was proposed in [18]. The studies reviewed show that DH systems are progressive systems that can integrate new technologies as they emerge and utilise previously untapped sustainable energy sources (renewable energy or waste heat) if comprehensive planning based on the principles mentioned earlier is undertaken.

European regulators are looking into the idea of combining various generation methods, in particular CHPs, to boost the efficiency and flexibility of the heating sector [19]. Through energy and exergy analyses of the cogeneration mode, it is possible to increase electricity generation, improve heat load, and reduce heat loss in the DH network [20]. Centralised CHP units have been identified as a priority for meeting the European energy sector’s decarbonisation targets. Increased use of CHP and renewable energy sources is widely recognised by the EU administration as an effective way to improve the overall energy efficiency of energy systems, reduce CO_2 emissions, and minimise dependence on imported fuels. The heating sector is often characterised by old, inefficient equipment that loses a lot of heat. According to [21], the heating sector accounts for the majority of energy consumption and carbon emissions. District heating companies have tremendous potential for reducing energy consumption, boosting efficiency, and eliminating CO_2 emissions due to well-developed infrastructure and a significant capacity for increased flexibility to cover heat demand. The potential transition to sustainable DH, which can boost efficiency and balance the thermal and electrical loads at CHP units, was considered in one study's analysis of technical alternatives to increase the flexibility of CHP units [22]. The importance of CHPs in the integrated energy sector was analysed in [23]. Installation of HPs and electric boilers as well as low-carbon capacity utilisation after system integration were covered in [24].

The heating system's energy and exergy efficiencies were investigated, with the energy and exergy flow diagrams presented in [25]. The importance of identifying appropriate methods and reference parameters was discussed in [26], with a particular emphasis on applications that require the determination of allocation factors and potential effects. In [27], exergy and economic analyses of CHPs were performed in order to determine the specific exergy-economic rates and CO_2 emissions of end products. Much better indicators of economic and environmental sustainability, demonstrated using actual project inputs, were noted in [28], implying that similar concepts can be developed for other networks in accordance with the approach, resulting in a flexible, modular DH solution that is based on CHPs.

1.2 Overview of Demand-Side Management in DH

About three-quarters of the heat supply in today's European DH networks comes from CHP facilities. The integration issues of the power and heating industries were addressed by a variety of modelling methodologies, as per a review of the literature [29]. Of course, the demand for thermal energy will never be perfectly synchronised with the demand for electricity [30]. The CHP economic dispatch problem was described as an optimisation problem [31]. The minimum and maximum limits of electricity and heat generation at CHP units must be considered as part of the practical challenge of economic scheduling, which makes the pursuit of optimal scheduling difficult [32]. The optimal economic dispatch for various types of CHP units was analysed in [33].

Additionally, some studies have been conducted to address the DH operating issue together with the optimal dispatch for the power system [34-36]. Minimising operation costs and maximising profits are the usual goals of economic dispatch of CHP units [37]. The main problem of CHPs is that their operation is highly dependent on the heat load, which makes them rather inflexible and reduces the overall efficiency when the heat load is insufficient [38]. A CHP unit that is flexible due to the coupling of the heat and power energy vectors and provides real-time demand-side management [39] was used as an example to illustrate the significance of demand-side management for the efficiency of heat production. This improved the CHP unit's overall business case in comparison to traditional load-following operations [40]. Decentralised intelligent metering is an important component of sustainable district heating [41]. Decentralised intelligent metering allows for the collection of additional information on consumer behaviour, which provides DH companies with numerous advantages such as the ability to effectively manage the grid, increase production efficiency, optimise thermal energy storage, and quickly identify faults at substations [42]. Some researchers have proposed an analysis of the potential of a return temperature differential regulation strategy for substation control in order to reduce the thermal peak in the DH system [43]. Changes in the schedules of the heating systems installed in the buildings used for virtual storage were investigated in [44]. In [45], the energy consumption planning problem was described for both individual substations and the DH operator. An electricity and heat coordinated retail market framework was presented in [46] to achieve coordinated shedding of electrical and heat loads and to manage the district's energy generation and consumption through transactive control methods. In [47], the focus was on determining the proper use of demand-side management based on network dynamics. The benefits of heat consumption forecasts include the identification of demand response actions and peak power demand [48]. Demand-side management is the cost-effective management of complex DH systems, which must include the rationalisation of all components involved in heat production and distribution [49]. Demand-side management uses demand process data related to production status, heat distribution, and weather forecasts to manage production and heat distribution, as well as tools that allow for the dynamic calculation of control parameters that help achieve maximum efficiency while ensuring adequate heat supply [50]. However, this indirect decarbonisation method cannot be used for a climate-neutral energy system, as it is almost impossible to reduce CO_2 emissions any further [51]. The integration of DH demand-side management will contribute to the achievement of this ambitious goal by reducing total CO_2 emissions from energy supply by several percent.

1.3 Overview of Biomass as an Alternative to Fossil Fuels in DH

The replacement of fossil fuels with biomass is becoming increasingly important in the context of the requirements for decarbonising production and industry. An analysis of the literature indicates that greenhouse gas emissions, primarily from the combustion of fossil fuels, are the primary source of the issue at hand. As previously stated, replacing fossil fuels with renewable energy sources (RES) is essential for decreasing the amount of greenhouse gases in the environment [52]. Biomass, namely woody biomass from land clearing and woodlands, is one such sustainable resource [53]. In Europe, biomass makes up around 90% of sustainable heating [54]. For the most part, DH systems in Europe continue to rely heavily on fossil fuel [54] due to the scarcity of locally available, sustainable, and cost-effective biomass fuels [55]. Many European countries have effective but fossil-fueled systems and therefore face significant hurdles in reaching their projected decarbonisation goals, such as environmentally friendly energy generation in 2030–2050 [56]. A study [57] examined the economic and energy aspects of a biomass CHP unit and found that the optimal configuration varies depending on which aspects are prioritised.

Another study [58] explored biofuels for heating systems and discovered that wood chips can replace some fossil fuels. In a similar study [59], the potential of utilising various biofuels for energy purposes was examined, and experimental results on their usage for thermal energy production and environmental impact were provided. In [60], a new biomass-based fuel was developed that can be used for co-combustion at coal-fired power plants. The paper in [61] investigates the application of biofuels at coal-fired boilers and power plants. The article in [62] describes a system for biomass combustion in a fluidised bed. In [63], the distribution of different biomass types was analysed for different cases.

1.4 Overview of Heat Pump Integration in DH

Active research is being conducted all over the world, especially in Estonia, to analyse the potential of employing low-grade heat in DH. The main sources of low-grade heat are surface water (seawater, rivers, and lakes), waste heat from industries and power plants, and urban waste heat (metro, tunnels, and shopping centres).

HPs are used to transform low-grade heat into higher-temperature heat appropriate for heat supply. Several studies investigated the potential and features of using HPs in the energy sector under various technological and economic scenarios [64]. Some of the studies explored the environmental and market aspects of incorporating HPs into current heating systems [65-67]. Potential solutions for utilising HPs in DH systems are being investigated under various national energy markets [68,69]. The operation of HPs that use the excess heat from hot water boiler flue gases was analysed in [70]. In this study, a heat exchanger was installed in the boiler to cool and condense flue gases. The HP utilised condensation heat. Furthermore, this solution is very cost-effective, with a fairly quick return on investment. The paper [99] analysed how hourly temperature changes from different heat sources affect the seasonal coefficient of performance (SCOP) of HPs when supplying DH. It has been demonstrated that using HPs to utilise waste heat carriers in power supply sources may require significant fuel savings [71]. The study in [72] found that HPs have the maximum energy efficiency and may be used to replace heat sources of virtually any capacity.

According to [73], the performance of HPs in combined DH is superior to the conventional system, resulting in 50% less energy consumption, 11% less carbon emissions, and better savings. The article examined the use of HP in the Baltic region, noting that, according to the investment support scenario for 2050, up to 68% of heat in the Baltic countries will be produced by HPs [74].

There is a great deal of interest in the potential of utilising low-temperature energy resources with HPs and CHPs because there is a lot of unused low-grade heat at the CHPs. Efficient use of waste heat from power plants is crucial for energy savings and emission reduction [75]. The paper in [76] addressed various modes for utilising HPs at CHPs. It was demonstrated that the use of HPs is both thermodynamically, technically, and economically beneficial. The article in [77] examined the operating principles, theoretical foundations, construction, and application examples of HPs coupled with CHPs.

Compared to other methods [78, 79], that are widely utilised in many countries to utilise low-grade heat and boost the efficiency of heat-generating energy sources [80, 81] installing HPs together with CHPs requires minimal investment. The major source of heat loss for a CHP is the heat rejected by the condenser, which can be up to half of the thermal energy at the turbine inlet, as stated in [82], while other papers describe values ranging from one-third [83] to half of fuel input depending on the technology used for power generation. The energy balance for a unit of 200 MW (as regarded in this work) was created in [84]. This unit rejected about 300 MW_{th} through the condenser cooling water, accounting for half of the total heat input. This is a lot of heat, so heat recovery must be considered. For example, the Clean Water Act requires the regulation of water thermal discharge from cooling water systems in order to protect aquatic wildlife [85]. Therefore, the cooling of the discharged water must be taken into account. Given the importance of the condenser, cooling it is vital, so heat rejection is unavoidable; nevertheless, recovering heat from the cooling water can turn the heat loss into something useful. Based on the information presented above, it can be concluded that any heat recovery solution that uses condenser cooling water must also cool wastewater discharge to the environment.

The study's findings [86] demonstrate that using an absorption HP to recover waste heat from steam turbine exhaust steam in a combined cycle power plant can significantly improve system performance [87]. DH summer operating mode, when the efficiency of combined CHP generation decreases and favourable conditions for HPs appear, is of particular importance in the development of hot water load replacement schemes. Today, Estonia aims to become a carbon-neutral country by 2050, and DH will play an important role in achieving this goal. The integration of carbon-neutral HPs by 2050 will help reduce the total CO_2 emissions from energy supply by several percent. In addition to utilising low-grade heat, it is critical to consider the use of alternative non-fuel natural sources, such as heat generation from solar collectors [88].

1.5 Overview of Solar Thermal Systems in DH

Solar energy is one of the most widespread renewable sources. It is well known that even a modest amount of solar energy can significantly reduce the use of fossil fuels. Solar water heating is one of the most popular water heating systems in the world [88]. Large-scale solar thermal systems have become a viable technology in many countries throughout the world [89, 90]. There are few review papers that focus on the use of solar energy in DH systems. In [91], various aspects of solar DH systems were considered. A solar community heating and cooling system with borehole thermal energy storage was reviewed in [92]. A detailed review of large-scale hot water tank and pit thermal energy storage systems in terms of solar DH application was conducted in [93].

An exergy analysis of the characteristics of biomass and solar energy in DH was conducted in [94]. According to [95], most approaches related to using solar collectors for RES integration are built around minimising investments. Solar thermal collectors (STCs) can reduce CO_2 emissions, although they often raise system investments [96].

In 2019, the largest solar district heating plant in Eastern Europe was built in Salaspils, Latvia. The annual productivity of the local heat producer Salaspils Siltums' 1,720 STC panels is 12 GWh. The solar panels have an area of 21,595 m^2. An accumulation tank with a capacity of 8,000 m^3 was installed for heat storage [97]. Together with the utilised boilers, solar collectors form an integrated system. The total DH thermal capacity is approximately 35 MW, while 60 GWh of heat are produced every year. It is estimated that the local DH system will receive 61% of the heat produced by burning wood chips, 20% of the heat provided by solar heating, 10% of the heat returned by the flue gas scrubber, and 9% of the heat produced by natural gas [98].

Thus, incorporating STC into DH networks is cost-effective since the solution can compete with other heat production technologies [99]. According to the simulations, combining PV panels with a HP has technical, economic, and environmental advantages over installing solar collectors [100].

To achieve substantial emission reductions in the energy sector, significant increases in global investments in renewable energy, an accelerated phase-out of fossil fuels for heat generation, and extensive political support for the direct use of renewable energy are required.

1.6 Overview of a Hybrid DH Solution (Solar Energy and Heat Pumps)

The combination of waste energy from cooling water and solar energy helps reduce the use of traditional energy carriers as well as the emission of dangerous elements into the environment. An HP can improve efficiency and make low-temperature heat sources available, allowing heat from air, groundwater, rivers, or land to be utilised in a heating system that would otherwise be unavailable. HPs are typically used as an efficient way to generate heat and are, in most cases, powered by electricity. High-efficiency HP systems driven by renewable electricity have a negligible environmental impact. Inefficient HP systems that utilise ineffectively generated electricity from fossil fuels cause environmental damage comparable to burning fossil fuels [101]. The greater the temperature of the heat source, the higher the efficiency of the HP system. Therefore, an effective solution for improving efficiency is a combination of heat sources that can generate higher temperatures when used as a single hybrid source. The combination of HP and STC can be implemented in various ways. The study in [102] analysed various alternative systems for heat supply with combinations of STCs, while the study in [103] conducted analytical and experimental studies of solar heat, with STC acting as an evaporator of the HP. The indirect use of solar heat via HPs enables the installation of low-temperature solar systems [104]. The study in [105] demonstrated the great efficiency of the hybrid solution of STC and HPs. The use of renewable energy sources (RES), such as the solar-assisted HP, has been demonstrated to increase efficiency and achieve carbon neutrality [106]. However, there have been few studies on the methodologies and advantages of integrating STC with DH, which is typically supplied by large CHP units with low heat generation costs, as discussed in [107]. Solar heating can be used together with fuels to produce heat, but in some cases, for example, if the base load for the summer is met by waste incineration, industrial waste heat, or heat produced via CHPs - solar heating may not be cost-competitive.

In order to increase energy efficiency, studies on DH reconstruction have developed new methodologies, approaches, and metrics. They have also produced examples of DH reconstruction with all the essential calculation formulas, as well as conclusions and generalisations on the subject. Most of the articles under consideration are theoretical in nature, which provides a basis for the study of the subject. During the review of the articles, the problems of DH reconstruction were identified, along with methods that can significantly improve the industry's energy efficiency.

After examining papers and articles on the methods for reconstructing DH in order to increase energy efficiency, we can conclude that today's energy saving policy is a priority in the development of energy and heat supply systems. When it comes to energy conservation and smart energy use in DH, there are a lot of strategies that can be mentioned along with the primary sources of savings.

2 Background

2.1 Estonian Energy Sector Overview

The European Green Deal aims to achieve climate neutrality by 2050. Climate neutrality targets have been established for all EU member states, including Estonia. As a member of the European Union (EU), Estonia intends to increase the share of renewable energy production and consumption, as well as reduce environmental pollution and greenhouse gas emissions. The EU's targets stimulate support for renewable energy. At the moment, the issues of reducing primary energy consumption and CO_2 emissions, incorporating renewable energy sources, and energy savings are primary concerns for the development of Estonia's energy sector.

The following are the fundamental goals of EU energy and climate policy [108]:

- 2030: 40 % reduction in GHG emissions (Estonia: 70%);
- 2030: 27% of renewable energy (Estonia: 42%).
- 2050: climate-neutral Europe (Estonia: 80% reduction since 1990);

The energy sector in Estonia is one of the most carbon-intensive in the EU. According to the EU Climate and Energy Framework, the EU aims to reduce Estonian CO_2 emissions by at least 70% by 2030 (6,500 t/a) compared to 1990. It is planned to cut emissions by 80–90% by 2050 compared to 1990 [125]. A further increase of 85% (3,300 t/y) is predicted by the end of 2029 in order to reach zero emissions by 2050 [109]. The transition from the 2050 target to 100% renewable energy in the EU has been analysed as a series of steps in [110].

The reduction in greenhouse gas (GHG) emissions were 40.4 $MtCO_{2eq}$ in 1990 and 14.0 $MtCO_{2eq}$ in 2019 (incl. 12.3 $MtCO_{2eq}$ from the energy sector). CO_2 emissions in Estonia increased from 9.3 $MtCO_{2eq}$ in 2020 to 14.9 $MtCO_{2eq}$ in 2021. GHG emissions are projected to be 11–12.5 $MtCO_{2eq}$ in 2030 when existing and additional measures in the plan are implemented.

Estonia's target for 2030 is to reduce total GHG emissions by about 70% compared to 1990, which means reducing emissions to 12 million tonnes tCO_{2eq}. According to the Estonian Environmental Research Centre, electricity and heat production will account for up to one-third of the 12 million tCO_{2eq} in 2030. Forecasts of CO_2 emissions from electricity and heat production and the oil shale industry (Figure 2.1):

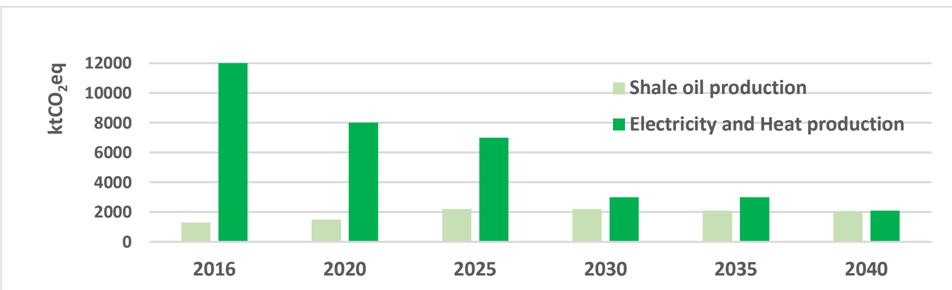

Figure 2.1. Forecasts of CO_2 emissions from electricity and heat production and the oil shale industry [111].

Estonian energy and climate policy goals until 2030:

- increasing the share of renewable energy in total final energy consumption in 2030 to 42%, including 50% of the final energy consumption;
- increasing the share of renewable electricity production from renewable sources in 2030 to 40% of the total final consumption of electricity;
- increasing the share of renewable energy in DH to 63% of the total final consumption of heat;
- increasing the share of renewable sources in the transport sector to 14% of the total final consumption of transportation fuels;
- keeping final energy consumption at the current level (32 TWh/a).

Annual energy consumption in Estonia is approximately 32 TWh, with approximately 5.6 TWh consumed as heat, 7.2 TWh consumed as electricity, 9.2 TWh consumed as transportation fuels, and the remaining 10 TWh consumed as other fuels. Furthermore, the national energy and climate plan in Estonia is valid until 2030, and it states that final energy consumption should remain at the current level of about 32-33 TWh per year.

Making the Estonian energy system carbon neutral is challenging because all aspects of the system electricity and heat generation must be modified. The process of creating the Energy Economy Development Plan until 2035 [113] began in 2022. The development plan focuses on local renewable energy production and increased energy efficiency while ensuring Estonia's energy security. The development plan is expected to be enacted by 2025 at the latest, and it will cover the period until 2035 with a view to 2050. It is based on the goal of achieving energy security in Estonia through climate-neutral energy production.

According to Elering, Estonian transmission system operator, 2,578 GWh of electricity was produced from renewable sources in Estonia in 2021, accounting for 27% of total electricity consumption (Figure 2.2). Biomass and biodegradable waste account for 1,519 GWh, or more than half of the electricity generated by renewable sources. Wind generated a total of 731 GWh of electricity in Estonia in 2021.

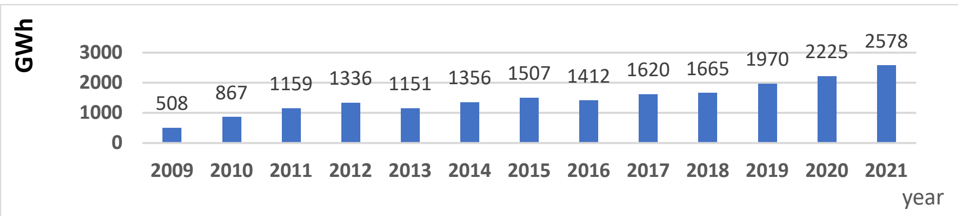

Figure 2.2. Electricity generated using renewable sources in Estonia [112].

According to Elering, the country's power plants generated 2,569 GWh of electricity from renewable energy sources (about 1% less than in 2021). Last year, biomass and waste accounted for 54% of renewable energy production (1,378 GWh). Estonia is a unique country in that it extensively uses oil shale. For many decades, oil shale has been Estonia's primary energy source and mineral resource. The EU is pressuring Estonia to reduce its oil shale use.

The rapid growth of the proportion of solar electricity in recent years has firmly defined the development of the renewable energy sector, which continued in 2021 as well. According to aggregated network operator data, 399 MW of solar power plants were connected to the grid and attained production capacity in Estonia by the end of last year, with 179 MW added to the grid in 2021 (Figure 2.3):

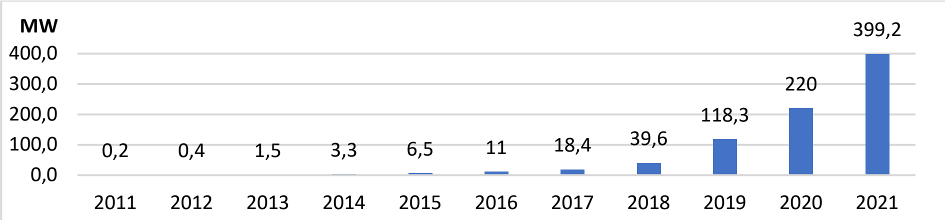

Figure 2.3. Solar power generating facilities connected to the electricity grid in Estonia [114].

According to Elering, 305 GWh of solar power was generated in the electricity grid in 2021 (Figure 2.4).

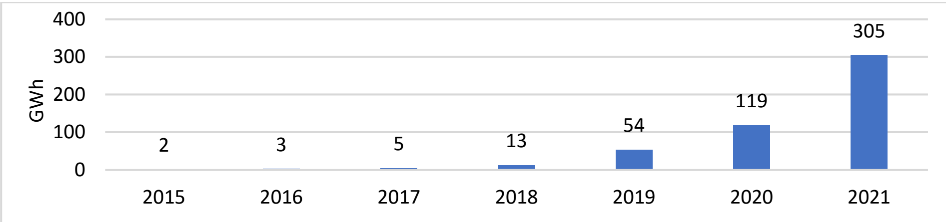

Figure 2.4. Production of solar power supplied to the grid in Estonia [112].

The solar energy capacity is expected to be even greater by the end of 2023, and hopefully this trend will continue in the years ahead.

According to Elering, 1,519 GWh of electricity was generated from biomass, including organic waste, for the Estonian electricity grid last year (Figure 2.5):

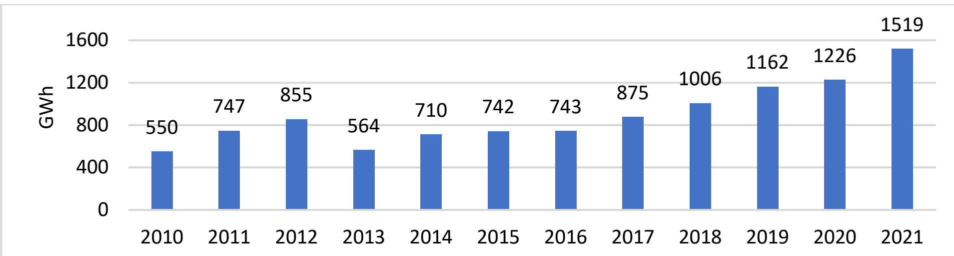

Figure 2.5. Amount of biomass-based power supplied to the grid [112].

Micro-production is gaining traction in Estonia, and according to network operators, their number expanded by leaps and bounds at the start of this decade, reaching nearly 4,500 facilities by the end of 2021 (Figure 2.6):

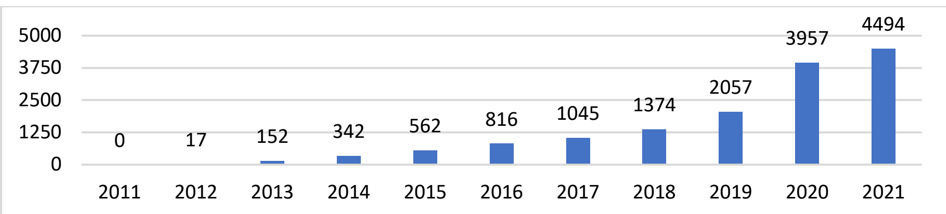

Figure 2.6. Total number of micro-producers in Estonia who have joined the network [114].

According to EREA, as of the end of 2021, 882 MW of renewable electricity-generating facilities had been installed in Estonia. The increase in overall capacity, as in the previous year, is mostly due to the connection of solar power plants to the grid (Figure 2.7).

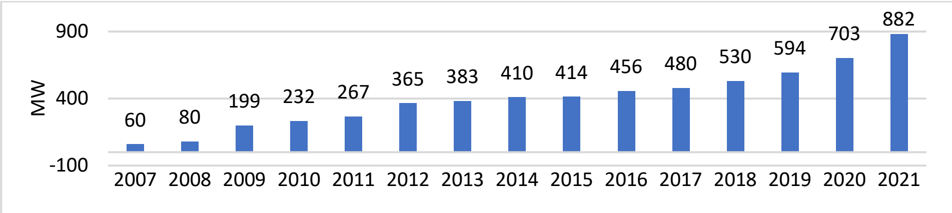

Figure 2.7. Renewable electricity production capacity in Estonia by year [115].

The proportion of renewable energy has been on the rise year after year (Figure 2.7). In 2021, approximately 179 MW of extra renewable electricity production capacity was added to the electricity grid, the lion's share of which came from solar power plants across Estonia (Figure 2.8):

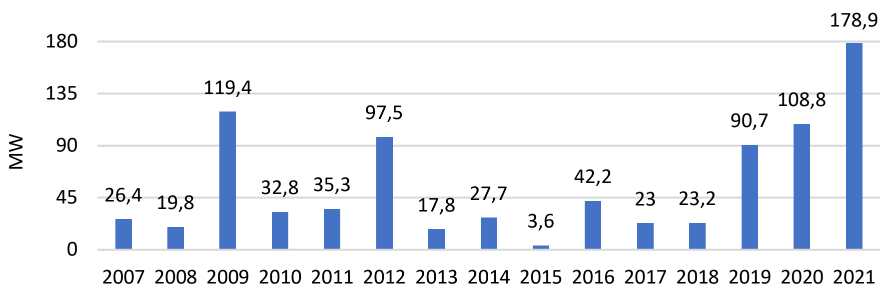

Figure 2.8. Additional renewable electricity production capacity in Estonia by year [115].

In 2017, solar electricity accounted for only 4% of total renewable electricity production capacity in Estonia, but by the end of 2021, solar plants had surpassed wind turbines, accounting for 44% and 36% of total installed capacity, respectively (Figure 2.9):

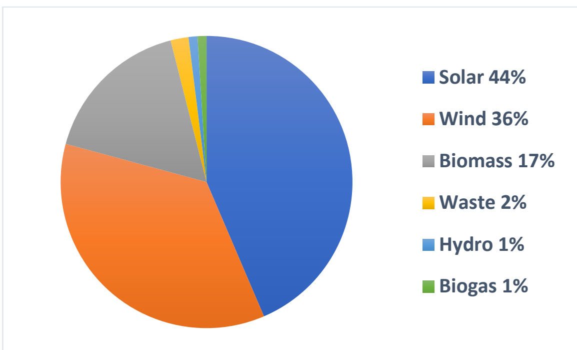

Figure 2.9. Renewable electricity production capacity in Estonia by source [115].

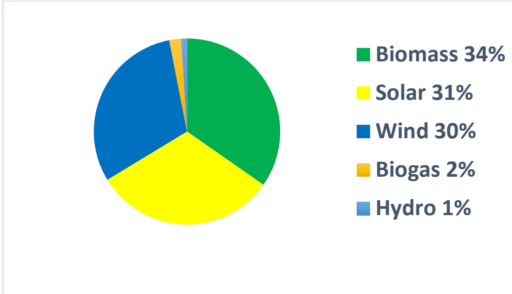

Figure 2.10. Distribution of investments in renewable energy technologies in Estonia [115].

According to EREA, estimates that as of the end of 2021, total investments in renewable electricity production in Estonia exceeded 1.5 billion euros. The overall investment in wind energy, solar parks, and solid biofuel use is nearly evenly divided into three segments in terms of technology (Figure 2.10).

Over the past 10–15 years, Estonia has actively engaged in growing the share of domestic and renewable fuels, which is why the usage of renewable fuels in cogeneration plants has effectively increased over the past ten years, reaching as much as 76% in 2020 as per the latest data (Figure 2.11). Biomass used as fuel is obtained within a reasonable distance of cogeneration plants and has no other use in most cases. Despite growing climate ambitions, a large share of energy in Estonia is still produced from non-renewable local resources such as oil shale and shale oil. In Estonia, the use of shale oil and natural gas has been on the decline since 2010, while the use of biomass for heating has increased, which can be explained by strong government support.

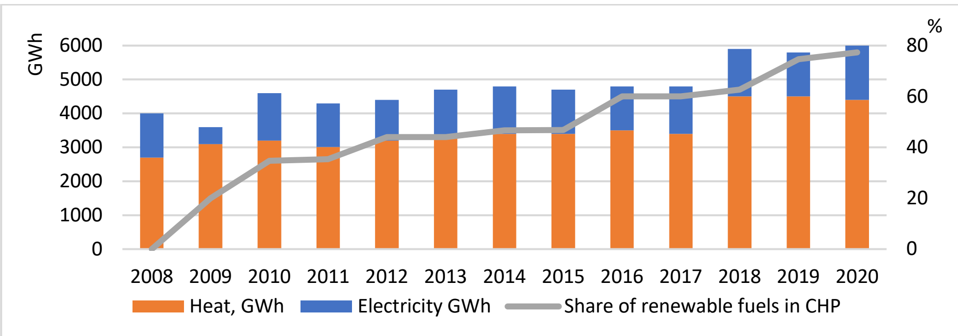

Figure 2.11. Share of renewable fuels used at CHPs [111, 115].

The EU cogeneration objective was also valid for Estonia, which stated that the share of electricity produced in cogeneration facilities should be 20% of gross consumption by 2020. However, the target was missed by only 19.9% (Figure 2.12).

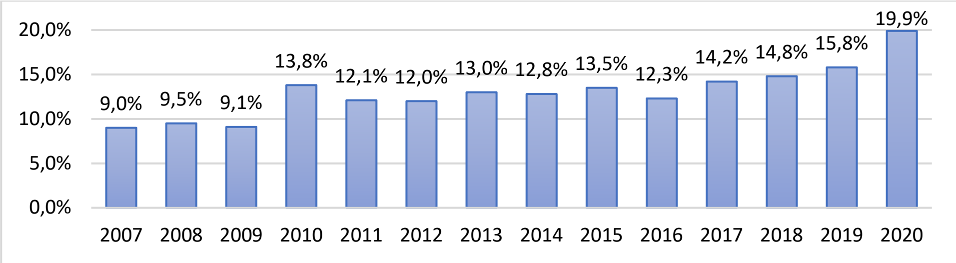

Figure 2.12. Share of cogeneration electricity in Estonia's gross electricity consumption [111, 115].

Estonia is located in a climate zone where heat is required to heat buildings for approximately two-thirds of the year, and heat is consumed more than electricity in Estonia. All in all, heat represented around 39% of Estonia's total final energy consumption in 2020. Transport fuel and electricity accounted for 29% and 22% of total energy final consumption, respectively (Figure 2.13):

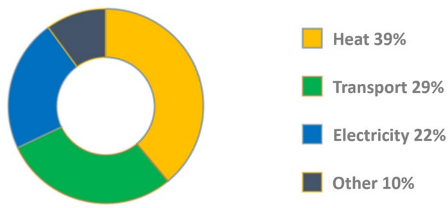

Figure 2.13. Distribution of final energy consumption in Estonia [111, 115].

More and more boiler houses and cogeneration plants are switching to renewable fuels. According to Statistics Estonia, renewable energy accounted for 71% of DH in 2020, a percentage that has increased dramatically over the years (Figure 2.14).

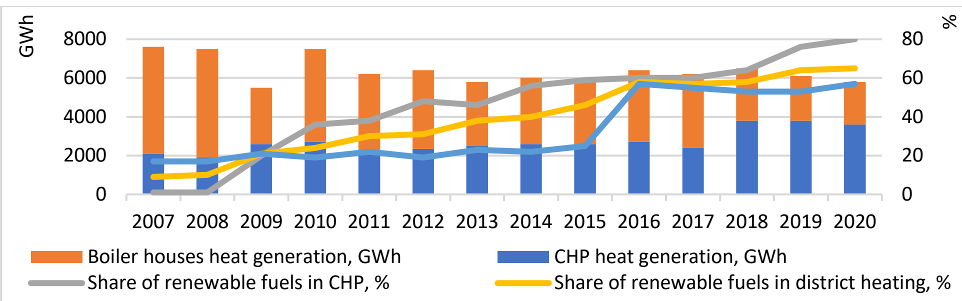

Figure 2.14. Heat produced by CHPs and boiler houses and share of renewable fuels in Estonian district heating [111, 115].

Winters in Estonia are usually very cold and Estonian households need a heating system, and DH is one of the most efficient and effective ways to meet those needs. One of the main EU directives for Estonia is to have near-zero energy buildings by 2050. Government and state-owned buildings are already undergoing transformation. There are currently 17 CHPs operating in different parts of Estonia. CHP units generate around

1,000 GWh of power per year, accounting for 11% of total generation in Estonia. About 56% of heat is produced using local fuels. The overall efficiency of heat production is 82%, which is quite good.

Estonia has a moderate share of renewable electricity, almost 60% of which is produced from biomass. Another RES is geothermal energy, but there are very few potential locations in Estonia for using geothermal energy for DH. Solar energy in Estonia is mainly used for electricity generation [116].

As of 2020, waste heat and renewable energy sources provided 74% of the heat in Estonian DH systems. Fossil fuels accounted for 26%. Wood chips made up 58% of total DH heat production, while natural gas accounted for 20% (Figure 2.15).

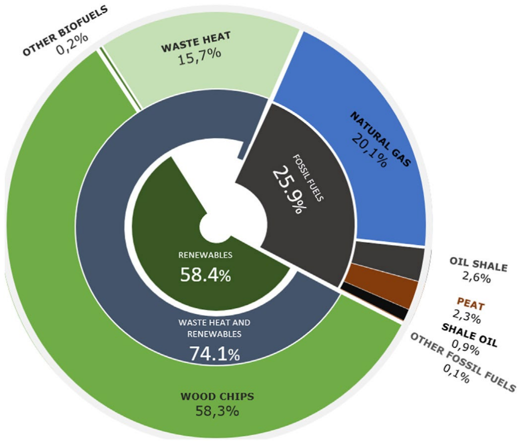

Figure 2.15. DH heat by fuel and energy type [117]

Estonia has a large DH sector, which provides heat to 60% of the residential sector. Biomass is the key source of energy for DH production, accounting for nearly half of total DH generation (Figure 2.15). Natural gas accounts for 25% of overall DH production, while oil shale-related fuels account for 19%. Around half of DH is produced by CHP units, which frequently use biofuels and waste or oil shale. The proportion of CHP-generated heat has increased in recent years.

Estonia is frequently cited as an excellent example of a centrally regulated DH market with a harmonised regulatory framework in which the various stakeholders' roles and responsibilities are clear and functional. The national regulatory authority determines the price of heat for end users in order to cover the costs of the DH company while obtaining a reasonable return (regulatory Wacc), which is calculated according to the methodology publicly available on the Estonian Competition Authority (ECA) website [118]. The District Heating Act (DHA) governs the operations linked to the production, distribution, and sale of heat via DH networks, as well as the connection to such networks in Estonia. Based on DHA, heating companies can apply to the ECA for approval of a price formula for up to three years. This price formula is used when factors beyond its control that affect the price of heat become apparent [119].

The vision for the development of the Estonian heating sector up to 2050 must be based on the goal of ensuring that the heating sector is long-term sustainable and does not require additional investments or operational subsidies for normal economic activity. The vast majority of heat is produced from local and renewable fuels and non-fuel energy sources.

2.2 Available Non-Fuel Sources

2.2.1 Renewable Energy Potential

Renewable energy sources such as biomass, solar energy, geothermal energy, waste heat (heat recovered from sewage water, seawater, rivers, lakes, data centres, and electrolyser stacks), and surplus heat sources (industrial excess heat) are the most promising energy sources for carbon neutral heating when combined with suitable heating technologies.

Heat producers in Estonia are increasingly striving to increase the use of RES while reducing the use of fossil fuels (oil shale or shale oil). The main areas of development for energy efficiency in heat supply in Estonia are building sector renewal, pipe maintenance, replacement of fuel boilers with biomass boilers, and installation of CHP units where possible. CHPs use waste heat from electricity generation and are fuel-efficient.

District heating systems must comply with the requirements for efficient heat and power cogeneration, the principles for calculating primary energy savings, and the reference values for separate generation of electricity and thermal energy for determining efficient cogeneration based on European Parliament Directive 2012/27/EU. One of the primary infrastructures enabling decarbonisation is district heating. This ensures the efficient use of renewable energy sources such as biomass, geothermal energy, or solar energy, as well as the use of various forms of surplus heat and low-grade heat. To meet its climate and energy targets, the EU must dramatically reduce demand and replace fossil fuels with renewable, waste (excess), and low-grade heat.

Estonia's renewable energy potential is mostly manifested in bioenergy-based cogeneration of electricity, heat, and wind energy. Small-scale hydropower is also being developed, and the use of solar panels is becoming more widespread. Despite its numerous rivers, Estonia is a rather flat country with little hydropower potential. Figure 2.16 depicts renewable energy generation in Estonia by fuel type in 2021.

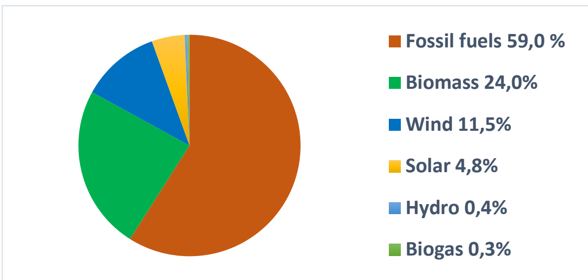

Figure 2.16. Percentage distribution of electricity generation in Estonia by fuel type in 2021.

2.2.2 Solar Energy Potential

Solar energy is an almost inexhaustible and environmentally friendly source of energy. Due to the restricted availability of solar energy in colder climates, reliable district heating is essential [120]. Estonia is a country in the northeast of Europe, on the Baltic Sea's eastern shore.

Sunshine duration deviates substantially from latitude for the region of Narva. This is because the region is characterised by Atlantic air mass cyclones. The average duration of sunshine per year is 35–40%, with 110–125 days without sun, primarily during the colder seasons. The annual number of sunshine hours fluctuates between 1,600 and 1,900. In Narva, the approximate yearly solar radiation of the annual direct solar radiation on a horizontal surface with a clear sky is 4,000 MJ/m^2. However, Narva is distinguished by high cloudiness, which reduces the value to 3,100–3,300 MJ/m^2. Narva produces 160–220 kWh/m^2 of electricity when using photovoltaic converters and 680–1,070 kWh/m^2 of heat when utilising a thermal collector according (Figure 2.17):

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0 - 1												
1 - 2												
2 - 3												
3 - 4						1						
4 - 5					6	15	10					
5 - 6				4	33	40	34	12				
6 - 7			0	53	103	111	92	61	18			
7 - 8			65	170	233	233	209	167	109	19		
8 - 9		26	219	312	370	362	341	297	222	98	4	
9 - 10	18	112	349	444	485	473	457	413	327	188	53	5
10 - 11	69	172	445	532	561	544	529	482	384	254	86	32
11 - 12	95	200	473	576	596	576	561	511	391	242	88	48
12 - 13	92	200	479	572	581	560	542	498	390	242	87	48
13 - 14	75	188	453	542	550	532	511	471	364	231	72	27
14 - 15	38	155	391	465	480	469	452	404	299	172	34	8
15 - 16	2	104	275	353	374	378	366	317	207	79	2	
16 - 17		18	154	218	259	273	264	209	113	9		
17 - 18		0	31	94	133	152	152	106	32			
18 - 19			0	18	46	60	59	31	2			
19 - 20				0	17	30	26	5				
20 - 21					1	8	5					
21 - 22												
22 - 23												
23 - 24												
Sum	389	1,176	3,334	4,354	4,829	4,817	4,611	3,984	2,857	1,533	425	168

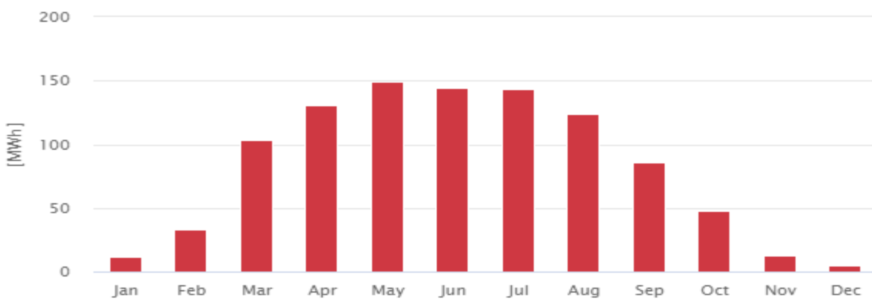

Figure 2.17. Global horizontal irradiation in Narva [121]: (a) average hourly profiles, (b) total photovoltaic power output.

Solar energy is growing in popularity, as evidenced by an increase in its share of overall electricity output. The costs associated with the implementation of solar energy have recently decreased, and the development of solar panel technology for power generation has reduced the price of panels while boosting their efficiency. The largest solar park in Estonia has a capacity of 4.5 MW; the average capacity of a solar power plant is around 40 kW; by year 2022, the total production capacity connected to distribution networks installed in Estonia was around 474 MW, featuring 13,113 installations. Solar panel installation has been more popular than anticipated in recent years, as the process has become relatively easy and quick. Most existing solar units have a capacity of less than 50 kW, and the installation's primary purpose is to minimise the amount of electricity consumed from the grid.

2.2.3 Geothermal Energy Potential

Geothermal energy is the combination of solar energy stored in the ground and energy stored deep beneath the Earth's crust. Low-temperature geothermal energy, which is widely used in Estonia, is extracted by a HP at a depth of one to two metres. In Estonia, the potential for medium- and high-temperature geothermal energy contained in the

Earth's crust at depths over 500 metres has not been explored. Geothermal energy well fields (< 500 m) in Narva and groundwater geothermal energy in the Narva region also promise potential domestic energy sources for geothermal HPs, although technical feasibility is yet to be determined [122].

The EU and the Estonian government's goal is to achieve climate neutrality by 2050, which necessitates new measures in all areas of energy production technologies that promote renewable energy and environmental goals, including geothermal energy. Geothermal energy is a rapidly emerging and understudied field in Estonia.

The main conclusion is that it is not possible to use a higher-temperature resource from groundwater in bedrock layers because water temperatures do not exceed 15 degrees [123]. Water, on the other hand, is perfectly suited for the use of HPs, and recent research suggests that they could be used in far deeper projects where there is no water at all. Geothermal energy from ultra-hot rocks, as well as other techniques of generating electricity and heat utilising deep wells, would allow for significantly greater energy extraction than lower (up to 2 km) wells. These technologies are already being tested in neighbouring and faraway countries, but no clear success stories have emerged so far. Thus, it seems more reasonable for Estonia to focus on medium-depth thermal wells, which, like deep projects, are still in their early stages but have substantially lower risks and capital requirements. At the moment, geothermal heat in Estonia is separated by rustic ground-source HPs. The next step will feature wells of medium depth with a temperature ranging from 20 to 40°C. This method produces more energy, which is perfect for larger communities and can already be used in industry. Based on the available data, it is likely that Northern Estonia has the same or even better geothermal conditions deep in the Earth's crust than its northern neighbours. In other words, heat modelling and calculations carried out in southern Finland should be a great fit for importing geothermal projects to northern Estonia. In Estonia, the issue is inaccuracy in heat flow and thermal conductivity studies, which do not provide a complete picture for the selection of test wells. The identification of areas with increased heat flow is a prerequisite for the initial search for geothermal resources worthy of use through specific technical approaches. In addition, an unexplored dependence of the temperature field of bedrocks in Estonia is the mass of granitic rocks and higher temperatures caused by their radioactivity. The geology of Estonian bedrock, particularly in the north, is comparable to that of southern Finland. The basic structure of Estonia is only known from a few scattered boreholes and regional geophysical surveys. As a result, geothermal and structural properties are not well understood. Given Estonia's geological conditions, where sedimentary rock thickness is 100–200 m in the north and 700–800 m in the south, initiating research and projects in Northern Estonia utilising existing geothermal technology would be the most cost-effective option. Groundwater is the primary source of drinking water in Estonia, and maintaining its quality is critical. Therefore, factors affecting groundwater must be considered in any initiatives related to the Earth's crust that also involve the extraction of geothermal heat. Based on the technologies described, we can say that Estonia has excellent conditions for preventing groundwater pollution. The boundary of the lower aquifers ends at an appropriate depth so that heat can be extracted both with and without fissures without compromising the pressure or water quality of the aquifers. Of course, in the case of wells, a sturdy and high-quality casing pipe that prevents water flow is required. When it comes to groundwater, keep in mind that the currents surrounding the upper part of the thermal well have no effect on its thermal performance. Medium-depth thermal wells are now the most promising alternative for geothermal heat recovery in Estonia, according to the technologies studied. Geothermal power generation, like heat generation, should be considered in the future; however, in order to assess the usage of this technology, deep wells must first be drilled.

2.3 Waste Heat Potential

Waste heat and cold are defined as unavoidable heat or cold generated as a product in industrial or power generation installations or in the tertiary sector, which would be dissipated unused in air or water without access to a district heating or cooling system, where a cogeneration process has been used or will be used, or where cogeneration is not feasible by the European Parliament Directive 2018/2001.

The Renewable Energy Directive definition emphasises usability as district heating or district cooling. The utilisation of heat generated as a byproduct of industrial installations within the facility is deemed energy efficient and does not fall under the category of waste heat recovery. This overview does not analyse energy efficiency, although it can be difficult to draw a line between energy efficiency potential and waste heat utilisation potential. All fuels used to generate electricity via industrial installations are eventually converted into heat, which is subsequently transported or discharged into the environment along with cooling water, flue gases, exhaust ventilation, wastewater, or mechanical cooling. Even though the same method is used to obtain the heat generated as a byproduct of a process, the energy that can be characterised as waste heat may differ in various settings and depending on the installation. There may be differences between the more energy-efficient design and construction of new installations and the heat recovery systems retrofitted in older installations. Classification practices may also differ across EU member states. Unclear and inconsistent waste heat definitions make collecting waste heat statistics difficult.

The comprehensive assessment in accordance with Article 14 of the EED 2012/27/EU includes an overview of the potential for utilising waste heat. There are no easy and quick solutions for the integration of waste heat sources in DH, yet today's fundamental decisions and long-term meaningful work yield results. The solutions must be comprehensive, particularly in terms of support measures, such as encouraging the development of infrastructure suited for receiving low-temperature heat in addition to acceptable transmission infrastructure. Waste heat integration in the DH system can be classified as direct or indirect. It depends on the waste heat temperature and the operating temperature of the DH network. Direct waste heat can be used without increasing the temperature via a heat exchanger, but when the heat source temperature is too low to use in DH systems, the temperature must be raised and the heat source integrated indirectly.

Waste heat from businesses has already been introduced or can be used in Estonia, where its parameters are suitable for transfer to the electricity supply network (directly via a heat exchanger or HP), uniform and year-round availability is guaranteed, and the business is located close to the district heating network. The collection and beneficial use of waste heat requires time, labour, and money, but it still has potential. Unfortunately, in order to use waste heat in district heating, it is frequently insufficient or technically impossible to transmit it to the district heating network, and this may not be economically viable due to the high cost of investment and the network's distance. This strengthens the case for utilising waste heat internally.

Wastewater treatment plants, data centres, flue gas condensation, and the construction of low-temperature DH areas will have the best low-temperature waste heat potential if they can be fed from existing DH networks backflow lines. The development of low-temperature heat sources and networks in residential structures appears to be more promising. There are both final and transitional solutions for this.

The increased use of waste heat in district heating systems requires the availability of suitable infrastructure, i.e. a low-temperature district heating network. Redevelopment of existing district heating systems is a time-consuming but potentially beneficial process for society, which is why a separate, more detailed analysis of how to lower the temperature of the network in existing infrastructure, connect consumers to the return pipeline, and build a low-temperature network in new development areas on the basis of existing pipelines is necessary.

Unused or small amounts of low-temperature (below 100°C) waste heat were utilised mostly in industrial enterprises, service sector enterprises, and residential construction. They prevail in heat recovery to heat the ventilation air that is sucked into the building, wastewater heat reuse, and domestic water heating. The use of particular low-temperature waste heat with high potential was modelled in this paper, and the ensuing energy savings, cost-effectiveness, and influence on CO_2 emissions and RES were assessed. A competent authority with limited powers to adopt additional measures could be considered as a minimum set of initiatives to increase the share of renewable energy/waste heat by at least one percentage point per year. That competent authority could also define and publish non-discriminatory and transparent standards for connecting waste heat sources to the DH network, as described in the preceding paragraph.

2.3.1 Waste Heat Potential of Wastewater Treatment Plants

Wastewater treatment plants are another source of low-grade heat. The temperature and flow rate are the most crucial factors for using waste heat from treated wastewater. The waste heat potential of wastewater treatment plants is mostly comprised of the amount of cold and hot water consumed. During the winter, cold water enters buildings at 5–10°C, heats up in pipelines, combines with hot water, and exits at 20–30°C. As a result, sewer drains take away a considerable amount of heat that can be used. In the winter, when it is the coldest, the design temperature of wastewater entering the treatment facility is 10°C. There are several heat recovery schemes. The most basic approach is to use a low-grade coolant directly in the heat exchangers of the first stage of hot water heating. This type of scheme does not necessitate significant expenses, but a low temperature difference of no more than 20°C does not allow for complete resolution of heat supply problems in the DH system and necessitates additional funds to heat the flow to the required temperature. To improve the useful temperature difference in the heat recovery system utilising HP, an HP operating on a low-boiling refrigerant is used. This technique requires additional capital investments, but it allows for coolant temperatures of up to 75°C in heating systems. The low-grade heat treatment facilities at Narva wastewater treatment plant according (Figure 2.18):

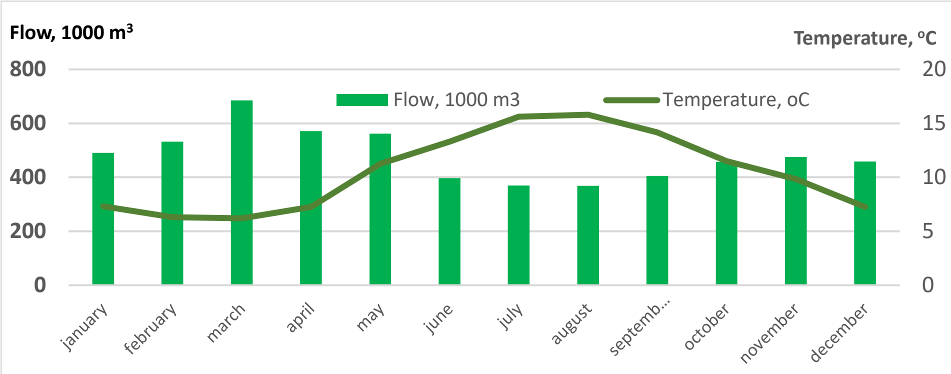

Figure 2.18. Average monthly flow and temperature of low-grade heat treatment facilities at Narva wastewater treatment plant.

It is possible to produce only about 5% of the required heat for the considered DH system using waste heat from wastewater.

2.3.2 CHP Waste Heat Potential

Waste heat is generated at any CHP, with the steam turbine condenser being the main source of low-grade waste heat, with up to 2/3 of the heat obtained in the steam boiler lost during exhaust steam condensation. As is well known, one technique to improve the efficiency of the CHP cycle is to minimise the final steam parameters; hence, in modern CHPs, the temperature of the steam in the condenser is kept between 20 and 35°C. Such a temperature cannot be effectively used for any purpose. As a result, it is proposed to increase its potential via HP to the point where this heat can be used productively, thereby boosting the thermal efficiency of the CHP cycle. HP's ability to significantly contribute to energy savings by boosting the potential of a vast amount of underused low-grade heat (air, water, and soil) is an essential attribute. HP enables the utilisation of novel energy sources, such as waste heat from wastewater, that were previously inaccessible due to their low potential. The fuel exergy is turned into the exergy of combustion products at the CHP unit and in boiler houses, which is utilised to create electricity and transported to other energy carriers (water and steam). Traditional heat supply systems consume new amounts of primary energy (fuel) to generate new amounts of exergy. In HP, a large part (3/4) of exergy is obtained from low-potential heat while only a small fraction (1/4) of the main exergy is expended. As developed countries experience shows, an effective way to use HP is in energy savings associated with the utilisation of low-temperature waste heat (5–30°C), particularly the cooling water from CHP technological cycles, in order to reduce harmful emissions into the atmosphere while obtaining heat with higher parameters. The following are the advantages of using HP in DH: the availability of a large number of low-grade heat sources, which saves nonrenewable energy resources (solid and liquid fuels), and the protection of the environment by reducing harmful emissions into the atmosphere, such as CO, CO_2, SO_x, NO_x, and oil shale ash.

At the moment, Balti Power Plant (BPP) alone discharges into the environment approximately 180 million m^3 of industrial water per year, with an average temperature of about 18°C (with an initial temperature of about 9°C), resulting in approximately 1,600 GWh of heat per year, which is equivalent to approximately 2,000 GWh of primary energy from the initial fuel consumption per year. There is a technical possibility of recycling about 10% of low-grade heat (about 1/4 of the total amount of heat released). Example of fluctuations of waste heat production at Narva CHP unit (Figure 2.19):

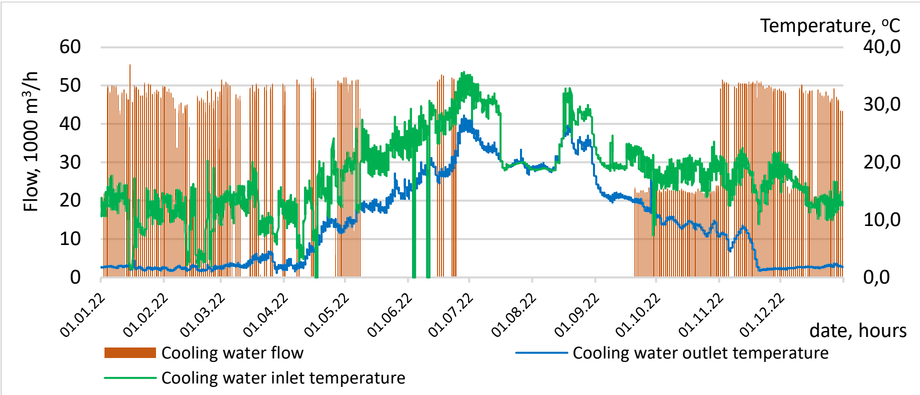

Figure 2.19. Waste heat potential of cooling water at Narva CHP unit.

2.4 Overview of the DH system in Narva

The DH system in Narva (North-East Estonia) is based on a CHP unit at the BPP, which has a maximum heat capacity of 160 MW and an electrical capacity upto 215 MW (depending on the heat capacity). The DH company supplies heat to about 60,000 residents. The annual heat production is approximately 450 GWh. Narva's DH network (Figure 2.20) is 80 km long, connects over 730 buildings, and is located 4 km from the heat source (CHP).

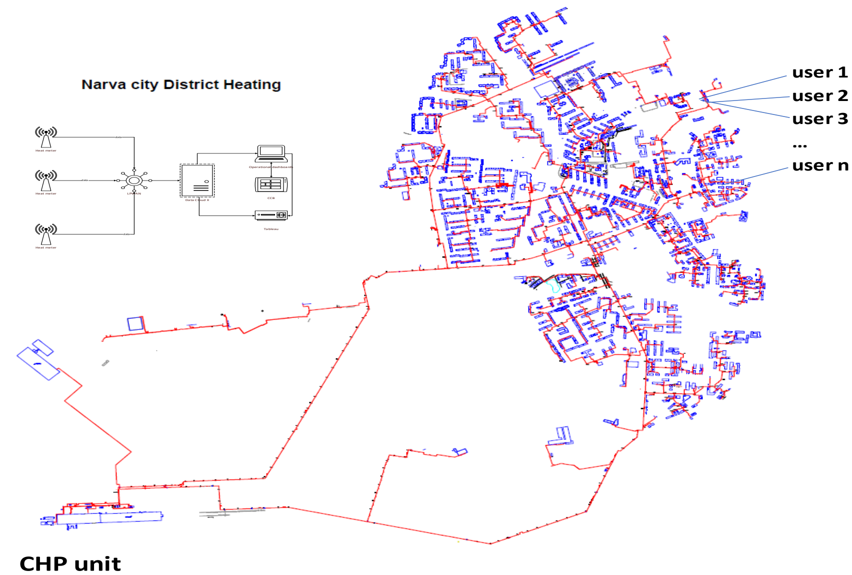

Figure 2.20. Diagram of Narva DH network.

Narva's DH follows a 120/70°C temperature schedule. The actual temperatures at the DH network's inlet and outlet are based on the outdoor temperature and the yearly demand profile in 2021 (Figure 2.21):

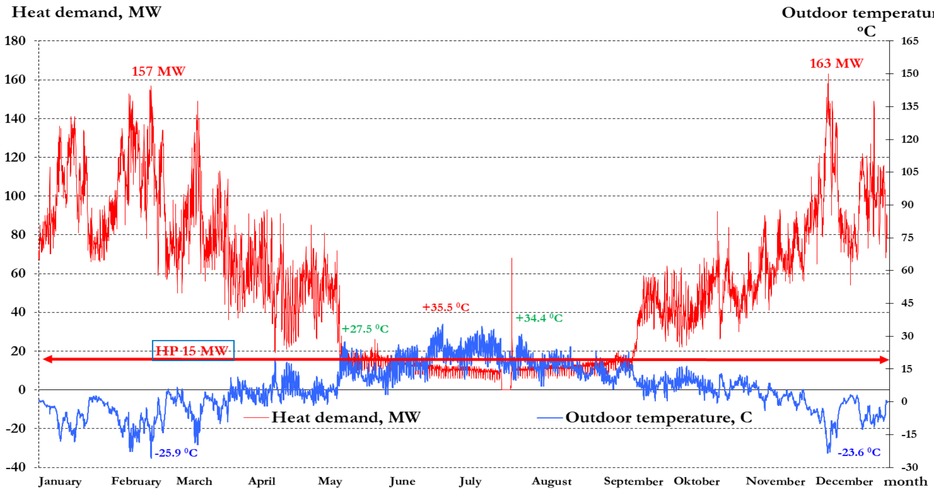

Figure 2.21. Actual heat demand for the Narva DH in 2021.

The heat consumption of the DH network of the city of Narva in 2021 was 404 GWh. In the same year, the thermal output of the BPP was 462 GWh, and the heat loss of the DH network was 58 GWh (12.5%). During the same period, peak loads have averaged 155 MW.

In case of severe cold (above -15°C), the inflow temperature of the DH is 120°C and the flow rate is about 1,900 m^3/h and the return temperature is about 50°C. In the summer period, the inflow temperature of the DH is 70°C and the flow rate is about 400 m^3/h and the return temperature is 40°C (Figure 2.22):

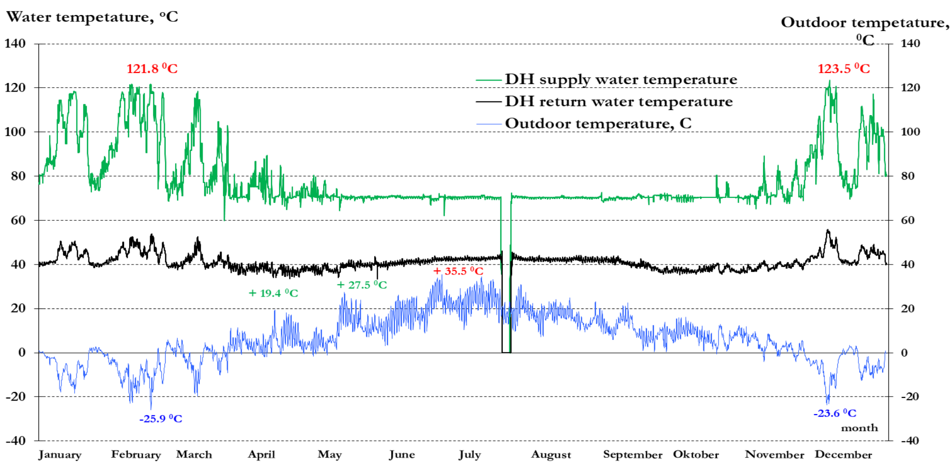

Figure 2.22. Actual supply and return water temperatures for Narva DH in 2021.

The temperature curve of the supply and return network water affects the consumption of network water (Figure 2.23):

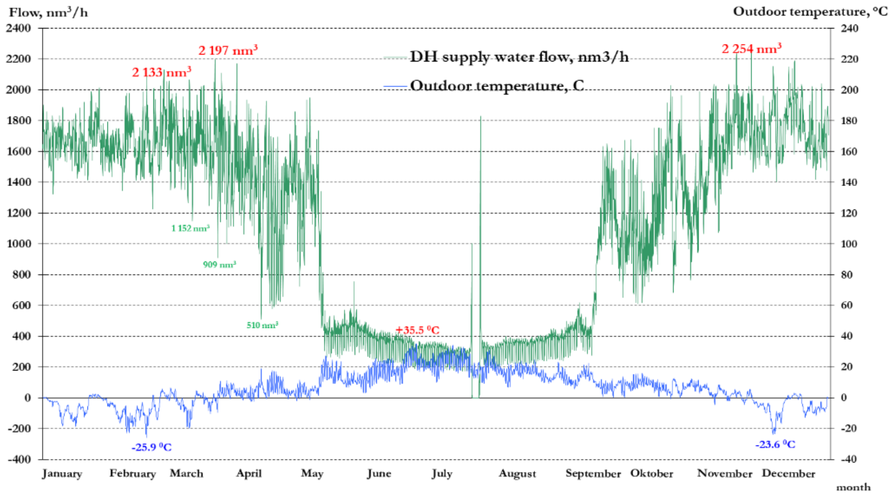

Figure 2.23. Actual supply water flow rate of Narva's DH network in 2021.

This work is based on the situation where building renovation takes place at a slower pace and additional industrial heat consumers may be added. As a result, the work has analyzed the base situation where the heat consumption is at the average level of the last years, the situation where the heat consumption has decreased by 10% and the situation where a 15 MW HP is added to the DH network at the base heat consumption.

In the winter, the network heater receives the most steam after the intermediate pressure turbine cylinder (120 MW_{th}), and the peak load is taken from the hot reheat steam line before the intermediate pressure turbine cylinder (40 MW_{th}) to cover the entire heat load of up to 160 MW, as illustrated in Figure 2.24.

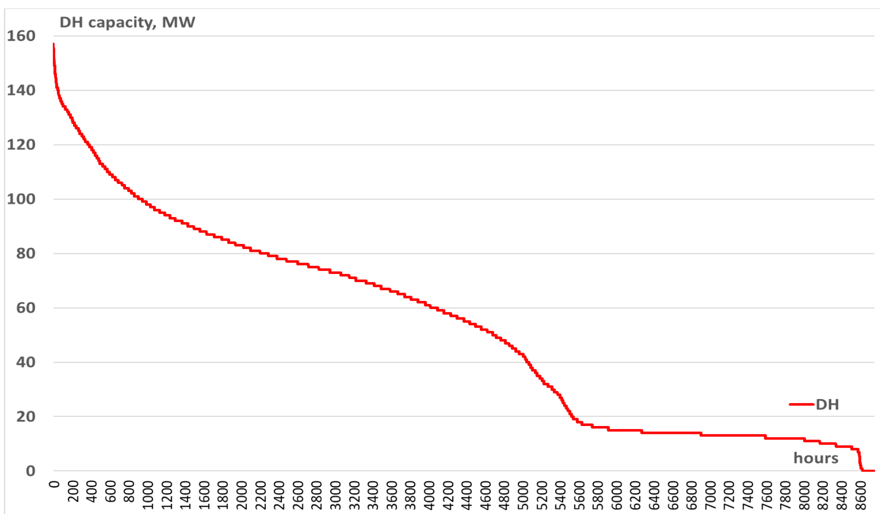

Figure 2.24. Narva DH cumulative demand curve.

Figure 2.25 shows Narva DH heat load based on outdoor temperature:

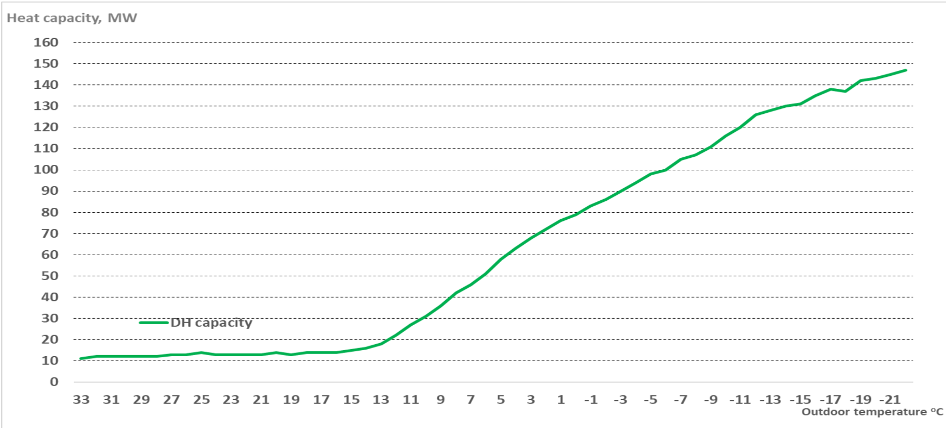

Figure 2.25. Narva DH capacity based on outdoor temperature.

The BPP CHP unit generates heat via two circulating fluidised bed boilers and a steam turbine. The fuel used at the Balti Power Plant is a combination of local fossil fuel oil shale and wood waste biomass (Figure 2.26) [124].

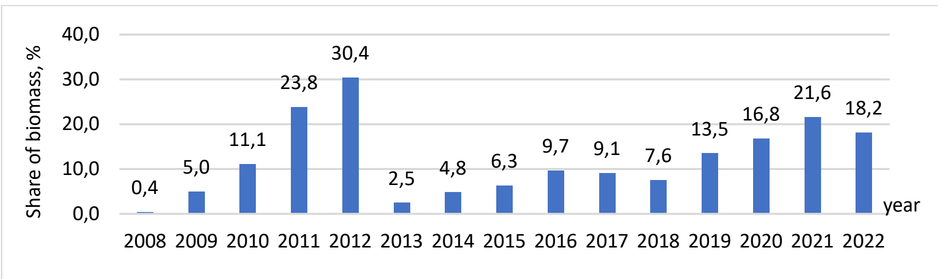

Figure 2.26. Share of biomass at the CHP unit.

The DH circulating water is heated in a base DH heater using steam (120 MW_{th}) between the medium and low-pressure parts of the turbine (Figure 2.28). Extra steam (40 MW_{th}) from the hot reheat steam line is used to cover the peak load. Narva's average annual DH production is approximately 450 GWh, with winter peak demand of about 160 MW_{th} and summer supply around 15 MW_{th}. The CHP unit will cover Narva's full load. The CHP unit consists of a fuel boiler (a 60% oil shale and up to 40% biomass mix) that produces high-pressure steam, a steam turbine, and a set of heat exchangers that recover heat from turbine exhaust steam [125].

The efficiency of a CHP unit is determined not only by the electrical load, but also by the amount of heat supplied. Figure 2.27 depicts the relationship between the electrical efficiency of the CHP unit and the electrical load for various heat loads.

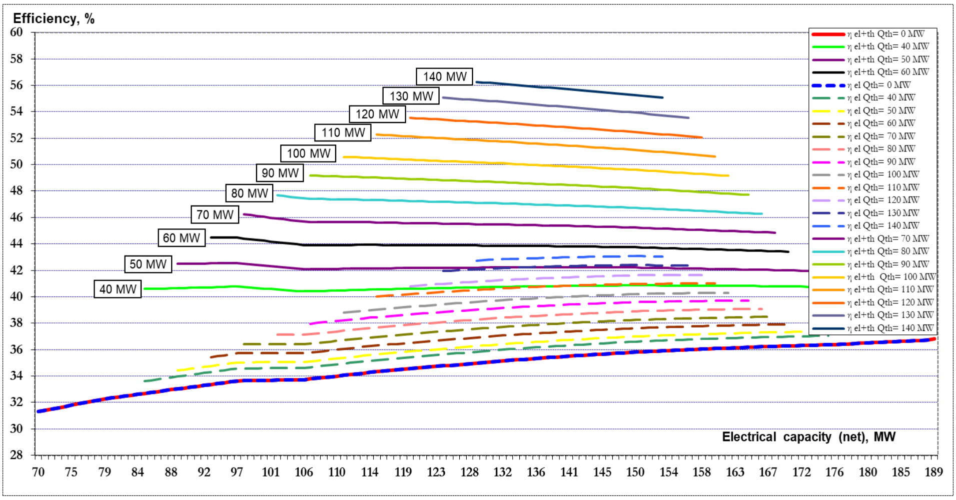

Figure 2.27. Overall efficiency of the CHP unit based on heat load.

Simplified models demonstrated the relationship between fuel input and heating plant output.

Figure 2.28 depicts the analysed CHP steam turbine balance.

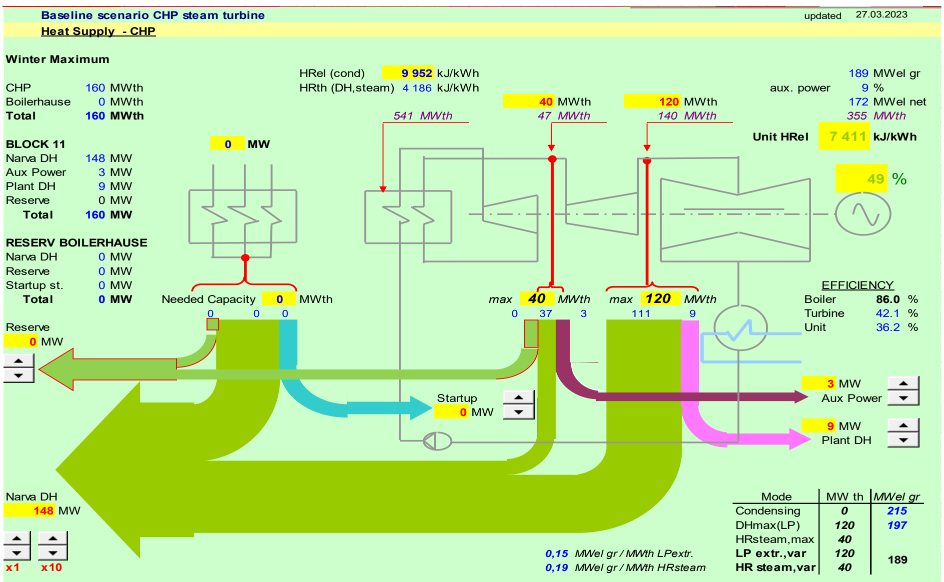

Figure 2.28. Diagram of energy flows of the Narva CHP unit.

In addition to the CHP unit, heat can also be supplied via the boiler house in the event of the unit's failure or during maintenance.

3 Methodologies

The methodologies employed to achieve the objectives of this thesis have been extensively expounded upon in the associated papers and were presented during scientific conferences. Below, we provide concise integrations to the most significant methodologies.

3.1 Identification of Factors Affecting the Improvement of DH Systems

The comparative methodology devised to assess the potential for enhancing district heating systems comprises two primary sections. The first section covers key national-level factors, encompassing geographical and climatic considerations alongside economic and legal factors. Further, calculations were conducted to determine parameters such as the number of consumers, fuel consumption, CO_2 emissions, and the proportion of district heating in the urban energy landscape, among others.

The overarching objective of this analysis was to pinpoint vulnerabilities within these systems and elucidate the reasons why, in certain instances, district heating cannot be regarded as a sustainable or environmentally friendly heating alternative. For a more detailed exploration of each group of factors, please refer to Paper I.

3.2 Optimisation of CHP Operation based on Demand Side Management

In recent years, the approaches employed to address the optimisation of power equipment's operating modes have grown in both intensity and complexity. These changes aren't solely rooted in technical considerations; they also encompass financial and economic aspects that mirror the evolving market requirements.

In Paper II, a methodology for determining energy efficiency was proposed and an optimisation algorithm was developed to solve problems related to choosing the optimal load distribution for the CHP unit under daily and long-term schedules of electrical and thermal loads. This approach ensures effective control of CHP equipment by optimising the distribution of loads.

The overall efficiency of a CHP unit is defined as the sum of electricity production and useful heat output, divided by the amount of fuel consumed in the cogeneration process to generate heat. To calculate the efficiency of various comparison options, a statistical relationship was established between the consumption of standard fuel and electricity generation at the CHP unit for various levels of thermal energy supply.

The overall operating efficiency $\eta_{overall}$ of the CHP unit can be described with equation (3.1):

$$\eta_{overall}(P_i) = \sum_{i=1}^{n} \; (\eta E_i + \eta H_i) \tag{3.1}$$

where*:*

$\eta_{overall}$ – the overall efficiency of the CHP unit, %;

η_{Ei} – the efficiency of electricity production of the CHP unit at hour *i*, %;

η_{Hi} – heat production efficiency of the CHP unit at hour *i*, %;

n – the total number of hours, h.

The efficiency curve of a conventional heating unit can be approximated using a quadratic function, whereas a CHP unit exhibits a convex cost function for both power and heat generation. To simplify the bi-objective economic dispatch problem, we introduce the maximum overall efficiency as follows:

$$\max \eta_{overall} = (\eta E_i(a_i P_i^2 + b_i P_i + c_i) + \eta H_i(d_i P_i^2 + e_i P_i + f_i)) \quad (3.2)$$

The electricity production efficiency per hour at maximum power output is determined as follows:

$$\eta E_i(P_{Ei(max)}) = a_i P_{Ei(max)}^2 + b_i P_{Ei(max)} + c_i \quad (3.3)$$

The heat production efficiency per hour at the required supply is determined as follows:

$$\eta H_i(P_{Hi(demand)}) = d_i P_{Hi(demand)}^2 + e_i P_{Hi(demand)} + f_i \quad (3.4)$$

The operating efficiency, determined using the quadratic equation mentioned above, is obtained by approximating the power in MW. The incremental efficiency is then calculated as follows:

$$\frac{d\eta E_i}{dP_{Ei}} = a_i P_{Ei} + b_i \quad \text{and} \quad \frac{d\eta H_i}{dP_{Hi}} = d_i P_{Hi} + e_i \quad (3.5)$$

By differentiating the function (3.3) or (3.4), a characteristic indicating the relative increase in reference fuel consumption for various comparison alternatives can be derived. This process involves determining electrical loads based on consumption data and inputting data on the current distribution of heat and electrical loads. Using this information, the algorithm calculates the efficiency of heat and electricity generation.

The algorithm identifies the optimal operating mode for the power unit and enables effective load redistribution. If necessary, additional data on the optimised operating mode of the heating network is collected, which is then used to calculate and select the optimal mode for future loads. The implementation of procedures for optimising energy output at CHP units will ensure that CHP employees make educated and appropriate decisions about technical, economic, and organisational elements related to the efficient management of heat and electrical equipment. The algorithm is depicted in the diagram (Figure 3.1):

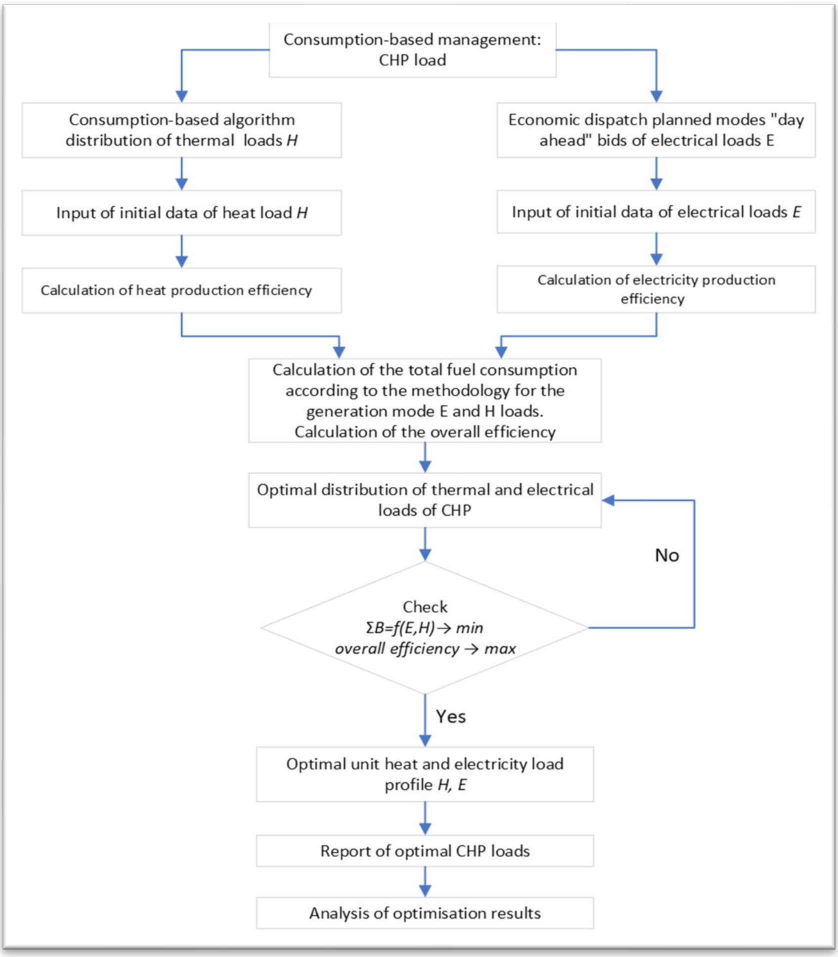

Figure 3.1. Algorithm for Calculating and Choosing the Optimal Operating Mode CHP Equipment.

Information concerning the operational status of the CHP system is inputted into the calculation model. An initial data form is created for the current time, considering the electrical and thermal load graphs, and the fuel consumption at the CHP is computed. If there is sufficient time before transitioning to a new mode of electricity and heat supply, aligned with the thermal and hydraulic parameters of the heating network, we determine the optimal operating mode and efficiently redistribute the load at the CHP. Subsequently, data is gathered pertaining to the optimised operating mode. The calculation and selection of the optimal future loading mode for the CHP are contingent upon modifications in performance by participants in the wholesale electricity market and changes in the temperature regime of heat supply to consumers, as directed by the heating network dispatcher. Simultaneously, a report is generated for the transition to a new mode of electricity and thermal energy generation at the CHP. These considerations are particularly relevant when dealing with systematically evolving schedules for dispatching electricity and heat supply in accordance with the heating network schedule and for planning equipment loading modes for the coming day and longer-term periods.

3.3 Optimal scenario indicators

In Paper III, various configurations of CHP turbines have been compared. To facilitate scenario comparisons, several key indicators have been calculated, including energy efficiency, exergy efficiency, and CO_2 emissions.

3.3.1 Energy Efficiency

The efficiency of power production is calculated using electrical efficiency:

$$\eta_{el} = \frac{N_E}{B_f \cdot Q_{LHV}} \tag{3.6}$$

where

B_f – fuel consumption, t;

Q_{LHV} – lower calorific value of fuel, MWh/t;

N_E – electrical load of turbine, MWh.

The overall efficiency of a CHP unit encompasses both electricity generation and useful heat output. The efficiency of a CHP unit that produces both electricity and heat can be calculated using the following energy efficiency equation:

$$\eta_{CHP} = \frac{N_E + Q_H}{B_f \cdot Q_{LHV}} \tag{3.7}$$

where

Q_H – thermal energy of district heating, MWh.

3.3.2 Exergy Efficiency

Exergy efficiency, which considers different energy types, can be calculated using the previously determined ratio of electric power to heat load as a more objective indicator of the heat supply source's efficiency. It can be expressed as follows:

$$\eta_{ex} = \frac{N_E + L_{DHw}}{B_f \cdot Q_{LHV}} \tag{3.8}$$

where

L_{DHw} – useful work of network water, MWh.

If the value of the exergy efficiency, which is the ratio of thermal work to the energy of the consumed fuel.

3.3.3 CO_2 Emissions

The addition of biomass to the mix allows for maximum CO_2 savings and the potential elimination of all emissions from fossil fuel systems. Carbon dioxide emissions can be calculated using the formula listed below that takes into account the efficiency of the CHP unit η_{CHP} and the carbon dioxide emission factor of the specific CO_2 emission per MWh of oil shale consumption for an oil shale fluidised bed unit k_{CO_2}= 0,36 tCO_2/MW.

The integration of biomass into the mix maximises CO_2 savings and has the potential to eliminate emissions from fossil fuel systems. Carbon dioxide emissions can be calculated using the formula listed below that, which takes into account the efficiency of the CHP unit η_{CHP} and well as the carbon dioxide emission factor of the specific CO_2 emission per MWh of oil shale consumption for an oil shale fluidised bed unit emission factor k_{CO2} = 0,36 t_{CO2}/MW.

$$C_{CO2} = \frac{k_{CO2}(1 - s_{bio})}{\eta_{CHP_i}} \tag{3.9}$$

where

k_{CO2} – specific CO_2 emission factor, t_{CO2}/MWh;

s_{bio} – share of biomass, %;

η_{CHPi} – energy efficiency of the i heat load.

4 Results

4.1 Identification of factors influencing the improvement of district heating systems

Decarbonization of DH systems can play a significant role in elevating the proportion of renewable energy usage and reducing CO_2 emissions in the energy sector. This analysis has identified the weaknesses in district heating and elucidated why it may not be considered a sustainable and environmentally friendly heating option.

Based on these analyses, the following recommendations can be made to improve DH systems in Serbia, including Kragujevac:

- The introduction of CO_2 taxes to incentivize renewable energy use for heat production.
- Revisions to the DH tariff system in Serbia to encourage both consumers and companies to enhance energy efficiency.
- Mandating DH operators to prioritise energy efficiency improvements, which would have a substantial impact on system enhancement.
- Consideration of DH region implementation with the improvement of DH systems to ensure base heat load guarantees for DH operators.

Consistent governmental support, both in terms of regulations and financial aid, will facilitate increased energy generation, distribution, and consumption efficiency within DH systems. Furthermore, exploring the potential for expanded use of geothermal energy for DH is advisable. Based on Paper I analysis, factors affecting DH at the national level are presented in Table 4.1:

Table 4.1 Analysis of factors affecting DH systems.

Factor	**Estonia**	**Impact on DH development.**
Climate factors	Cold climate	In warmer climates, annual heat consumption and peak heat load are lower.
Local fossil fuels	Oil shale, Shale oil	When local fossil fuels are available and at lower prices, it is more difficult to implement renewable sources.
Renewable energy availability	Biomass availability is high	Biomass availability allows to produce heat from renewable energy sources
Legislative and regulatory instruments	Electricity market act: feed-in premium tariffs for biomass CHP	Specific support mechanisms introduced in 2007 over the course of several years led to an increase in renewable electricity in Estonia from 2% to 15% due to the installation of a new biomass CHP.
Emission regulations	CO_2 emission taxes	There are no financial benefits in Serbia to replace fossil fuels with renewable energy.
District heating regulations	District heating act: DH regions	Estonian DH operators have guarantees that there will be heat consumers in the future.
Tariff system	Tariff stimulates improvement	DH tariffs are competitive with other heating options

With these conditions met, DH systems can significantly contribute to increasing the proportion of renewable energy and reducing CO_2 emissions in the energy sector. Figure 4.1 shows a diagram of the system of the CHP DH system in Paper I.

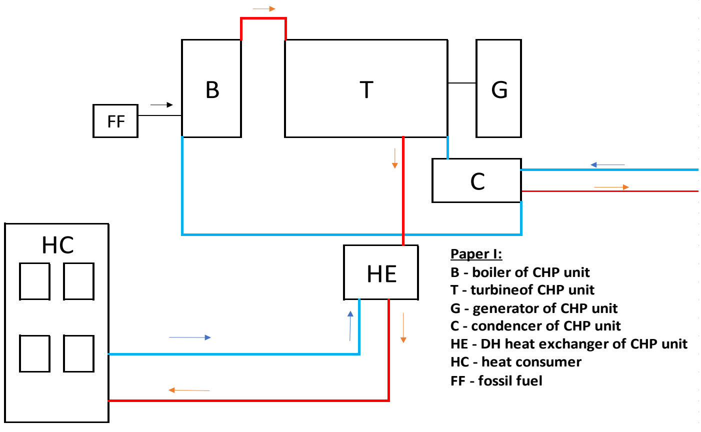

Figure 4.1. Scheme of the CHP heating unit in Paper I.

4.2 Economic Dispatch of CHP Operation based on Demand Side Management

Optimisation of heat and electrical load distribution, where the objective function is the maximum efficiency of the CHP unit for a given load range, can be done considering the limitations of electrical power and the heat load. Economic dispatch makes it possible to determine a reasonable additional increase in the electric power of the CHP unit and to optimise the supply temperature and mass flow of the district heating network. It's important to note that economic dispatch does not address all the challenges faced by CHP units in the wholesale electricity market, such as issues related to forced generation at minimum loads and accounting for the need to activate peak hot water boilers for electrical generation.

According to the analysis of calculation results, primary energy savings during the heating season due to differences in supply efficiency might reach around 10,000 MWh per year with more optimum planning of a portion of the load at the CHP unit. Additionally, fuel savings during the heating season would amount to around 18,000 metric tonnes of CO_2 per year. These results can be instrumental in enhancing the effectiveness of energy-saving measures and optimising CHP system operations.

Simulation of a real CHP unit coupled with a district heating network demonstrates that demand-side management can enhance the overall economic efficiency of the CHP unit and extend its operating range. Consequently, optimising the operating mode of the CHP unit allows for determining the optimal increase in the unit's electrical load at a given consumer heat load, resulting in an average efficiency boost of up to an additional 1.5%. Figure 4.2. shows a diagram of the system of the CHP unit DH system in Paper II.

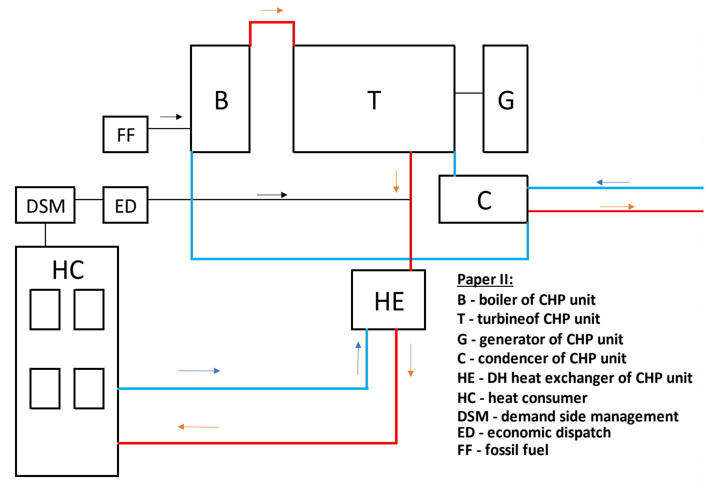

Figure 4.2. Scheme of the CHP heating unit in Paper II.

4.3 Optimal Scenario Indicators

The objective of this analysis is to generate optimal scenarios and parametric solutions for CHP units, as well as to evaluate the feasibility of incorporating various turbine modifications into an existing CHP system. When dealing with CHPs, the task becomes notably intricate due to the substantial impact of increasing heat consumption parameters on electricity generation in alternative scenarios.

As the presented comparative analysis of various sources of heat supply has shown in Paper III, it is more expedient to produce electric and thermal energy at steam turbine CHP units. However, it is essential to acknowledge that such a path for the further development of heat supply may not be considered promising, given that it retains the shortcomings inherent in the existing district heating system. Hence, for the continued advancement of heat supply, it becomes imperative to introduce alternative sources and low-temperature heat technologies.

Under alternative scenario I, the commissioning of new highly efficient combined-cycle energy sources (CHP gas turbines) leads to a significant increase in electricity generation at the expense of reduced heat production. To compensate for the shortfall in thermal energy, the installation of a heating water boiler becomes necessary, which restricts the most efficient approach to electricity generation through heat consumption. Consequently, this scenario is characterised as unbalanced in terms of optimising heat and power production and consumption, resulting in considerable excess fuel consumption.

The proportion of electrical energy in determining exergy efficiency significantly outweighs the heat flow exergy in the overall efficiency calculation. Under alternative scenario II (CHP gas turbine), an exergy efficiency of 42% is achieved, compared to the baseline scenario (CHP steam turbine), with an exergy efficiency of only 33%.

Energy efficiency, which assesses the efficiency of fuel consumption, diminishes as electricity generation increases. This poses challenges in accurately evaluating the quality of the heat supply source. For a more comprehensive assessment of heat supply sources, it is recommended to consider exergy efficiency. Here, the contribution of electrical energy to exergy efficiency far surpasses that of heat flow exergy. Alternative scenario II

(CHP gas turbine) demonstrates the highest exergy efficiency at 42%, while the baseline scenario (CHP steam turbine) lags behind at 33%.

The baseline scenario (CHP extraction steam turbine) boasts an energy efficiency of 78%, while alternative scenario II (CHP gas turbine) achieves a thermal efficiency of 68%. At the same time, alternative scenario I records a thermal efficiency of 76%.

As a result, alternative scenario II (CHP gas turbine) emerges as the primary source of useful energy. It's worth noting that power generation at CHP gas turbines surpasses the thermal energy supplied by the source. In situations where there is low electricity demand but high heat demand, a consideration arises regarding the integration of new combined-cycle energy sources. A comparative analysis is necessary, juxtaposing the baseline scenario (CHP extraction steam turbine) and alternative scenario II (CHP gas turbine) as heat and power sources within the Narva district heating system. Figure 4.3. shows a diagram of the system of the CHP unit DH system in Paper III.

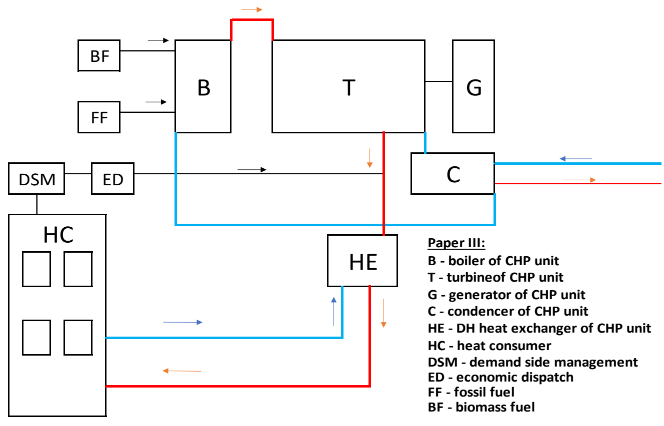

Figure 4.3. Scheme of the CHP heating unit in Paper III.

4.4 Summary of the Results

Enhancing heat transfer efficiency (as discussed in Paper I), optimising fossil cogeneration plant operations through economic dispatch (Paper II) or configuring CHP systems in the most optimal way (Paper III) can contribute to a reduction in CO_2 emissions, albeit to a limited extent. Therefore, it is imperative to consider the incorporation of fuel-free, renewable, and low-grade waste heat sources.

From a technological perspective, the simultaneous production of electricity and heat at CHP units is more efficient than the separate production of electricity at condensing thermal power plants and heat at standalone boiler houses. However, there is a notable loss of heat in this process. The integration of HPs can enhance heat supply conditions and decrease the consumption of primary energy, particularly fossil fuels. The efficiency of HP utilisation depends on the selection of an appropriate source of low-grade heat. Further research looks into the feasibility of employing high-power HPs to heat water circulation condensation cycles, using Narva as an example. The integration of HPs at this facility is advantageous due to the substantial waste heat availability, well-established heating networks, reliable power supply, and skilled workforce. Furthermore, the adoption of HPs will lead to a reduction in heat emissions into the atmosphere.

5 Heat Pump Integration within District Heating System

The research results indicate a modest reduction in CO_2 emissions. It is evident that additional technical solutions must be implemented to achieve a higher level of decarbonisation in DH. Based on literature reviews and background research, there is considerable potential for integrating non-fuel heat sources, such as waste heat and solar heat, which can yield the most significant reduction in CO_2 emissions associated with district heating. This section presents an analysis of the feasibility of integrating waste heat derived from the cooling process water of the CHP as a source of low-grade heat for HPs. Figure 5.1. shows a diagram of the system of the CHP unit DH system with HP Integration:

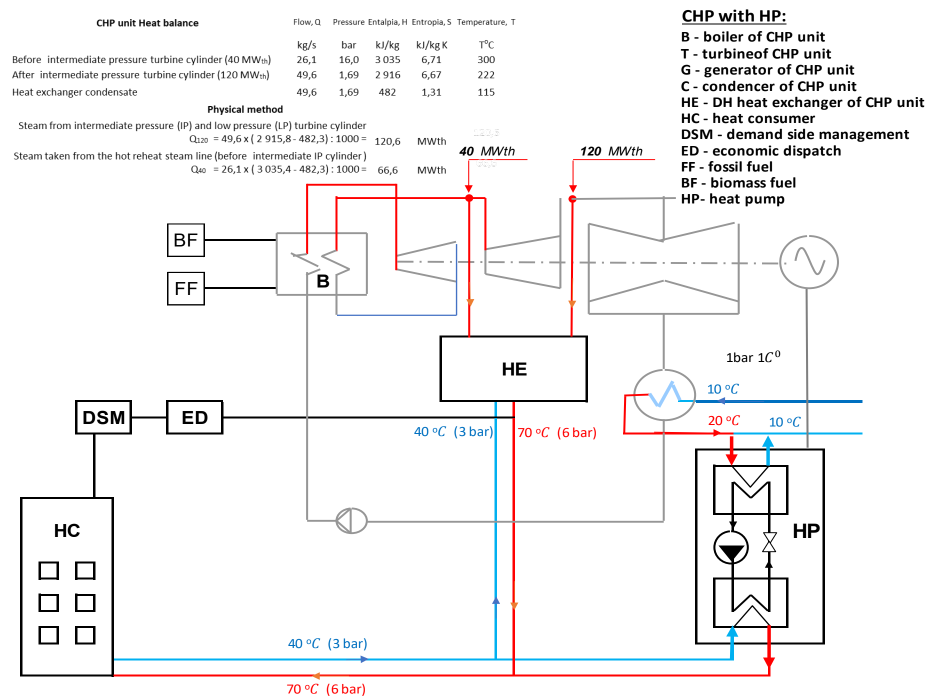

Figure 5.1. Scheme of the CHP heating unit with HP integration.

5.1 Methodology

Such waste heat can be utilised to heat mains water using HPs. The efficiency of the HP cycle process can be described by the Coefficient of Performance (COP). COP represents the ratio of useful heat QHP per electric work EHP consumed. The practically feasible COP depends on the efficiency of the specific HP, the temperature of the heat source and sink, and the temperature difference between the heat source and sink. The energy performance flow is illustrated in the following example (Figure 5.2.) [126]:

Power supply E_{HP} = **0,25** MW → Waste heat (10°C) H = **0,75** MW →	Heat pump (el.driven) **COP = 4**	Received heat **1** MW (75°C)

Figure 5.2. The power consumption and low-temperature heat to delivery 1 MW with COP = 4.

The theoretical COP is calculated as the Carnot COP, which relates mechanical work to temperature differences in power generation, refrigeration, and HP technology. Carnot considers a single refrigeration cycle with one condenser and one evaporator, relating mechanical work to the temperature difference between the condenser and evaporator. In an ideal cycle (without loss of heat and work) in the Carnot cycle, COP efficiency of the HP cycle can be expressed as follows:

$$COP = \frac{Q_{HP}}{E_{HP}} \quad (5.1)$$

where:
Q_{HP} – is the heat supplied by the HP, MW;
E_{HP} – is the energy needed to operate the HP, MW;

The Carnot efficiency C_h (fraction of exergy in the useful heat) describes the maximum theoretical efficiency (ideal process). It depends on the temperature difference between source and sink. Heat is isothermally supplied at a temperature T_{source} and isothermally removed at a temperature T_{sink} or mean temperature of the source and sink heat exchangers. Temperatures should be inserted as an absolute temperature, e.g. Kelvin (K). Compression and expansion occur at constant entropy, work is supplied from an external engine. Using the definition of entropy and the laws of thermodynamics, it can be shown that the Carnot efficiency, C_h, for useful heat at different temperatures is defined as:

The Carnot efficiency C_h representing the fraction of exergy in the useful heat, describes the maximum theoretical efficiency achievable in an ideal process. It depends on the temperature difference between the source and sink. Heat is supplied isothermally at a temperature T_{source} and removed isothermally at a temperature T_{sink}, or the mean temperature of the source and sink heat exchangers. Temperatures should be provided in absolute units, such as Kelvin (K). Compression and expansion occur at constant entropy, with work provided by an external engine. Using the definition of entropy and the laws of thermodynamics, it can be shown that the Carnot efficiency, C_h,%, for useful heat at different temperatures is defined as:

$$C_h = \frac{T_{sink}}{T_{sink-}T_{sourse}} \quad (5.2)$$

This implies that no HP can have an efficiency better than the limiting Carnot cycle. To determine the COP of a real-life machine, while accounting for the degree of thermodynamic perfection in an actual process and taking into account all irreversible losses in the actual thermodynamic cycle (including compressor compression, hydraulic losses, and throttling of the working fluid), a scale-down factor (the quality grade η) is applied to the Carnot efficiency, %:

$$COP = \mu = \eta \cdot C_h \quad (5.3)$$

Typical values ($0 \leq \eta \leq 1$) of quality grades are 0.4–0.5 for air-source HPs, 0.55 for ground-source HPs using a ground heat exchanger, and 0.5 for HPs using groundwater as a source. For high-temperature HPs, quality grades are between 0.4 and 0.6. In our calculations, conservatively assuming the minimum value η = 0.4 is accepted due to the absence of more precise data.

The maximum transformation ratio is achieved when there is a minimal difference between the temperature of the mains water and the temperature of the waste heat.

Therefore, it is most advisable to use HPs to heat the return network water and cool the return cooling circulating water. The temperature Tl of the low-potential heat source used by the HP can vary widely, ranging from 2 to 40°C.

Additionally, the heat source's temperature may remain relatively constant during the heating period or change during the operation of the HPs. In our case, we will consider the cooling water from the CHP condenser as a source of low-grade heat.

When selecting the maximum water temperature after the HP condenser Th, it is necessary to monitor the value of the HP conversion coefficient (COP) corresponding to this temperature for a specific temperature level of the low-potential heat source. In the model, the temperature of the DH supply line for most of the annual period (from April to November) is assumed to be 70 + 5 = 75°C (corresponding to an outdoor temperature of 0°C based on the DH temperature profile).

The HP COP value in this case should not be less than the value that ensures equal primary energy consumption for heat production via the HP and the base source CHP. In the case of CHP, the specific consumption of primary energy for the production of heat energy for CHP, %:

$$q_{CHP} = \frac{1}{\eta_{CHP}^{h}} \quad (5.4)$$

Specific consumption of primary energy for thermal energy production for HP is calculated as follows, %:

$$q_{HP} = \frac{1}{\eta_{CHP}^{h} \cdot \mu} \quad (5.5)$$

Equating the right-hand sides of expressions (5.4) and (5.5) determines the minimum effective conversion coefficient COP of the HP, %:

$$\mu_{min} = \frac{\eta_{CHP}^{h}}{\eta_{CHP}^{e}} \quad (5.6)$$

In the model, electricity from a CHP unit is considered, so the minimum allowable HP conversion factor μ_{min} is about 2. Thus, measures aimed specifically at reducing the cost of electricity production determine the conditions for the economic implementation of HP installations. As a result of the verification calculation, the actual values of heat output, the final temperatures of the heated coolant (DH network water) and the cooled coolant (circulating water of the HP condenser) are determined. A block diagram illustrating the algorithm for calculating a HP integration for a given set of initial data is shown in the Figure 5.3 below:

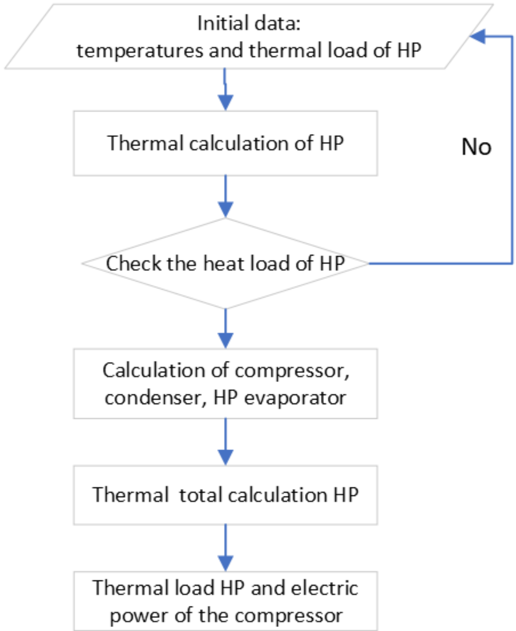

Figure 5.3. Block diagram of the algorithm for calculating a HP.

The calculation involves determining the thermal efficiency indicators of the CHP system according to the proposed methodology. The primary determinants of CHP's thermal efficiency are as follows:

Efficiency of electricity production, defined as the ratio of the power generated by the CHP to the calorific value of the portion of fuel allocated for electricity generation efficiency of power generation η^e_{CHP}:

$$\eta^e_{CHP} = \frac{N^e_{CHP}}{B^e_{CHP} \cdot Q_{LHV}} \quad (5.7)$$

where:

N^e_{CHP} – electric power of CHP, MW;

B^e_{CHP} – consumption fuel per CHP for the generation of electrical energy, t;

Efficiency of heat generation, characterised by the efficiency of heat production, defined as the ratio of heat delivered to an external consumer to the heat of combustion of the portion of fuel allocated for thermal energy production efficiency of heat generation η^h_{CHP}:

$$\eta^h_{CHP} = \frac{Q_h}{B^h_{CHP} \cdot Q_{LHV}} \quad (5.8)$$

where:

N^h_{CHP} – heat power of CHP, MW;

B^h_{CHP} – consumption fuel per CHP for the generation of heat energy, t;

Overall Efficiency of the CHP, defined as the ratio of the sum of electric power and heat produced to the heat content of the fuel used in the CHP system overall efficiency of CHP B_{CHP}^{ov}:

$$\eta_{CHP}^{ov} = \frac{N_{CHP}^{e} + Q_h}{B_{CHP}^{ov} \cdot Q_{LHV}} \quad (5.9)$$

where:
B_{CHP}^{ov} – overall consumption fuel per CHP for the generation of heat and power energy, %.

In this study, one of the key criteria for assessing efficiency is proposed, which involves considering overall fuel consumption for the combined provision of heat and electricity by the CHP system – overall fuel consumption B_{CHP}^{a}:

$$B_{CHP}^{a} = B_{CHP}^{ov} + B_{re}^{h} + B_{re}^{e} \quad (5.10)$$

where:
B_{re}^{h} – fuel consumption at the thermal unit that replaces the heat load, MWh;
B_{re}^{e} – fuel consumption for the replacement of electricity for the HP, MWh.

When comparing HP options, the power generation coefficient will be less than one and can be calculated as follows:

$$k_e = \frac{E_{CHP-HP}^{a}}{E_{CHP}^{a}} \quad (5.11)$$

where:
E_{CHP-HP}^{a} – electricity generation in the propose scenario with a HP, MWh;
B_{CHP}^{h} – electricity generation in the initial scenario, MWh.

Consequently, the heat consumption of fuel for the 'replacement source' of thermal energy is also equal to the heat consumption for the CHP unit used for heat generation, MWh:

$$\Delta E^{a} = E^{a}(1 - k_e) \quad (5.12)$$

The heat consumption of fuel for the 'replacement source' of electricity:

$$\Delta Q_{re}^{e} = \frac{\Delta E_a}{\eta_{re}^{e}} = \frac{E_a}{\eta_{re}^{e}}(1 - k_e) \quad (5.13)$$

$$B_{re}^{e} = \frac{\Delta E_a}{\eta_{re}^{e}} = \frac{E_a}{\eta_{re}^{e} Q_{LHV}^{re}}(1 - k_e) \quad (5.14)$$

where:
η_{re}^{e} – efficiency of the power generation for HP, %
Q_{LHV}^{re} – calorific value of the fuel of the replacement source, MJ/kg.

We use a CHP unit as a 'replacement power'. The value of the heat generation coefficient in the compared version will be determined by:

$$k_Q = \frac{Q_{CHP-HP}^{a}}{Q_{CHP}^{a}} \quad (5.15)$$

The replace of heat ΔQ^a will be determined by:

$$\Delta Q^{a} = Q^{a}(1 - k_Q) \quad (5.16)$$

Therefore, the heat consumption of fuel for the 'replacement source' of thermal energy, MWh is equal to:

$$\Delta Q_{re}^{h} = \frac{\Delta E_a}{\eta_{re}^{h}} = \frac{E_a}{\eta_{re}^{h}}\left(1 - k_Q\right) \tag{5.17}$$

Fuel for 'replacement source' B_{re}^{h}, MWh is equal to:

$$B_{re}^{h} = \frac{\Delta Q_a}{\eta_{re}^{h}} = \frac{Q_a}{\eta_{re}^{h} Q_{LHV}^{re}}\left(1 - k_Q\right) \tag{5.18}$$

This approach allows us to reveal the real fuel savings (or overconsumption) of one option relative to another. Utilising this criterion enables an objective assessment of the advantages of different thermal schemes involving CHP with HPs without needing to categorise fuel by type of energy generated.

The fuel energy-saving ratio (FESR) criterion can be used to assess the overall efficiency of HPs. This includes the following components [127] fuel energy-saving ratio:

$$FESR = 1 - \frac{1}{\frac{\eta_e^*}{\eta_e^{HP}} + \frac{\eta_h^*}{\eta_h^{HP}}} = 1 - \frac{1}{\left(\frac{\eta_e}{\eta_e^{HP}} + \frac{\eta_h}{\eta_h^{HP}}\right) + \alpha_{CHP} * \frac{\eta_W}{\eta_e^{HP}} * \left(\frac{\eta_e^{HP}}{\eta_h^{HP}} * \mu - 1\right)} \tag{5.19}$$

where:
η^{HP} is the average efficiency for the generation of thermal and electrical energy when installing an HP into a CHP system, %;
η_e, η_h – efficiencies for the production of electricity and heat, respectively, calculated based on the heat of combustion of fuel, %. The sum of these values characterises the overall efficiency of combined thermal and electrical energy production, following the first law of thermodynamics; α_{CHP} is an energy shifting factor indicating the relative proportion of energy consumed by the HP, particularly in its electric component.

A CHP system is used to substitute heat generation units. The difference in total fuel consumption across the options under consideration demonstrates the actual fuel savings (overconsumption) of one option over another. The application of this criterion allows for the objective identification of the advantages of the contrasted types of thermal schemes of CHP with HP without the use of methods for separating fuel by types of energy generated.

The operation of HPs as part of CHP requires, first and foremost, that their installed capacity be used to the greatest extent feasible throughout the heating period, allowing the benefits of HP technologies to be fully utilised. The annual primary energy consumption of W^a_{ov} for heat generation at a CHP is the sum of its individual heat sources annual primary energy consumptions:

$$W_{ov}^{a} = W_{CHP}^{a} + W_{HP}^{a} \tag{5.20}$$

where:
W_{CHP}^{a} – annual consumption of primary energy by the CHP, MWh;
W_{HP}^{a} – annual consumption of primary energy for the generation of electricity consumed by the HP, MWh.

The final step of the calculation involves determining the indicators of thermal efficiency for the CHP based on the proposed methodology. The following expression determines the reduction in fuel consumption in the CHP system due to the use of HP:

$$\Delta B_{CHP} = \frac{Q_{HP}(1+W)}{\eta_{CHP} \cdot Q_{LHV}} \tag{5.21}$$

where:
w – specific power generation per heat consumption.

The difference in fuel consumption to generate power for the HP:

$$\Delta B_{unit} = \frac{Q_{HP}\left(\frac{1}{\mu}+W\right)}{\eta_{CHP} \cdot Q_{LHV}} \tag{5.22}$$

The difference between equations (5.21) and (5.22) represents the increase in fuel consumption to generate power for the HP:

$$\Delta B_{unit} = \frac{Q_{HP}\left(\frac{1}{\mu}+W\right)}{\eta_{CHP} \cdot Q_{LHV}} - \frac{Q_{HP}(1+W)}{\eta_{CHP} \cdot Q_{LHV}} = \frac{Q_{HP}}{Q_{LHV}} \left\{ \frac{\frac{1}{\mu}+W}{\eta_{CHP}} - \frac{1+W}{\eta_{unit}} \right\} \tag{5.23}$$

This difference in fuel consumption, attributed to the unit of recycled thermal energy, is calculated as follows:

$$\Delta b = \frac{860/7}{1-\frac{1}{\mu}} \left\{ \frac{\frac{1}{\mu}+W}{\eta_{CHP}} - \frac{1+W}{\eta_{unit}} \right\} \tag{5.24}$$

The use of HPs allows for the utilisation of low-grade heat discharged from the cooling water of the CHP condenser. Additionally, the adoption of HP instegrations is environmentally advantageous as it reduces the level of thermal pollution in the environment.

Taking into account the primary energy required for the CHP and the HP, the expression is as follows:

$$W_{ov}^{a} = \frac{Q_{CHP}}{\eta_{CHP}} + \frac{N_{CHP}^{e}}{\eta_{re}^{e}} = \frac{Q_{CHP}}{\eta_{CHP}} + \frac{Q_{HP}}{\eta_{re}^{e} \cdot \mu} \tag{5.25}$$

Decrease in primary energy consumption can be expressed as:

$$\Delta w = \frac{\Delta W}{Q_{DH}^{a}} = \frac{1}{\eta_{CHP}} - \frac{\left(\frac{Q_{CHP}}{Q_{DH}^{a}}\right)}{\eta_{CHP}} + \frac{\left(\frac{Q_{HP}}{Q_{DH}^{a}}\right)}{\eta_{CHP} \cdot \mu} \tag{5.26}$$

where:
Q_{DH}^{a} – annual heat generation for DH, MWh.

The principal energy savings coming from the integration of the HP are largely dictated by the HP's optimally selected operating modes. For cases involving various HP operating modes and heat loads throughout the year, the average annual value of primary energy savings can be determined as follows:

$$\Delta B_{a} = \frac{\sum_{i=1}^{n} \Delta B_{i} \cdot \tau_{i}}{\tau_{a}} \tag{5.27}$$

where:
ΔB_i – primary energy savings from the integration of the HP for the i-th mode of operation of the HP, MWh;
τ_i – duration of the i-th mode of operation of the HP, h;
τ_a – HP annual duration of work, h.

These proposed criteria enable the assessment of the energy efficiency of HPs throughout the year under different operating conditions. The highest values of primary energy savings for HPs correspond to the maximum load share of the HP.

CO_2 emission calculation used methodology for the emission calculation according to Estonian regulation nr 94 [128]. Emissions calculated in ton of carbon dioxide, which are calculated as fuel - is the amount of fuel consumed for CHP and boilerhouse multiplied by emission factor for fuels used in plant. CO_2 emissions are calculated based on the specific emission factors to the primary consumption about 0,36 t CO_2/MWh for oil-shale and 0,20 t CO_2/MWh for natural gas.

The suitability of HPs in comparison to other heat supply options is determined by three criteria: primary energy consumption, environmental benefits from reduced CO_2 emissions, and economic benefits from lower costs and annual savings in heat energy production for consumers.

The calculation of primary energy consumption relies on specific fuel consumption values for the generation of electric and heat energy by the CHP unit. The energy efficiency of HP use is evaluated based on the expected annual savings in primary energy. We will assess the primary energy efficiency of HPs in the DH system, depending on the option in which the HP unit is used. An economic evaluation of the effectiveness of HP use compares the conversion coefficient of the HP with the efficiency of the main heat source of the CHP unit running on fossil fuels, considering the electricity consumed by the HP or the reserve and peak source gas boilerhouse. Environmental efficiency from using HPs comprises the reduction of CO_2 emissions associated with flue gases.

An essential condition for performing calculations based on these indicators is the economic comparability of the options under consideration, ensuring the equal supply of heat energy to consumers meeting the required parameters, along with consistent electricity generation. Meeting these conditions necessitates including a cost estimate in the criterion for the economic evaluation of options.

5.2 Financial and Economic Criteria for Evaluating Effectiveness

5.2.1 Levelized Costs of Energy (LCOE)

The LCOE method allows for the comparison of generation units with different generation and cost structures. LCOE is calculated by comparing all costs incurred over the lifetime of the unit, including construction, operation, and the total energy generated. Total annual costs comprise fixed and variable costs for power plant operation, maintenance, servicing, repairs, and insurance payments. The portion of debt and equity can be explicitly included in the analysis through the weighted average cost of capital (Wacc) over the discount rate. The discount rate depends on the amount of equity, the return on equity over the lifetime, borrowing costs, and the proportion of contributed debt.

The levelised cost of heat incorporates common evaluation factors in LCOE calculations. The present value of capital (Capex), operating (Opex), fuel costs (Fuel), and CO_2 emissions (Carbon) per generation source over its entire useful life is compared to the present value of reduced energy production (thermal H, electric E, and total Q) over the same period to accurately compare the cost of energy produced from different sources and gauge this cost against a competitive price level. The levelized cost of energy represents the cost per MW over a unit's life that equates the present value of revenue from heat or electricity generation and sale to the present value of power plant construction and operating costs. The LCOE provides a long-term cost per MW, ensuring a stable energy price for consumers and an acceptable rate of return for investors. Figure 5.4 shows the most common methodology for assessing the competitiveness of projects for generating capacity construction is used for investment analysis and tariff setting:

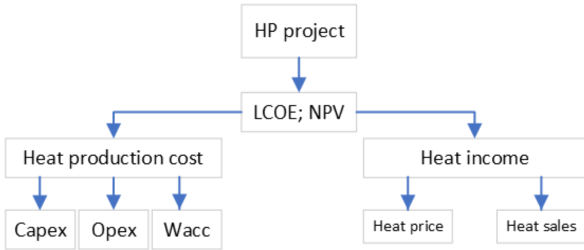

Figure 5.4. Economic evaluation LCOE flow chart.

Heat savings are assessed using the LCOE approach by calculating the unit cost of saving heat and the unit cost of supplying heat. For the purposes of the study, we distinguish the normalized cost of electricity LCOE [129, 130] and the normalized cost of thermal energy LCOH [131-133]. This value corresponds to the average long-term costs of the unit, since we've divided the total yearly costs by the total production.

The formula for total annual costs in the calculation of LCOE is as follows Electricity, Heat, HP and CHP with HP:

$$\boldsymbol{LCOE} = \frac{\sum_{t=1}^{y} \frac{Capex(t)_E + Opex(t)_E + Fuel(t)_E + Carbon(t)_E}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E(t)_E}{(1+r)^t}} \tag{5.28}$$

$$\boldsymbol{LCOH} = \frac{\sum_{t=1}^{y} \frac{Capex(t)_H + Opex(t)_H + Fuel(t)_H + Carbon(t)_H}{(1+r)^t}}{\sum_{t=1}^{y} \frac{H(t)_H}{(1+r)^t}} \tag{5.29}$$

$$\boldsymbol{LCOH_{HP}} = \frac{\sum_{t=1}^{y} \frac{Capex(t)_{HP} + Opex(t)_{HP} + Price_{el}^{CHP} \cdot E_{HP}(t)_{HP}}{(1+r)^t}}{\sum_{t=1}^{y} \frac{H(t)_{HP}}{(1+r)^t}} \tag{5.30}$$

$$\boldsymbol{LCOQ_{CHP+HP}} = \frac{\sum_{t=1}^{y} \frac{Capex(t)_{CHP+HP} + Opex(t)_{CHP+HP} + Fuel(t)_{CHP+HP} + Carbon(t)_{CHP+HP}}{(1+r)^t}}{\sum_{t=1}^{y} \frac{Q(t)_{CHP+HP}}{(1+r)^t}} \tag{5.31}$$

where:
Capex(t) – capital expenditures (CHP heat part, HP initial investment) in year t, €;
Opex(t) – operating expenditures (CHP electrical/heat, HP) in year t, €;
Fuel(t) – fuel cost (CHP electrical/heat) in year t, €;
E(t)/H(t) – amount of electrical/heat energy produced in year t, €;
$E_{HP}(t)$ – annual power comsumption for HP in year t, €;
$Price_{el}^{CHP}$ – price of CHP electricity, €/MWh;
r – discount rate, %, in Estonia is regulatory Wacc (weightd average cost of capital) to calculate the Wacc, the ECA is using [134], for DH company 5.8%; Wacc is considered as a discount factor;
y – unit lifetime, years.

The Capex varies from 0.48 to 0.95 M€/MW for different authors [126]. The average Capex is around 0.67 M€/MW. The Opex of HPs are very low compared to CHP or boilerhouse, as a rule to consider the Opex as a fixed percentage from the total Capex as around 2%.

A 5.8% interest rate *r* was chosen and an economic lifetime *n* of 10 years have been chosen. LCOH serves as a comparative indicator representing the cost of heating from any system, taking into account capital, operating, and maintenance costs over the system's lifetime. If the LCOH of the propose solution (HP) is lower than that of the existing system (CHP), it indicates a positive return on implementing the new system. This is an appropriate performance metric for evaluating different heat-generation technologies. Figure 5.5 shows LCOE methodology initial data flow chart:

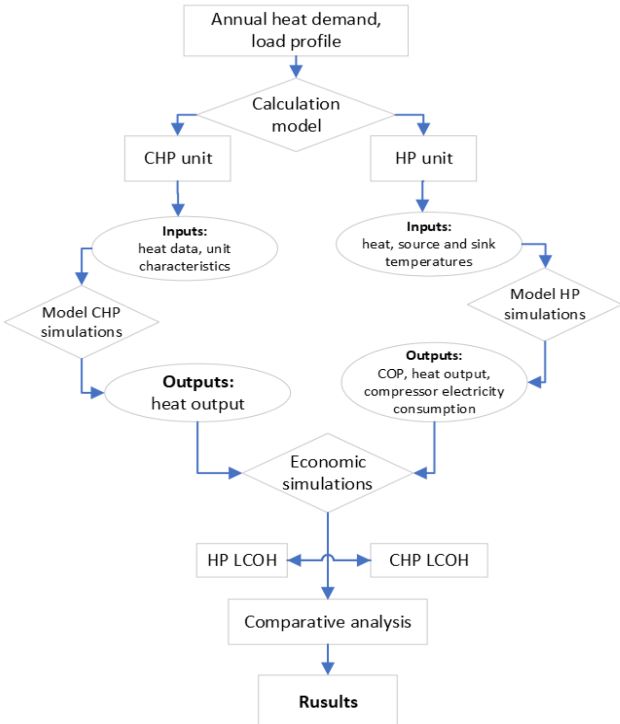

Figure 5.5. Methodology flow chart of the economic criteria.

The figure above illustrates the flow chart of the methodology used for analysis and workflow in this study. The evaluation is carried out through annual heat and power energy simulations conducted with dynamic simulation software, and a systematic approach is followed to provide readers with the necessary information to understand the results. It underscores the distinction between the cost of production and the selling price of thermal energy.

The economic significance of LCOE lies in its ability to provide a constant price for energy over time, ensuring that investments break even (income – outcome): NPV (LCOE) = 0.

5.2.2 Net present value NPV and internal rate of return IRR

The calculation can be conducted using either the net present value method (NPV) or the annuity method. When applying the net present value method, the expenses for the investment, as well as the payment flows of revenues and expenditures during the unit's lifetime, are calculated by discounting them to a common reference date. For this purpose, the present values of all expenses are divided by the present value of energy (heat or power) generation. The effectiveness of investments is determined by integral indicators, including net present value, internal rate of return, and profitability index, with the payback period used as an additional indicator.

The net present value is defined as sum of discounted cash flows. NPV is the difference between discounted receipts and payments for the billing period – takes into account the dynamics of changes in profit during the billing period. The efficiency criterion is a positive NPV:

$$NPV = \sum_{t=1}^{n} \frac{R_t}{(1+r)^{t-1}} \tag{5.32}$$

where:

R_t – net cash flow (inflow minus outflow) at period t, €;

NPV is the sum of discounted cash flows. In other words, NPV shows the difference between cash inflows and outflows given to the current point in time. When this indicator takes a negative value, the project becomes unprofitable and the invested funds do not pay off. Simple definition: the present value of future cash flows minus the purchase price. Decision making: NPV > 0 – the HP investment would add value; NPV < 0 – the HP investment would subtract value; NPV = 0 – the HP investment would neither gain nor lose value. The profitability index (PI) is the ratio of the present value of future cash flows to the initial investment Capex:

$$PI = \frac{NPV + Capex}{Capex} \tag{5.33}$$

The internal rate of return (IRR) is the discount rate at which the present value of future cash flows (receipts) equals the present Capex, resulting in a net present income of zero. IRR can serve as an estimate for efficiency assessment compared to the rate on the capital market when the investor allocates free cash. IRR represents the maximum cost of capital raised at which the investment project remains profitable. In other words, it's the discount rate at which the NPV is zero:

$$\sum_{t=1}^{T^p} \frac{R_t}{(1+IRR)^{t-1}} - Capex = 0 \tag{5.34}$$

In simpler terms, IRR is the 'annualised effective compounded return rate' or discount rate that makes the NPV of all cash flows equal to zero. IRR is a relative number, whereas NPV is an absolute number. The project should be implemented if the IRR exceeds the discount rate. If the IRR is less than the discount rate, the project is unprofitable and impractical to implement.

Maximising the NPV returns the investment with the highest absolute value based on the lifetime. Conversely, by maximising the IRR, the investment with the highest rate of return is chosen, which means selecting the investment that returns a positive NPV in the quickest possible way, potentially leading to a different investment or, in this case, a different HP.

The methodology for assessing the feasibility of integrating HP into the technological scheme, considering the operating modes of the CHP, is illustrated in Figure 5.6:

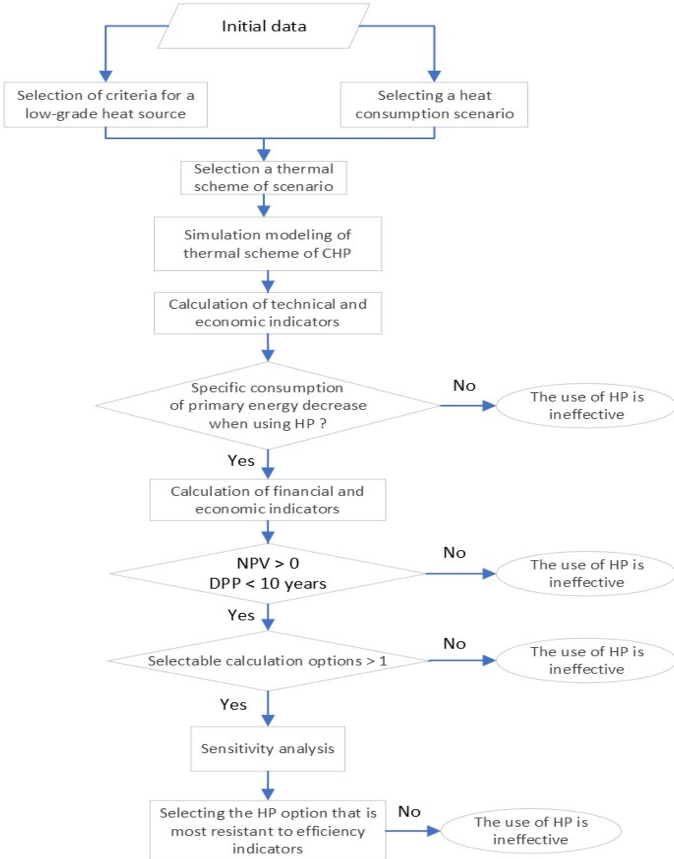

Figure 5.6. Flowchart of the methodology for analysing the possibility of incorporating HP into the technological scheme of the CHP.

It is important to highlight that the economic advantage of using an HP instead of a boiler plant relies on reduced fuel consumption for heat generation. This reduction is achieved by utilising waste (inoperable) heat to meet the heating load. Conversely, the impact generated by the operation of the HP should, within an acceptable timeframe, offset the higher capital expenses associated with installing the HP compared to the heating component of a CHP unit.

5.3 Results and Discussions on HP Integration

Since implementing HP at CHPs reduces fuel costs, lowering the cost of heat production, the author of this dissertation proposes using the criterion of total fuel consumption by system effect, in addition to financial and economic criteria, to assess the effectiveness of these systems. The total fuel consumption for the system effect takes into account an equal supply of heat and electricity from the CHP.

Three comparative scenarios for meeting the heat load of the heating network have been examined. In each scenario, operations are conducted with either only fossil fuel or a mix of 40% biomass and 60% fossil fuel, specifically oil shale in our version.

The assessment of HP's impact on CHP performance considers characteristic modes of CHP equipment operation. In the first scenario, the CHP caters to both the heating load (winter mode) throughout the heating season and the load of hot water supply year-round (winter and summer modes). The second scenario involves the CHP handling the heating load (winter mode) during the heating season and the hot water supply load in the heating season only, with a reserve gas boiler house (BH) taking over hot water supply during the inter-seasonal period. The third scenario considers using HP to meet the hot water supply load all year (winter and summer modes), substituting the CHP's role during the heating season (winter mode) and reducing fuel costs at the backup reserve gas BH during the inter-seasonal period (summer mode).

Simulation results of using HP, scenarios:

1.a CHP heating and hot water supply 0% biomass.
1.b CHP heating and hot water supply 40% biomass.
2.a CHP heating and BH hot water supply 0% biomass.
2.b CHP heating and BH hot water supply 40% biomass.
3.a CHP heating and HP hot water supply 0% biomass.
3.b CHP heating and HP hot water supply 40% biomass.

Simulation results for the proposed third scenario compare the operation of the HP throughout the year for part of the heat load for hot water supply. Figure 5.7. illustrates the proportion of the HP in the total heat supply load.

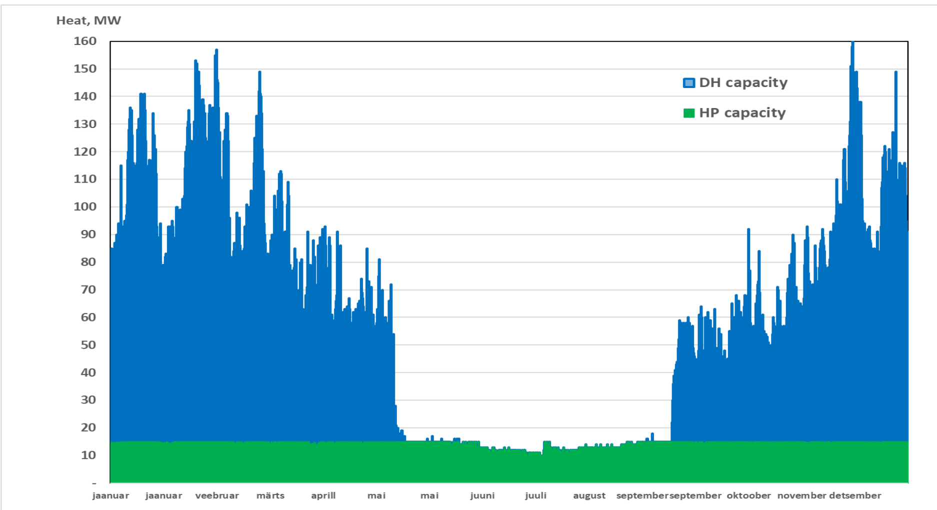

Figure 5.7. The total annual load of heat supply and the coverage of part of the load with a HP.

The integration of an HP to meet the hot water supply load proves to be the most expedient option for utilising waste heat from circulating water. This load persists throughout the year, increasing the number of hours of HP usage. To analyse the impact of HP on the technical and economic indicators of CHP operation, primary energy consumption for electricity and heat generation in characteristic CHP operating modes was calculated. The results were analysed by comparing primary energy consumption during CHP operation throughout the year (scenario 1), CHP operation during the heating season with hot water supply load replacement using a reserve gas boiler house during the inter-seasonal period (scenario 2), and the comparative version considering HP integration (scenario 3).

The incorporation of an HP into the structure of a CHP plant can significantly enhance the efficiency of heat generation and the overall effectiveness of the CHP, considering both heat and electricity generation. Optimal redistribution of the annual heating load among the heat sources in the scenarios, maximising the load of the most economical one, contributes to an increased overall system efficiency for the CHP. Comparative results are depicted in Figure 5.8.

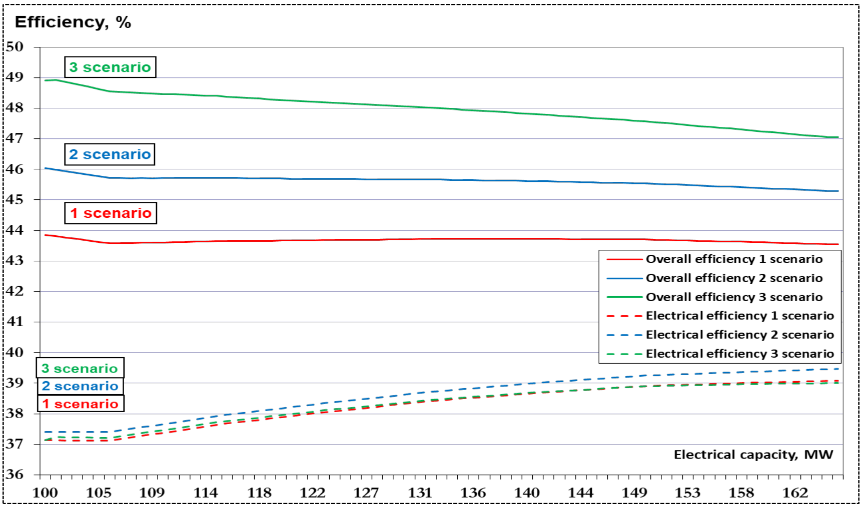

Figure 5.8. Efficiency for electricity supply and overall efficiency (for heat and electricity supply) for three scenarios of the heating network, contingent on the electrical load of the CHP.

Figure 5.9 displays the variation in primary energy consumption throughout the year for three scenarios of the DH system:

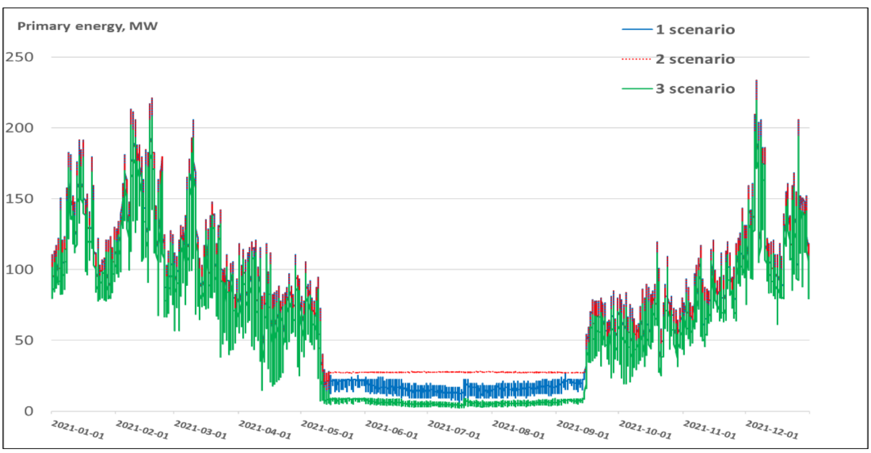

Figure 5.9. Consumption of primary energy for heat generation for for three scenarios of the heating network.

A comparison of alternative scenarios based on the degree of primary energy consumption reveals that the most efficient and rational scenario involves the use of an HP. In Figure 5.10, the total CO_2 emissions for the three scenarios of CHP operation are presented:

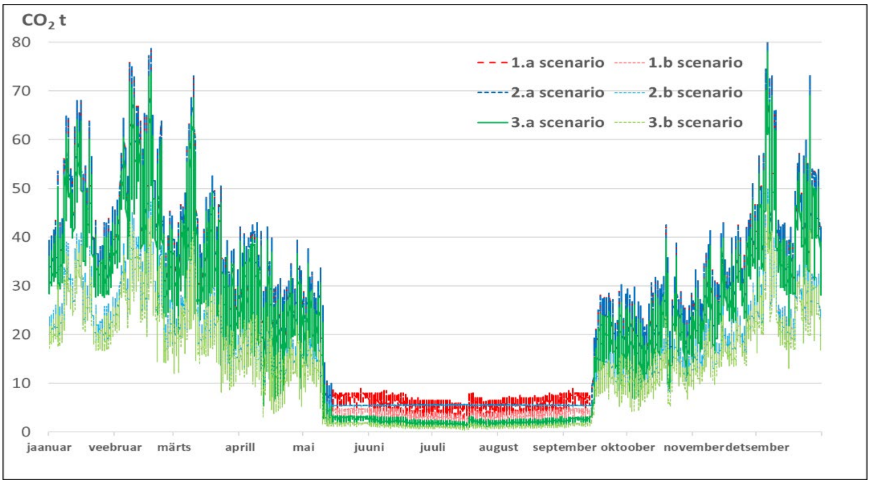

Figure 5.10. Total CO_2 emissions for the three scenarios of CHP operation.

The first two scenarios provide insights into CHP operation without utilising an HP for waste heat recovery, and subsequent calculations are based on values derived from waste heat recovery using an HP. Figure 5.11 outlines the annual consumption of primary energy and CO_2 emissions for the three scenarios of CHP operation:

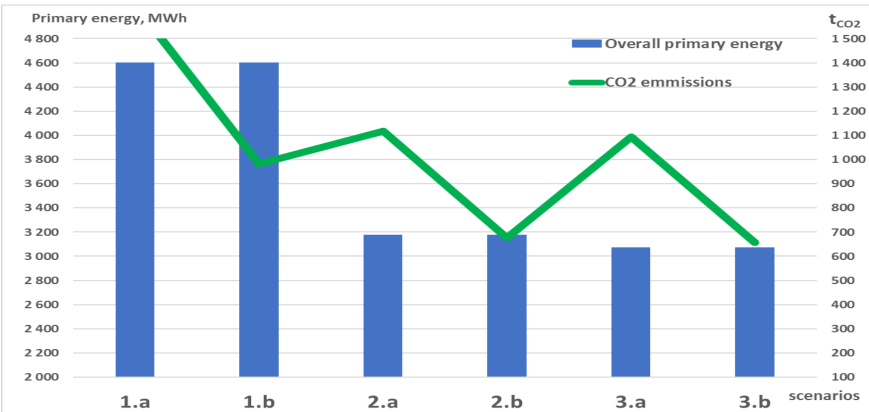

Figure 5.11. Annual consumption of primary energy and CO_2 emissions for the three scenarios of CHP operation.

The impact assessment of HP integration on heat supply and electricity generation was conducted for the third scenario. A comparative evaluation of heat production options, factoring in the influence of HP operation on CHP operating modes, was carried out. Calculations led to the compilation of a summary table indicating annual savings when CHPs operate in conjunction with HP, presented in Table 5.1.

Table 5.1 encapsulates annual performance indicators for various scenarios of CHP operation and heat pump integration:

Table 5.1. Annual performance indicators for various scenarios.

scenarios		1.a	1.b	2.a	2.b	3.a	3.b
Electricity production	**MWh**	**1 530 236**	**1 530 236**	**979 454**	**979 454**	**979 454**	**979 454**
Heat production:	**MWh**	**462 635**	**462 635**	**462 635**	**462 635**	**462 635**	**462 635**
heat production CHP	MWh	462 635	462 635	427 813	427 813	342 225	342 225
heat production BH	MWh			34 822	34 822	0	0
heat production HP	MWh			0	0	120 410	120 410
Overall efficiency	**%**	**43,2**	**43,2**	**45,4**	**45,4**	**48,7**	**48,7**
electrical efficiency	%	38,5	38,5	38,8	38,8	38,5	38,5
heat efficiency	%	71,8	71,8	64,2	64,2	97,8	97,8
Overall primary energy	**MWh**	**4 604 397**	**4 604 397**	**3 178 254**	**3 178 254**	**3 073 586**	**3 073 586**
oil-shale primary energy	MWh	4 604 397	2 762 638	3 097 396	1 858 438	3 073 586	1 844 152
biomass primary energy	MWh	0	1 841 759	0	1 238 959	0	1 229 434
gas primary energy	MWh	0	0	80 857	80 857	0	0
Electricity primary energy	MWh	3 984 095	3 984 095	2 529 978	2 529 978	2 546 148	2 546 148
Heat primary energy	MWh	620 301	620 301	648 275	648 275	527 438	527 438
CO_2 emmissions	**t**	**1 637 360**	**982 416**	**1 117 630**	**677 047**	**1 092 992**	**655 795**
Overall primary energy savings	**MWh**	**0**	**0**	**0**	**0**	**104 668**	**104 668**
Electricity primary energy savings	MWh	**0**	**0**	**0**	**0**	**-16 170**	**-16 170**
Heat primary energy savings	MWh	**0**	**0**	**0**	**0**	**120 837**	**120 837**
Overall CO_2 emmissions savings	**t_{CO2}**	**0**	**0**	**0**	**0**	**24 639**	**21 252**
Oil shale CO_2 emmissions savings	t_{CO2}	0	0	0	0	8 467	5 080
Gas CO_2 emmissions savings	t_{CO2}	0	0	0	0	16 171	16 171

The economic effect of HP introduction into the CHP was computed, considering an assessment of the main components of heat energy cost for the proposed circuit solutions. The results of the LCOH calculation for heat production are showcased in Table 5.2., providing comparative values for the cost of heat generation across different proposed work options:

Table 5.2. LCOH for three scenarios of CHP operation.

scenarios	unit	1.a	1.b	2.a	2.b	3.a	3.b
Total heat production	**MWh**	**462 635**	**462 635**	**462 635**	**462 635**	**462 634**	**462 634**
heat production CHP	MWh	462 635	462 635	427 813	427 813	342 224	342 225
heat production BH	MWh			34 822	34 822	0	0
heat production HP	MWh			0	0	120 410	120 410
LCOH	**€/MWh**	**73,54**	**65,72**	**81,30**	**72,56**	**57,73**	**51,99**

Three scenarios are compared for LCOH in heat generation. The maximum LCOH for heat production is estimated at €73/MWh with a biomass application of €65/MWh, while the minimum LCOH for heat generation using HP is calculated at €57/MWh with a biomass application of €52/MWh. District heating from renewable fuels (biomass) is highly recommended due to the reduction in greenhouse gas emissions and savings on carbon taxes. The LCOHs in scenario 3 are the lowest in this study. In addition to the system savings of primary energy, the cost savings from introducing a heat pump also include a reduction in payment for the purchase of necessary CO_2 quotas formed during the combustion of primary energy from fossil fuels (oil shale). Table 5.3 presents the key data obtained on the financial indicators of integrating a 15 MW heat pump into a CHP structure:

Table 5.3. Financial analysis of HP integration.

nr	**indicator**		**unit**	**Capex**	
				min	max
1	Net present value	NPV	mln €	17,0	8,9
2	Profitability index	PI		3,4	1,6
3	Internal rate of return	IRR	%	44%	17%
4	Net cash flow	R_t	mln €	3,3	3,1
5	Payback period	PP	years	2,2	4,6
6	Discounted payback period	DPP	years	2,4	5,5

With the available initial data, the investor can expect a net present value of 8.9 million euros for Capexmin and 17.0 million euros for Capexmax. Consequently, the expenditure for Capexmin and Capexmax, respectively, will pay off and yield the profit set by the discount rate of 5.8%. The profitability index exceeds 3.4 for Capexmin and 1.6 for Capexmax, indicating a significant return on investment for the investor. The internal rate of return for the project is 44% and 17% for Capexmin and Capexmax, respectively, a value significantly higher than the established discount rate, suggesting a substantial return to the investor. The discounted payback period for the project is 2.4 and 5.5 years for Capexmin and Capexmax, respectively, indicating the feasibility of investing in this HP. Based on the financial analysis results of introducing a HP into the CHP structure, we can confidently state that the investment in this project will break even. According to the calculations, it can be estimated that this project will be effective and profitable, with a payback time preferably under 10 years, making it a reasonable investment opportunity.

The payback of the HP aligns with existing economic constraints, ensuring investment feasibility. An evaluation of the economic efficiency of introducing an HP revealed that the average annual NPV at a discount rate of 5.8% for the Estonian DH company over a 10-year period exceeds 13 million euros. The dynamic payback period (DPP) does not exceed 6 years. Considering the HP's service life of at least 15 years, its installation promises substantial savings for the company.

For an average estimate, we calculate the NPV based on the average value of Capex as shown in the Figure 5.12:

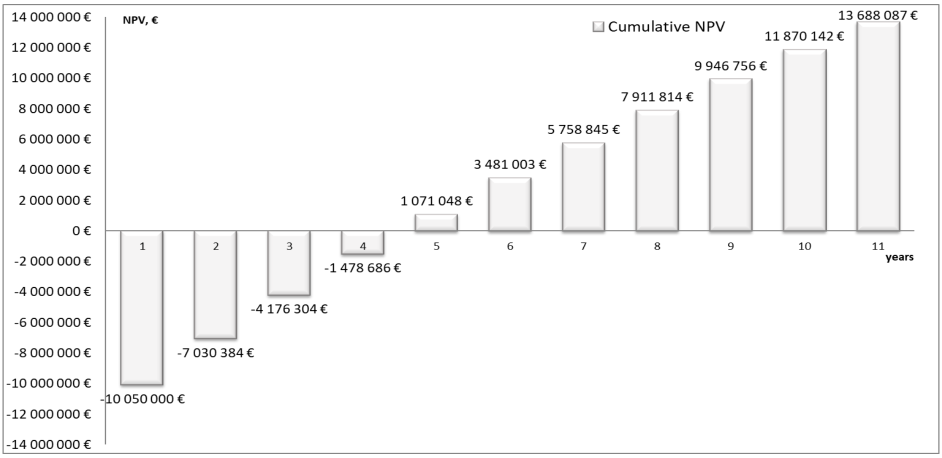

Figure 5.12. Dependence of NPV on the operating period with an average Capex.

To determine the sensitivity of the investment attractiveness of HP integration, we selected the HP's life period and NPV as parameters defining the boundaries of investment attractiveness. Subsequently, using Excel, we simulated and analysed situations in which the HP operates for various periods. The calculations led to the compilation of NPV for $Capex_{max}$ and $Capex_{min}$, along with the HP's operational period. The analysis examines changes in the payback period depending on the initial investment is carried out as shown in the Figure 5.13:

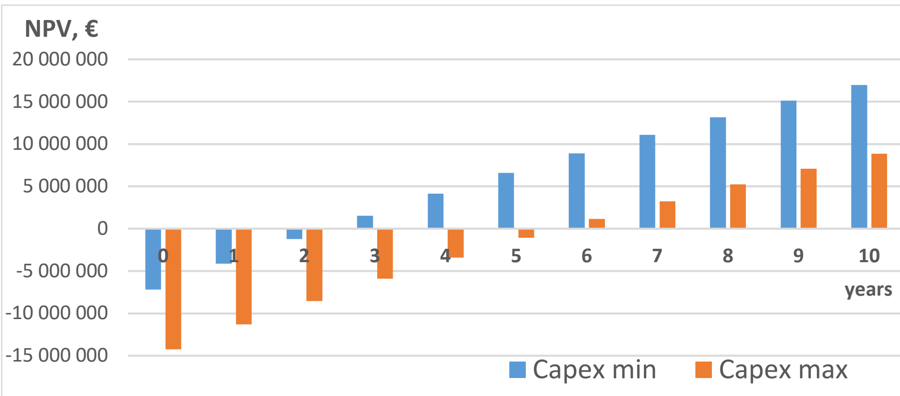

Figure 5.13. NPV index for $Capex_{min}$ and $Capex_{max}$.

An analysis of the sensitivity of the proposed investments was conducted, considering changes in initial investment and an increase in Capex. The study revealed that the most significant factors influencing project effectiveness are variations in the growth rate of primary energy costs and an increase in Capex. The overall outcome of this work encompasses scientifically grounded technical solutions contributing to the enhancement of the thermal efficiency of CHP systems through the utilisation of a HP that harnesses waste heat from the cooling water supply of the CHP. The results obtained include:

- Identification of the vapour compression HP with a 15 MW capacity as the most promising solution for improving the thermal economy of the CHP, particularly due to its ability to meet the heat demand during the inter-seasonal period.
- Development of a circuit solution for CHP process cycles aimed at increasing the thermal efficiency of CHP cycles.
- Formulation of a mathematical model for CHP operating modes, enabling assessment of thermal efficiency under variable operating conditions, considering the operation of the reserve heat supply source – a gas BH.
- Introduction of an energy efficiency coefficient in the methodology for calculating the thermal schemes of CHP with a HP. This coefficient allows for accounting for the influence of the HP's transformation coefficient on CHP thermal efficiency, facilitating a comprehensive assessment of energy processes.

Based on calculations of various CHP operating modes with a HP, it was determined that the overall efficiency of CHP, compared to a typical layout, increases by 3%. The most economical option involves deploying a HP during the inter-seasonal period to replace a gas boiler house, where the HP fully covers the city's heat load. Operating characteristics of a CHP with a HP were calculated, describing changes in heat generation efficiency and considering variations in electricity efficiency to optimise operating conditions for various CHP modes. An assessment of the economic feasibility of investing in the installation of a HP in existing CHP cycles demonstrated that the discounted payback period of projects does not exceed the average value established for energy facilities and is 5 years.

5.4 Summary of the analysis

A comprehensive study was conducted to assess the energy, environmental, and economic efficiency of the proposed scenarios. A comparative model of energy efficiency was developed, revealing that the introduction of a HP could reduce annual primary energy consumption.

The economic efficiency of integrating a HP into the structure of the CHP was determined under the following conditions:

- comparison of CHP indicators without a HP and with a HP;
- Calculation of financial differences to identify savings from integration,
- assessment of economic efficiency using the discounted cash flow method, considering indicators such as LCOH, NPV, PI, IRR, and DPP.

The theoretical significance of this study lies in considering the integration of HP as a beneficial method for utilising waste heat from the cooling system of modern CHP equipment. The integration into the technological process and the development of a methodology for calculating the energy efficiency of the HP, considering seasonal heat consumption patterns, the temperature schedule of the DH system, the temperature of the low-grade waste heat source, and climatic parameters (weather conditions in Estonia), is another significant aspect. The practical significance of the study involves the development of a scenario for the beneficial use of waste heat from CHP equipment. This included an assessment of the volume of lost thermal energy, proposing options for its beneficial use, and conducting technical and economic calculations to evaluate the payback of the proposed scenario. Using the heat power of the CHP as an example, the study assessed the influence of key technical and economic factors when introducing a HP into the CHP structure. This HP utilises waste heat from the technical circulating water cooling of the CHP condenser as a low-potential heat source. The quantitative dependencies of the impact of thermodynamic parameters on the system efficiency of CHP operation have been established.

As part of the work performed, an assessment was conducted on the effectiveness of utilising waste heat energy through a HP in the city of Narva. To address this, information sources were analysed, and data related to the topic were collected, encompassing technological principles and methods for utilising low-grade waste energy using HP, types and operation principles of HPs, sources of waste energy, and prospects for applying these technologies in Narva. The paper delves into theoretical studies on the efficiency of low-grade waste heat utilisation in CHP conditions, employing a comprehensive calculation to evaluate its effectiveness for each category of heat replacement sources. The results obtained from this assessment indicate the feasibility of utilising low-grade waste energy through HP to enhance the efficiency of the CHP unit in Narva. The incorporation of HP contributes to an increased efficiency of heat supply to the CHP.

The overall result of the dissertation comprises scientifically based technical solutions contributing to the enhancement of the thermal efficiency of the CHP through the integration of a HP. Key results obtained include the following:

- numerical studies of variable operating modes of CHPs with HPs revealed an overall efficiency increase of about 3% compared to the original scheme;
- operating characteristics of the CHP with a HP were obtained, describing changes in power unit output, primary energy consumption, and efficiency based on CHP unit capacity and cooling water temperature. This allows for the selection of optimal operating conditions under variable power plant modes;
- recommendations for the practical implementation of HPs in CHP technological cycles were proposed, minimising interference with the existing CHP cycle;
- a methodology for determining performance indicators and an algorithm for calculating CHP with HPs were developed. The algorithm was tested by creating a computational model, and efficiency evaluation criteria were proposed, encompassing total consumption of primary fuel energy, NPV, PI, IRR and PP;
- technical and economic indicators of the efficiency of CHP with HP were determined through the conducted studies;
- the expediency of using HPs as a replacement for the backup load source of hot water supply was demonstrated using the criterion of total primary energy consumption in the system;
- a systematic analysis methodology was developed for the fuel efficiency of HPs compared to CHPs, considering different types of fuel burned at sources with varying prices;
- an economic and mathematical model was created to study optimal schemes, parameters, and economic efficiency of HPs, including CHP costs;
- computational and theoretical studies established that the use of HPs in the CHP scheme, depending on the potential of the cold source, leads to significant fuel savings for heat generation;
- rational areas of HP use in DH systems were determined in comparison with DH from CHP and a reserve gas BH during the inter-heating period. The efficiency zone of HPs is expanded by purchasing additional CO_2 quotas for the combustion of fossil fuels.

6 Conclusions

The decarbonisation of the heating sector stands as a crucial component in achieving the EU's ambitious climate and energy targets. Reducing dependence on fossil fuels, enhancing energy conversion technologies' efficiency, and mitigating harmful emissions are among the significant economic, scientific, and political challenges today. The research conducted as part of this doctoral thesis aims to contribute to this collective vision for a sustainable energy future. This work focuses on enhancing the energy efficiency of the DH system from technical, operational, and economic perspectives. To fulfil the primary objective of this study, key areas of research were identified:

- factors influencing the enhancement of DH systems;
- economic dispatch of CHP through demand-side management of the DH;
- comparison of DH supply options for various CHP configurations;
- enhancing the energy efficiency of CHP plants by utilising waste low-grade heat from cooling water through the integration of a HP.

The dissertation aims to address the complex scientific problem of developing the DH system, using the city of Narva as an example. Improving the efficiency of the DH system is attainable only through a comprehensive analysis that considers the interplay between the economic efficiency of investments, the thermodynamic aspects of thermal energy production, and their relationship with the environment.

The optimisation criterion is the maximisation of electrical power generation relative to heat consumption through economic dispatch. Formulating optimisation tasks when distributing the CHP unit load using heat demand-side management involves minimising primary energy consumption and maximising the total useful electrical load of the CHP unit at consumer electrical and heat loads. In the context of the imperative to decarbonise heat and electricity production, advancements dedicated to biofuel utilisation are gaining particular significance.

However, this path for further development cannot be deemed promising because it preserves the shortcomings inherent in the existing DH system. Consequently, with ongoing heat supply development, alternative sources and technologies for low-temperature heat supply must be introduced. The most rational use of secondary energy resources, such as waste heat from circulating cooling water at CHP, is through the use of HP, especially for hot water DH load replacement. This approach is the most rational way to enhance the efficiency of CHP.

As part of the dissertation research, a set of regime methods and cost-effective modernisation strategies aimed at comprehensively enhancing the energy and environmental efficiency of the existing DH system was developed, substantiated, and implemented. A thorough analysis of the factors influencing the optimisation of cogeneration in CHPs was conducted. To optimise electricity generation at the cogeneration unit of the CHP, a system for recording heat consumption data was developed. The study includes a comparison of various heat supply scenarios in terms of their energy and exergy use. Real demand data for the city of Narva were utilised for the comparison, ensuring consistency in assumptions and simplifications regarding heat load for each scenario. The low-grade waste heat of the circulating water from the CHP serves as a low-potential source of heat energy in this work. An examination of the thermal and economic efficiency of using a HP was conducted, and a methodology for a system analysis of the fuel efficiency of CHP operation was developed.

The Main Results of the Thesis

The main results of the thesis indicate the economic advantages of the proposed research, attributed to the flexible operation of the CHP unit, which enhances the overall economic efficiency and expands the operational range of the CHP. For a CHP unit integrated within a DH network, demand-side management is demonstrated to improve the overall economic efficiency and expand the unit's operating range in the electricity spot market. Optimal loading of the CHP unit results in increased electricity efficiency by up to 0.5…1.0% and an overall efficiency gain of an additional 1.0…2,0% with a 40…130 MW heat supply. The calculations reveal that optimal load planning at the CHP can lead to primary energy savings of more than 10,000 MWh per year and fuel savings of around 18,000 tonnes of CO_2 per year during the heating season.

Furthermore, the dissertation proposes the use of criteria such as total fuel consumption by system effect and financial and economic considerations to evaluate the effectiveness of HPs in CHPs. Optimisation tasks formulated for CHP load distribution and heat consumption data management include the following:

- increasing the CHP unit's annual overall efficiency by approximately 3%;
- minimising primary energy consumption by about 100 GWh per year;
- achieving savings of approximately 22,000 tonnes of CO_2 emissions per year.

An analysis of the PP for the introduction of a HP reveals a DPP ranging from 3 to 6 years, indicating favourable profitability for such an investment.

Recommendations for Future Research

The provided recommendations offer insights into predicting rational modes of operation for HPs within the structure of CHP units. The proposed waste heat utilisation scheme, derived from the cooling system of CHP equipment, is versatile and applicable not only to the specific CHP unit examined in this study but can also be adapted to other CHP units, considering their unique features. This study has identified several potential areas for future research. Subsequent projects should expand on the comparison of various heating systems to include more scenarios, incorporating alternative and fuel-free sources. Additionally, comparing different alternative sources can provide valuable insights into optimal strategies for efficiently utilising RES. Future research should integrate optimisation considerations for both environmental impact and cost-effectiveness in the scenario development process. Further studies are necessary to enhance the method and provide a more detailed description of the efficiency changes in CHPs and the capabilities of consumers for the potential transition to the next generation of DH systems. In subsequent projects, the same algorithm and methodology could be applied to integrate more RES into existing DH systems and CHP units.

Today, the rising number of RES has a considerable impact on the volatility of electricity costs, particularly during the summer and particularly during rapid drops, sometimes reaching negative values. The introduction of a HP into a CHP technological framework will allow for full coverage of the thermal load during the inter-seasonal period, preventing significant losses for the CHP while addressing the thermal load during periods of low electricity prices. Conversely, the operation of the HP will yield substantial profits and enhance the flexibility of the CHP in the open electricity market. Further exploration and research on this issue may continue to be of significant interest, particularly in light of future plans for the global development of renewable energy.

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Abstract

Decarbonisation of Fossil-Fuel CHP Based District Heating System

Today, CHP is one of the most widely used technologies at power plants, aimed at conserving fuel and consequently reducing CO_2 emissions. The research conducted as part of this thesis aims to contribute to this collective vision for a sustainable energy future, focuses on enhancing the energy efficiency of the DH system from technical, operational, and economic perspectives. To fulfil the primary objective of this study, key areas of research were identified:

- factors influencing the enhancement of DH systems;
- economic dispatch of CHP through demand-side management of the DH;
- comparison of DH supply options for various CHP configurations;
- enhancing the energy efficiency of CHP plants by utilising waste low-grade heat from cooling water through the integration of a heat pump.

Improving the efficiency of the DH system is attainable only through a comprehensive analysis that considers the interplay between the economic efficiency of investments, the thermodynamic aspects of thermal energy production, and their relationship with the environment. This includes optimising heat supply systems, using consumption data to assist CHP dispatching, comparing various CHP configuration schemes, and utilising CHP waste heat using heat pump. The development of an optimisation methodology validates the theoretical possibility of using these options as technological solutions.

The solution of the problem of improving the efficiency of the CHP is accompanied by the consideration of technical and economic factors. These include the features of the technological scheme of the CHP, the condition of the equipment in operation, the operating modes of the CHP, the climatological characteristics of the facility. The actual modes of operation of the equipment affect the efficiency of the use of heat pump, which necessitates their accounting. The proposed and substantiated technical solutions hold the potential to significantly enhance the thermal efficiency of CHPs while simultaneously curbing their environmental impact.

The theoretical significance of this study lies in considering the integration of heat pump as a beneficial method for utilising waste heat from the cooling system of modern CHP equipment. The integration into the technological process and the development of a methodology for calculating the energy efficiency of the HP, considering seasonal heat consumption patterns, the temperature schedule of the DH system, the temperature of the low-grade waste heat source. The practical significance of the study involves the development of a scenario for the beneficial use of waste heat from CHP equipment. This included an assessment of the volume of lost thermal energy, proposing options for its beneficial use, and conducting technical and economic calculations to evaluate the payback of the proposed scenario. Using the heat power of the CHP as an example, the study assessed the influence of key technical and economic factors when introducing a heat pump into the CHP structure. The quantitative dependencies of the impact of thermodynamic parameters on the system efficiency of CHP operation have been established.

The overall result of the dissertation comprises scientifically based technical solutions contributing to the enhancement of the thermal efficiency of the CHP through the integration of a heat pump.

Lühikokkuvõte

Fossiilkütustel põhineva CHP kaugküttesüsteemi dekarboniseerimine

Tänapäeval on koostootmine elektrijaamades üks enim kasutatavaid tehnoloogiaid, mille eesmärk on säästa kütust ja sellest tulenevalt vähendada CO_2 emissiooni. Käesoleva töö osana läbiviidud uurimustöö eesmärk on aidata kaasa selle kollektiivse nägemuse kujundamisele säästvast energia tulevikust, keskendudes kaugküttesüsteemi energiatõhususe tõstmisele nii tehnilisest, operatiivsest kui ka majanduslikust vaatenurgast. Selle uuringu peamise eesmärgi täitmiseks määrati kindlaks peamised uurimisvaldkonnad:

- kaugküttesüsteemide täiustamist mõjutavad tegurid;
- koostootmise majanduslik lähetamine kaugkütte nõudluse poole juhtimise kaudu;
- erinevate koostootmisjaamade konfiguratsioonide kaugküttesüsteemide varustusvõimaluste võrdlus;
- koostootmisjaamade energiatõhususe suurendamine, kasutades soojuspumba integreerimise kaudu jahutusveest saadavat madala kvaliteediga soojust.

Kaugküttesüsteemi efektiivsuse tõstmine on saavutatav vaid tervikliku analüüsiga, mis arvestab investeeringute majandusliku efektiivsuse, soojusenergia tootmise termodünaamiliste aspektide ja nende seose keskkonnaga koosmõju. See hõlmab kaugküttesüsteemide optimeerimist, tarbimisandmete kasutamist koostootmisjaama dispetšerite hõlbustamiseks, erinevate koostootmise konfiguratsiooniskeemide võrdlemist ja koostootmise heitsoojuse kasutamist soojuspumba abil. Optimeerimismetoodika väljatöötamine kinnitab teoreetilise võimaluse kasutada neid võimalusi tehnoloogiliste lahendustena.

Koostootmisjaama efektiivsuse tõstmise probleemi lahendamisega kaasneb tehniliste ja majanduslike tegurite arvestamine. Nende hulka kuuluvad koostootmisjaama tehnoloogilise skeemi tunnused, töötavate seadmete seisukord, töörežiimid, rajatise klimatoloogilised omadused. Seadmete tegelikud töörežiimid mõjutavad soojuspumba kasutamise efektiivsust, mistõttu on vajalik nende arvestus. Kavandatavatel ja põhjendatud tehnilistel lahendustel on potentsiaali oluliselt tõsta koostootmisjaamade soojuslikku efektiivsust, vähendades samal ajal nende keskkonnamõju.

Selle uurimuse teoreetiline tähtsus seisneb selles, et soojuspumba integreerimine on kasulik meetod kaasaegsete koostootmisseadmete jahutussüsteemi heitsoojuse ärakasutamiseks. Tehnoloogilise protsessiga integreerimine ja soojuspumba energiatõhususe arvutamise metoodika väljatöötamine, võttes arvesse hooajalisi soojustarbimise mustreid, kaugküttesüsteemi temperatuurigraafikut, madala kvaliteediga heitsoojuse allika temperatuuri. Uuringu praktiline tähtsus seisneb koostootmisseadmete heitsoojuse kasuliku kasutamise stsenaariumi väljatöötamises. See hõlmas kaotsiläinud soojusenergia mahu hindamist, selle kasuliku kasutamise võimaluste väljapakkumist ning tehniliste ja majanduslike arvutuste tegemist, et hinnata pakutud stsenaariumi tasuvust. Kasutades näitena koostootmisjaama soojusvõimsust, hinnati uuringus oluliste tehniliste ja majanduslike tegurite mõju soojuspumba kasutuselevõtul koostootmissüsteemi. On kindlaks tehtud termodünaamiliste parameetrite mõju kvantitatiivsed sõltuvused koostootmissüsteemi töö efektiivsusele.

Lõputöö koondtulemus sisaldab teaduslikult põhjendatud tehnilisi lahendusi, mis aitavad soojuspumba integreerimise kaudu kaasa koostootmisjaama soojusliku efektiivsuse tõstmisele.

Appendix: Included publications

Publication I

Ruševjuk, P.; Volkova, A.; Lukić, N.; Lepiksaar, K.; Nikolić, N.; Nešović, A.; Siirde, A. "**Factors Affecting the Improvement of District Heating. Case Studies of Estonia and Serbia**" Clim. Technol. 2021, 24, 521–533, https://doi.org/10.2478/rtuect-2020-0121

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Factors Affecting the Improvement of District Heating. Case Studies of Estonia and Serbia

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Abstract **– Factors affecting both the Estonian and Serbian district heating improvement are analysed, including geographical and climate factors, as well as economic and legal factors. This analysis is added by evaluation of main technical and economic parameters related to the district heating networks from the case studies (Estonian Narva city and Serbian Kragujevac district heating). This analysis uncovered the weakest points of Kragujevac district heating and explain why district heating is not considered as sustainable and environmentally friendly heating option.**

Keywords **– Biomass; district heating; district heating network; fossil fuel; pipes; renewable energy**

1. INTRODUCTION

District heating (DH) can be considered the optimal/most preferable option only when heat production, transmission, and consumption is energy-efficient, competitive, and environmentally friendly [1].

Many studies have analysed the factors affecting DH. In [2], a method was proposed for describing the factors that affect energy systems. According to [2], there are several sets of technical and economic factors: energy sources, design considerations, environmental impact, performance analysis, and energy policy. It is also necessary to determine the necessary improvements to the system [1]. In [2], a different approach was proposed where key technical and economic factors were divided into three major groups: fuel-related factors, network factors, and energy production factors [3]. The factors related to fuel include fuel costs, environmental scenarios, existing fuel supply infrastructures, transportation and storage logistics, energy density, and fuel quality [2]. The factors associated with the DH network are heating load, energy efficiency of buildings and costs of DH pipeline installation/refurbishment. The factors that affect energy production are the selling price and subsidies.

To determine the importance of a factor, an assessment matrix can be built. In [4], an assessment matrix of 31 parameters was created and used to assess future DH challenges in the case of Austria for various future scenarios. The indicators in this assessment were heat consumption density, full load hours, available heat sources and temperature.

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In [5], a method was proposed for assessing the current state of DH and its development potential. This assessment is necessary to prevent stagnation in the DH sector. Technical factors include heating load, length of pipes, heating used in buildings, as well as degree days. Among the most important economic factors is the DH market share. According to [5], the most important factor is the heating load.

Technical factors that affect the DH improvement potential are described in [6]. To evaluate the current technical condition of the DH network, the following parameters should be taken into account: the duration of the heating season, average monthly ambient temperature, as well as temperature graphs showing the dependence of the supply and return temperatures on the ambient temperature. When considering these parameters, one can estimate the overall heat transfer coefficient of a DH network. To assess the DH network's improvement potential, an important factor to consider is friction loss, which depends on pipeline geometry, pipeline length, differential pressure necessary for boiler room operation, the amount of electricity used for pumping, heat loss due to pipe diameter and pipeline heating load.

Energy policy is another important factor affecting the DH sector, in addition to technical and economic factors. Energy policy measures, such as the tariff system and support policies, also affect DH. The economic feasibility of various development scenarios was studied in [7], and it was determined that for DH prosumers to continue investing in future developments, the DH tariff cannot be reduced. An appropriate tariff system can encourage DH prosumers to increase the efficiency and use of renewable energy sources [8].

DH support measures can also act as burden measures, market control or financial support [9]. Carbon taxes on fossil fuels are a good example of a burden measure. Financial support can be provided through grants for investments in initiatives related to expansion, efficiency and environmental improvements.

Legislation is also important in maintaining DH feasibility [10]. Legislation must consider the market situation to be able to promote DH in the country. In general, the market situation can be divided into 4 stages: consolidation, refurbishment, expansion and new development, as stated in [10].

DH is also affected by primary energy factors (PEF) due to Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings [11], which states that the number of nearly zero-energy buildings must increase and to achieve this, PEFs are introduced to determine the energy consumption of the building. [12] examined PEFs for DH in different EU member states. In [13], a methodology was proposed for evaluating PEF for energy-efficient DH.

2. Factors Affecting District Heating Development

As can be seen from the previous review, many factors affect the implementation and further development of district heating. DH implementation is usually associated with factors such as climate conditions and building density.

Climate conditions influence the district heating sector, which is confirmed by the fact that the most developed DH networks are in countries with colder climates [10], for example, in Sweden [14], Finland [15], Estonia [16], and Latvia [17]. On the other hand, there are countries with cold climates, such as Norway, the UK and the Netherlands, where the share of DH is not very high, which can be explained by the influence of other factors [11].

Another factor is the building sector. In the case when the building density is high and the proportion of multi-family apartment buildings is also high, this leads to a greater heat load, which is significant for district heating feasibility and sustainability.

DH should be a competitive heating option. If other heating options are more available and affordable, this can lead to a low share of DH. For example, in Norway, where electricity is cheap and widely available, the share of DH is about 12 % [18]. However, low-temperature DH can also be implemented in Norway. Possible development and transition towards low-temperature DH in Norway using various technical solutions, including large heat pumps, is discussed in [17].

Political factors, such as support measures and legislation changes have been analysed in various studies. However, in addition to these factors, there are other important external political processes/changes that have a big impact on improving DH.

For example, the high share of DH in the countries of the former Eastern Bloc is due to the fact that during the 1960s and 1970s cities were transformed via mass housing development projects, which included the development of DH networks. The urban infrastructure appeared as a result of rapid industrial expansion, urbanisation, and modernisation, supported by the socialist self-management system [19].

Other political processes, such as the independence of the Baltic countries, have led to a complete restructuring of the infrastructure, including DH. The decline of socialism has led to the transformation of property ownership, both for residential buildings, heat production units, and DH networks. Other changes, such as closing of industry and industrial enterprises that were either heat providers or consumers have had an impact on district heating. For example, the Krenholm Manufacturing Company (Narva, Estonia), one of the main consumers of steam produced by the Balti Power Plant in the second half of 2000, installed its own gas boiler.

Another problem faced during this period was an opportunity for buildings to disconnect from the DH network, thus reducing the district's heating load. In 2000, the two largest apartment buildings in Narva (700 apartments) refused DH installing gas boiler instead, and only in 2012 they returned to DH.

The same political processes influenced the availability of fuel used for DH. Fuel that used to be cheap and widely available before these political events was no longer as affordable. Higher prices for imported fuels caused a switch to local fuels, such as shale oil and wood in the case of Estonia.

In the case of Serbia, the key political events that affected the energy sector include the Yugoslav Wars and the breakup of Yugoslavia. For example, in Kragujevac during the war, a power plant that provided the city with heat was bombed and sustained serious damage. Industry closure occurred, and in some cities, such as in Kragujevac, heat production must be completely changed. For example, after 2000, most of the Zastava factory complex was closed, and the share of industrial energy needs fell below 10 % of the total Energetika (Kragujevac energy company) energy production. Since then, DH has become the goal of the Energetika Company. During this transition period, the network and heat production were in poor condition.

20 years ago, the situation with DH was almost the same in both Serbia and Estonia. But if we look at the DH sector now, we can tell that DH in Estonia is rapidly developing and numerous efforts are being made to transition towards the 4th generation DH. The DH sector in Serbia is also developing, but not as fast, and there are various specific barriers, both past and present, that do not allow DH to improve. These factors will be analysed in this paper. Two DHNs were selected for a more detailed analysis. Serbia's Kragujevac DHN will be compared with Estonia's Narva DHN. The annual heat consumption in Kragujevac is proportional to the heat consumption in Narva.

Existing problems, as well as measures aimed at improving DH, will be analysed and DH improvement scenarios will be developed based on this analysis.

3. Evaluation Methodology

The comparative methodology will include two sections. The first section will be related to the factors that affect both the Estonian and Serbian district heating sectors. Based on the literature review, the following key factors will be analysed and compared for Estonia and Serbia: geographical and climate factors, as well as economic and legal factors.

Geographical and climate conditions: as mentioned above, this group of factors has an impact on DH implementation and improvement. Geographical conditions associated with DH include the average outdoor temperature and the length of the heating season.

Another aspect related to geographical conditions is resource availability. The following resources need to be analysed: fossil fuel availability and renewable energy availability. In addition, all available heating options, such as electric heating, should also be analysed.

Economic and legal factors will be reflected in an analysis of the available government support instruments, such as supporting regulations, taxes, special loan conditions, etc. In addition, economic and legal factors will also be covered in an analysis of fuel prices, operating costs and the tariff system.

External social and political processes and their impact on DH will also be evaluated.

The second section of the analysis will include a set of the main technical and economic parameters related to the DH networks from the case studies.

The analysis of technical parameters will include the following steps: a brief description of the network and its improvement over the past 20 years, as well as the calculation of such parameters as the number of consumers, the amount of fuel used, CO_2 emissions, the share of DH in the city, etc.

Each city has a different way of calculating tariffs, therefore, for comparison, the recalculated tariffs (EUR/MWh) will be taken from the analysis conducted in [19]. The tariffs will be compared with other heating options in the region.

This analysis will uncover the weakest points and explain why DH is not considered a sustainable and environmentally friendly heating option. Based on this analysis, recommendations will be made for Kragujevac DH.

It should be added that the comparison of the two DH networks was limited by the availability of data from the Kragujevac DH systems. This can be explained by the fact that not all data was collected or provided by the operator. In addition, there is remote metering data available for Narva, but none is available for Kragujevac, so this type of data could not be used in the analysis.

4. District Heating in Estonia and Serbia

4.1. Climate factors

When comparing district heating in Estonia and in Serbia, it should be noted that the climate in Serbia is warmer than in Estonia.

For example, changes in outdoor temperature for Narva (Estonia) and Kragujevac (Serbia) are shown in Fig. 1., 1and as it can be seen, daily average outdoor temperature in Kragujevac is higher during all the year comparing to outdoor temperature in Narva.

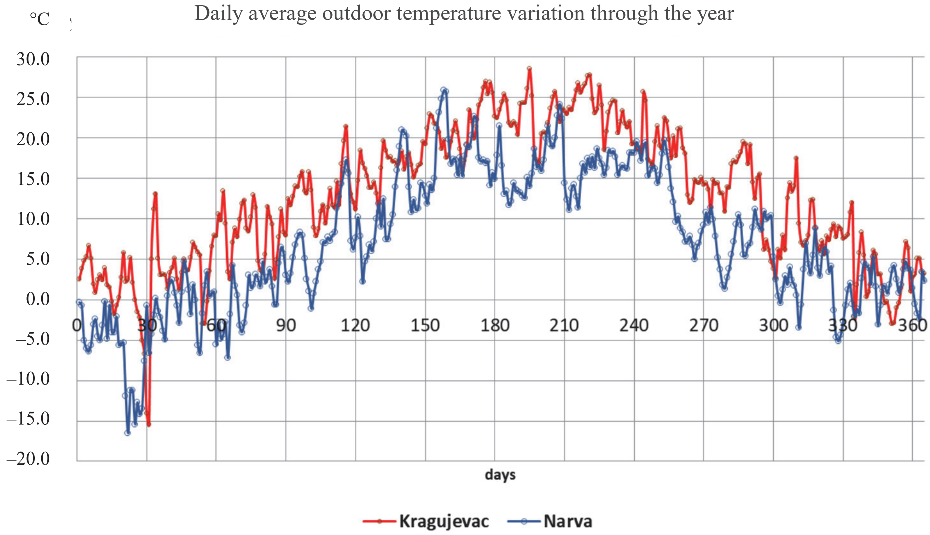

Fig. 1. Average daily outdoor temperatures for Narva and Kragujevac.

4.2. Availability of local resources

The energy resources used for DH can be seen in Fig. 2 (a) and (b) for both countries starting in 2010.

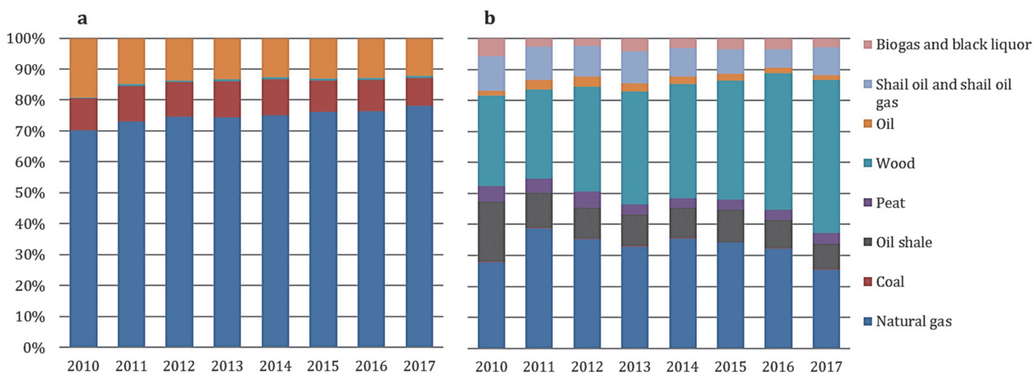

Fig. 2. Fuel consumption for DH in Serbia (a) and Estonia (b).

In Serbia, the share of natural gas is increasing every year. Coal is also used for heating, but the amount of wood consumed is very small. 20 years ago, boiler plants mainly used coal and fuel oil to produce thermal energy. Today, the share of such boiler plants has decreased significantly, because more and more boilers are switching to natural gas, which is also mandatory for new boiler plants.

As can be seen in Estonia, the use of oil and natural gas has been on the decline since 2010. The use of wood for heating has increased, which can be explained by strong government support. Additionally, it should be explained why the use of shale oil and shale oil gas has increased. This is due to increasing production of shale oil, where shale oil gas is considered a by-product and is used for DH.

20 years ago, the share of heavy oil-based boilers was rather high in Estonia. But it has been decreasing every year due to the high price of heavy oil and environmental regulations. This amount reflects available capacities, but oil-based boilers are mainly used as backup boilers.

Coal is the local fuel in Serbia, and oil shale is the local fuel in Estonia. These fuels are fossil fuels, but their price can compete with imported fuels, so these fuels (or products made from these fuels) are used for DH.

Biomass availability is higher in Estonia. In [21], the available mass of these types of biofuels is estimated for various EU countries. As a result, it was determined that in Estonia the available agricultural residue is about 1.1 million tons per year, forestry residue is about 0.99 million tons per year, and available biological waste is about 0.11 million tons per year. [22] also assessed the potential of woody biomass from forests, including stemwood, logging residues, and stumps, in EU countries. According to [22], Estonia is among the regions with the highest biomass availability, where the available biomass per hectare is between 0.51 – 0.75 tons per year. The share of forests in the total land area in Estonia is 51.4 %, of which 74 % are profitable forests and 26 % are nature reserves, according to Estonian Statistics [23]. As for biomass availability in Serbia, the total Serbian biomass energy potential can be estimated at 2.5 to 3 Mt, of which 40 % is wood biomass and 60 % is agricultural biomass.

Another renewable energy source is geothermal energy. Current studies show that in Estonia there is no potential for using geothermal energy for DH. In Serbia, the total Serbian energy potential of geothermal energy can be estimated at 320 MW. These are mainly low-temperature sources (20–100 °C), suitable for use as heating energy or for heat pump use.

Solar energy in Estonia is mainly used for electricity production. According to [24], in 2018, 13 GWh of solar electricity was produced, which is 0.8 % of the total RES electricity and 0.13 % of the total electricity production. Solar energy is not used as thermal energy in the DH sector in Estonia. And in Serbia, the total potential of solar thermal energy can be estimated at 10 million m^2 of installed solar collectors and 7000 GWh thermal energy per year [25]. Due to the lack of significant government subsidies and low electricity prices, the assessment of the potential of solar energy in Serbia is only theoretical. As for solar heat, this assessment is mainly for individual heating and only a small fraction of the heat load can be covered by central solar heating.

It should also be noted that in terms of local resources, cheap electricity is available for heating in Serbia. The low price of electricity is determined by factors, such as available coal resources that are used for electricity generation, as well as hydro sources.

4.3. Prices of energy resources

Energy prices are very important for analysing the competitiveness of DH. On the one hand, fuel prices affect heating tariffs; on the other hand, a low price of natural gas, for example, can lead to a switch from DH to gas heating. Cheap electricity will cause consumers to choose electric heating over DH.

The price of heating for consumers is lower than the cost of electricity in Estonia. As mentioned earlier, the price of electricity in Serbia is very low, which can be explained by the availability of coal and hydropower resources. Other factors include the lack of SO_2 and NO_x control and CO_2 penalties.

Often, Estonia is portrayed as a great example of a centrally controlled district heating market subject to a consistent set of regulations, where the roles and obligations of different parties are clear and reasonable. The history of the regulation and its fundamental characteristics can be found below [26].

Until 1998, municipalities carried out mild price regulation. In 1998, the Energy Act introduced ex-ante pricing for DH grids and heat-only boilers that is set on a case-by-case basis by the new national regulatory authority (the Energy Market Inspectorate at the time) as the maximum price for end users (DH price cap). The price of heat for end users is determined by the national regulatory authority in order to cover the costs of the DH company and receive a reasonable return (regulatory WACC), which is calculated today according to the methodology publicly available on the Estonian Competition Authority (ECA) website.

Estonian DH market is regulated by the District Heating Act (DHA) and the Competition Act; the maximum prices charged in network regions have to be approved by the Competition Authority. The DHA regulates the activities related to the production, distribution and sale of heat through DH networks and connection to said networks. The DHA entered into force in February 2003 and has been amended a number of times since. This requires heating companies to maintain separate accounts for the production, distribution and sale of heat, and other activities, as well as for the costs incurred in combined heat and power (CHP) plants. The DHA also stipulates that the price of heat produced in CHP processes is subject to approval by the Competition Authority. The task of the Competition Authority is to coordinate prices of DH in such a way as to avoid cross-subsidisation of electricity in the allocation of costs. Based on the DHA, heating companies can apply to the Competition Authority for approval of a price formula for a period of up to three years. This price formula is used if factors that are beyond its control and which affect the price of heat become evident [27].

The DHA, which was in force until 2010, did not foster competition or regulate market access for new producers. Since heat production and distribution networks are often owned by the same companies enjoying monopoly power, new heat producers have no alternative but to sell heat to the existing heating network.

At the beginning of 2020, the weighted average value of the maximum DH prices is 60 EUR/MWh; the lowest price is 35 EUR/MWh (excluding 20 % VAT), and the highest price is 86 EUR/MWh. As a rule, the actual selling price is very close to the defined maximum price. The procedure or methodology for coordinating the maximum price was developed by the Competition Authority, and since November 2010, all DH providers must request coordination of their maximum prices from the Competition Authority.

TABLE 1. DISTRICT HEATING PRICES IN KRAGUJEVAC [29]

Pausal payment			
Consumer category	Fixed, €/m^2	Variable, €/m^2	Total, €/m^2
Housing	0.23	0.49	0.71
Social activities	0.34	0.73	1.07
Other users	0.68	1.47	2.14
Payment by consumption			
Consumer category	Fixed, €/m^2	Variable, €/MWh	
Housing	0.23	41.89	
Social activities	0.34	62.84	
Other users	0.68	62.84	

The price of heat delivered to the DH system in the Republic of Serbia is regulated by local authorities in accordance with the established methodology [27], therefore it differs from city to city. The prices of DH for the city of Kragujevac are shown in Table 1.

4.4. Emissions

In accordance with the Kyoto Protocol, Estonia started selling Assigned Amount Units (AAUs) in 2009 as part of the Green Investment Scheme (GIS) and has earmarked the proceeds for projects that facilitate emission reduction. Examples include wind farms, CHP plants, improving DH networks, retrofitting boiler houses, improving energy efficiency in buildings and industries, as well as introducing more efficient buses, trams and electric vehicles. Under EU law, Estonia is obliged to limit the growth of GHG emissions from outside the EU-ETS sector to 11 % between 2005 and 2020 [3].

A CO_2 pollution charge applies to heat producers in the DH system. Since 2009, the rate has been 2 EUR per ton. Electricity producers also used to be subject to a pollution charge, but since January 2008 they are subject to an excise tax. The latest tax has been 4.47 EUR/MWh since March 1, 2013.

Serbia committed to and signed the Paris Agreement on Climate Change in April 2016 and ratified it in July 2017, pledging to cut 9.8 % of CO_2 emissions by 2030. This is a rather ambitious task. According to earlier forecasts, electricity producers will be faced with an obligation to pay for CO_2 in Serbia between 2020–2025, when the country is expected to join the EU [29]. Emission allowances are not implemented in Serbia. The reason is that such a measure could lead to an increase in the price of other energy sources, including electricity, the price of which in Serbia is one of the lowest in Europe. However, to further European integration, Serbia is obliged to introduce this measure at some point. The first step has already been taken at the end of 2019 when a tender was announced to prepare a study on the introduction of the CO_2 tax. The tender was held by the Energy Community with the ultimate goal of preserving the environment.

4.5. Financial support

The Environmental Investments Centre (EIC) was founded in Estonia in 2000, and it has been one of the main sponsors of environmental projects in Estonia over the past 20 years. In 2009, the EIC (KIK in Estonian) awarded grants to local governments, non-profit associations, businesses and foundations as part of the 'Broader use of RES for energy generation' programme that used funding from the European Regional Development Fund (ERDF). The state provides support to the heating sector mainly through environmental protection and regional development goals. From 2005 to 2009, the heating sector received EUR 13.9 million from the ERDF and Estonian environmental taxes, as well as EUR 0.9 million from the state budget and through the support scheme for investments in energy-saving solutions during the same period.

The 2009 application round had a total funding volume of approximately EUR 9.6 million and 17 projects received grants for the reconstruction of boiler houses, DH networks and construction of CHP plants in accordance with the support mechanism for the generation of electricity in cogeneration and from renewable sources.

The EIC manages a national programme called 'Extended use of renewable energy sources (RES) for energy generation and reconstruction of DH networks', which is funded by CO_2 quota sales. It supports three types of activities: construction of CHP plants that use RES;

reconstruction of boiler houses; reconstruction of DH networks to reduce thermal transmission losses.

In 2014–2020, the grant is allocated from the measure 'Effective Production and Transmission of Thermal Energy' for structural aid. The total budget of the application round is EUR 18 million. Of these, EUR 12 million are planned for boiler renovations. EUR 6 million has been allocated for the repair of heating pipelines, the construction of new connections and a new DH system. The grant is funded by the European Union Cohesion Fund.

In Serbia, financial support for DH is sporadic. Starting from 2001 investments for infrastructure have been provided by the European Bank for Reconstruction and Development. One of the biggest projects was supported by KfW Development Bank [30]. As a result of this support, 42 km of pipes were restored in 18 cities, 7 new boilers were installed, 2 boilers were renovated, 1 CHP was installed, pump stations were renovated, 1000 remote meters and 500 substations were installed. It is evident that this support is not regular and there is no continuing support from the government, and the improvement of DH is still very slow.

4.6. Additional support

In 2004, the District Heating Act entered into force in Estonia, allowing municipalities to create DH zones where DH is the only option for heat supply, with the exception of non-fuel (i.e., heat pumps) or renewable energy sources. However, this Act does not provide a methodology or criteria for creating a DH zone, leaving it up to municipalities. In 2010, the DH Act was amended to establish the ECA as the DH regulator, as well as third-party access rules. These rules consist mainly of the obligation of DH operators to organise a tender for new generation capacity, where tender documentation must be approved by the ECA.

Based on this analysis, factors affecting DH at the national level are presented in Table 2.

Additionally, a comparison of the Kragujevac and Narva DH systems is presented in Table 3.

Previously, the Kragujevac DH system had significant losses of water in the pipes due to water treatment capacities and, consequently, oxidation inside the pipes and its degradation. With the help of the EU loans, new pre-insulated pipes were partially implemented (to some per cent), and new combined (gas and oil) hot water boilers were installed instead of inefficient coal boilers.

25 years ago, the entire city of Narva was centrally supplied with heat through the Balti Power Plant, and domestic hot water (DHW) was supplied through a mixing valve system. Almost all heating units used a mixing valve system, and the DHW system was open. In 1996–1997, the city implemented a programme to replace mixing valve heating units in houses. 270 automated heating units were installed, and the domestic hot water system was rerouted into an independent circuit. Over the past 20 years, quite a few new DH consumers have been added to the system.

TABLE 2. ANALYSIS OF FACTORS AFFECTING DH SYSTEMS

Factor	**Estonia**	**Serbia**	**Impact on DH development.**
Climate factors	Cold climate	Warmer climate	In warmer climates, annual heat consumption and peak heat load are lower. DH improvement does not always have high feasibility. In warmer climates, heat loss is lower, while distribution efficiency is higher.
Local fossil fuels	Oil shale, Shale oil	Coal	When local fossil fuels are available and at lower prices, it is more difficult to implement renewable energy sources for heat production.
Renewable energy availability	Biomass availability is high. Wood chips are available in sufficient quantities.	Biomass availability is lower, but still available, as well as geothermal energy.	Biomass availability allows to produce heat from renewable energy sources
Legislative and regulatory instruments	Electricity market act: feed-in premium tariffs for biomass CHP	National plans to increase the share of renewable energy	Specific support mechanisms introduced in 2007 over the course of several years led to an increase in renewable electricity in Estonia from 2 % to 15 % due to the installation of a new biomass CHP. Only clear and consistent support mechanisms with a long-term perspective have an impact on DH.
Emission regulations	CO_2 emission taxes	Only planned, no restrictions	There are no financial benefits in Serbia to replace fossil fuels with renewable energy. The renovation is mainly focused on replacing coal boilers with gas boilers.
District heating regulations	District heating act: DH regions	No specific DH regulations	Estonian DH operators have guarantees that there will be heat consumers in the future.
Tariff system	Tariff stimulates system improvement	Every authority has its own tariff system.	DH tariffs are competitive with other heating options
Prices compared to other fuels, electricity, etc.	Competitive or lower	Higher than other options	In Serbia, consumers often prefer other heating options.

Unfortunately, it was not possible to obtain the necessary data from the DH company because this data was not collected or not provided. Even heat losses could not be compared. That is why it is rather difficult to compare the two systems. Smaller number of substations in Narva can be explained by colder climate and higher heat consumption per each substation. Another factor is that 9-floor large multifamily buildings are the main DH consumers in Narva city, and in Kragujevac smaller 3–5 floor buildings are more typical, as DH consumers. Larger number of employees in Kragujevac can be explained by the fact, that the DH company employs production, distribution and repair workers, but in Narva DH company employs only production and distribution workers.

TABLE 3. COMPARING OF KRAGUJEVAC AND NARVA DH SYSTEMS

Parameter	**Kragujevac**	**Narva**
Total nominal installed capacity	432.65 MW	160 MW (Power plant) + 240 MW (gas boiler house) = 400 MW
Heat generation units	coal boilers heavy oil/gas boilers	oil-shale/biomass power plant natural gas boilers
Heat production (2017)	385 000 MWh	389 000 MWh
Fuel	63 % coal, 24 % heavy oil 13 % natural gas	49 % Oil shale, 1 % Shale oil, 25 % biomass 25 % natural gas
CO_2 per MWh produced	0.39 tCO_2/MWh	0.26 tCO_2/MWh
Share of remote metering	0 %	99 %
Number of separate DH districts	3	1
Tariff (for a 50 m^2 apartment) per MWh	28.4 Euro/MWh for fix and 59.5 Euro/MWh for variable tariff	35.33 Euro/MWh
Tariff compared to electric heating DH tariff/Electricity tariff	28.4/70 = 0.41 and 59.5/70 = 0.85	0.36
Number of employees	300	50
Total number of substations	2095	724
Total length of heating pipes	81 km	77 km
Key issues	Water leakage Low efficiency Destimulating tariff system	High share of fossil fuel High CO_2 emission taxes Some consumers refuse DH High return temperature

As for tariffs, Kragujevac DH tariffs comparing with Narva DH tariffs are lower in Kragujevac when fixed tariff is applied and higher, when variable tariff is applied. It should be noted that Narva DH tariffs are the lowest in Estonia. If we compare the DH tariffs with local electricity prices, relation between heat and electricity prices is lower in Narva and this way of heat supply is more preferable, then electricity. This can be explained by the fact that Estonia's policy and support mechanisms are working well, which leads to system improvement.

5. DISCUSSION AND CONCLUSIONS

There are variable factors that affect DH improvement. During the implementation of DH, the determining factors are climate and types of buildings, but economic factors are more significant for DH improvement regulation. To assess the importance of these factors, factors affecting DH in Estonia and Serbia were compared. In addition, DH systems of Estonian Narva and Serbian Kragujevac were compared. The DH system in Narva has better operation efficiency parameters and environmental aspects, considering that Narva DH system is only supplied by an oil shale power plant.

Based on these analyses, the following recommendations can be made to improve DH systems in Serbia, including Kragujevac:

– CO_2 taxes will increase the use of renewable energy for heat production;
– Changes in the DH tariff system in Serbia can motivate both consumers and companies to increase energy efficiency;
– Obliging the DH operators to increase energy efficiency greatly affects system improvement;
– With the improvement of DH systems, the concept of DH regions can be implemented to give DH operators guarantees of base heat loads.

Strong and consistent government support, both through regulations and financial aid will lead to increased energy generation, distribution, and consumption efficiency in DH systems. In addition, the possibility of a wider use of geothermal energy for DH should be investigated. If these conditions are met, DH can significantly contribute to increasing the share of renewable energy and CO_2 emission reduction in the Serbian energy sector.

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Publication II

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Economic Dispatch of CHP Units through District Heating Network's Demand-Side Management

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Abstract: Optimisation of heat and electrical load distribution, where the objective function is the maximum efficiency of the CHP unit for a given load range, can be done considering the limitations of electrical power and the heat load. Simulating a real CHP unit with a district heating network shows that demand-side management can improve the overall economic efficiency of the CHP plant and increase the unit's operating range in the electricity spot market. Economic dispatch makes it possible to determine a reasonable additional increase in the electric power of the CHP unit, and to optimise the supply temperature and mass flow of the district heating network. The results obtained and the analysis performed indicate that the proposed methodology provides logical results and can be used to calculate the efficiency indicators of the cogeneration of electrical and thermal energy. The problem of optimising the operating mode of the CHP unit was solved, which allows us to determine the optimal additional increase in the unit's electrical load at a given heat load of consumers, which on average increases the CHP unit's efficiency up to an additional 1.5%.

Keywords: economic dispatch; CHP unit; demand-side management; efficiency; electrical and heat load; optimisation; district heating; consumption; demand

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1. Introduction

In today's European district heating networks, about three-quarters of the total heat supply is provided by CHP units. Since the beginning of 2013, the Estonian electricity market has been fully open to all electricity consumers and is run by Nord Pool. Electricity generated simultaneously with heat can be sold on the spot markets. Due to the increase in the variance of the price of electricity, it is important for the profitability of the CHP unit to produce electricity when the price is high. Of course, the demand for thermal energy will never be fully synchronised with the demand for electricity [1].

The traditional goals of economic dispatch of CHP units are minimising operation cost and maximising profits [2]. Optimisation of heat and electrical load distribution, where the objective function is the maximum efficiency of the CHP unit for a given load range, can be done considering the fact that electrical power is limited by the heat load. The main problem of CHPs is that their operation is highly dependent on the heat load, which makes them rather inflexible or reduces the overall efficiency during periods of insufficient heat load (condensing turbine [3]).

The combined heat and power economic dispatch problem is formulated as an optimization problem [4]. A practical economic dispatch problem should include minimum and maximum limits for power and heat generation of CHP unit, which makes searching for the optimal dispatching a challenging problem [5]. The optimal economic dispatch for various types of CHP plants was analysed in [6]. In [7], the flexibility of CHP and thermal energy storage was explored using a two-stage optimal dispatch, considering the day-ahead heat market and real-time wind power balancing. There are also some studies focusing on solving the district heating operation problem together with the optimal dispatch for the electric power system [8–10]. Electricity and heat networks were investigated as a whole by combined analysis in [11].

In recent studies, global optimisation techniques, such as genetic algorithms [12], the harmony search algorithm [13], and particle swarm optimisation [14], have been used for the optimal tuning of CHP economic dispatch-based restructure schemes.

In this paper, maximum overall efficiency and heat and power output for each heat demand are obtained using advanced calculus methods that involve the Lagrangian function [15], where the problem is to determine the power and heat produced by the CHP unit so that the system's overall production efficiency is maximised while the demand for power and heat, as well as other constraints, are met.

The importance of demand-side management for heat production efficiency was discussed using the example of a CHP unit that is flexible due to the coupling of heat and power energy vectors and provides real-time demand-side management [16], to external market signals, thus boosting their overall business case with respect to classic load following operation [17]. Following the preliminary work done in [18], this paper proposes a case-based system-level modelling approach that provides an innovative and integrated analysis of optimal and dynamic (as in real-time demand-based) control of CHP plants under uncertain market prices.

According to the fourth-generation district heating concept, decentralised intelligent metering is an important aspect of sustainable district heating [19]. Wireless collection of heat meter readings makes it possible to gather hourly data on each consumer. Decentralised intelligent metering allows one to collect additional information on consumer behaviour, providing DH companies with numerous advantages, such as the ability to effectively manage the grid, increase production efficiency, optimise thermal energy storage, and quickly identify faults at substations [20]. The technology of decentralised smart metering is well-developed and successfully used in district heating systems. More than 70% of the district heating companies in Estonia have remote metering [21]. The proportion of decentralised smart metering in Narva's district heating system is 100% [22]. Collecting detailed heat demand data using hourly smart metering can improve the efficiency of CHP heat and electricity production by applying the economic dispatch approach to demand-side management. Without demand-side management and smart metering, heat loads were determined based on the outdoor temperature, statistical data, and temperature measurements of the heat carrier in the district heating network [23,24].

Some researchers have proposed an analysis of the potential of a return temperature differential regulation strategy for substation control to reduce the thermal peak in the DH system [25]. Changes in the schedules of the heating systems installed in the buildings used for virtual storage application were studied in [26]. The energy consumption planning problem was formulated both for individual substations and for the district heating operator in [27]. In [28], an electricity and heat coordinated retail market framework was proposed to achieve coordinated shedding of electrical and heat loads, and to manage the district's energy generation and consumption through transactive control methods. In [29], the main focus was on ensuring that data that were automatically collected in substations were suitable for modelling purposes, for automatically detecting fouled heat exchangers, forecasting the thermal request evolution of the building, as well as determining the proper use of demand-side management based on network dynamics. Another approach to achieving peak shaving is using demand-side management, also called demand response or virtual storage [30]. The estimation of a thermal request is performed using a black box approach consisting of a linear programming model that provides the main characteristics of the curve for a given set of inputs using experimental data [31]. The best peak shaving should be evaluated at the plant level. Plant load is not the same as the sum of thermal requests in buildings, because it is influenced by the thermal transient processes in the network additionally [29]. Several articles demonstrate an interest in achieving higher performances and flexibility in [32].

The benefits of heat consumption forecasts include the identification of demand response actions and peak power demand [24]. Demand-side management is the cost-effective management of complex DH systems that must include the rationalisation of the operations of all components involved in heat production and distribution [25]. Demand-side management uses demand process data related to production status, heat distribution, and weather forecasts to manage production and heat distribution, and tools that allow for the dynamic calculation of control parameters that help achieve maximum efficiency while ensuring adequate heat supply [26].

Demand-side management allows multivariate calculations to determine the expected CHP indicators for the forecast period based on the outdoor temperature and the range of possible deviation. A special role is currently played by short-term forecasting for one day for the participation of power units in the formation of the electric schedule based on the results of open market trading. Taking into account the obtained heat load forecast, it is possible to choose the optimal hourly loads and submit the most favourable price offers.

Thus, there is a need for justification and an adequate mathematical relationship describing the process of changing the heat load depending on several parameters that have a direct impact on the change. The results of the study will make it possible to create the most effective and cost-efficient technical solutions to optimise the operating modes of thermal power units.

Demand-side data were used to identify and validate the heat demand model. This model can be used to replace the simplified average heat load approach to predict the potential electrical load to create an offer for the wholesale electricity market.

The optimisation algorithm performs the following actions:

- Analysis of entered data to ensure that it adheres to existing restrictions;
- Selection of power modes from the database that satisfy the given loads and consider the imposed external constraints;
- Optimization of the distribution of heat and electrical loads of each mode as a function of many variables with linear constraints, such as inequalities and balance equations for the electrical and heat loads of the CHP unit.

Thus, the model uses regression analysis of the empirical dependence of the thermal energy demand on the outdoor air temperature to predict the thermal energy demand with a high degree of accuracy of approximation of the actual demand measurement results. Demand-side management with consumer input also minimises the risk of data errors, while forecasting can reduce potential losses from production efficiency, calculate future consumption demand for each user, and determine total demand.

The study develops in four sections. After introducing and highlighting aspects of the literature in Section 1, Section 2 of the article provides the materials and methods, an overview of the methodology for economic dispatch modelling through demand-side management. Section 3 presents the discussion and Section 4 presents the study results of the model validation using the example of Narva's district heating network and the fossil-fuelled Balti Power Plant CHP unit that provides heat to the DH network. The conclusions are presented in Section 5.

2. Materials and Methods

2.1. Problem Formulation

One of the problems in heat sales management is the inability to estimate the future supply for each customer [33]. Since thermal energy cannot be supplied in a volume that exceeds the real demand for it, the surplus must be minimised at the sales planning stage. This can be done by using an automatic system for calculating demand, which includes individual heat meters and a tool for predicting heat demand [29]. With the help of forecasting, an objective assessment of the current state of control over the sale of heat becomes possible [26]. The main task of the forecasting tool is to calculate individual demand for each customer based on their recorded demand data from the database [34].

The proposed model based on thermal energy demand-side data is dynamic and uses a database of remotely transmitted hourly heat demand data. This makes it possible to use a model instead of statistical data during planning. In this case, obtained data will be based on regression dependences on the values of the current regime parameters of demand, depending on the outside air temperature. By summing the demand data of all customers and taking into account the losses determined via the balance method as the difference between production and demand for thermal energy for the predicted outdoor temperature, we can predict the heat demand for each hour.

The main advantage of this model when solving the forecasting problem compared to models based on information for the past period is that the resulting model can take into account previously unknown information about district heating networks. This information includes changes in heating networks, their reconstruction, the transition to new conditions of demand, and the emergence of new installations among consumers during the predicted period. Taking account of these changes leads to a decrease in the forecast error. Demand-side management data are measured at thermal substations with an automatic download of historical data for each substation. Based on these data, we can obtain a consumption profile for each facility, depending on the outdoor temperature.

Solving the problem of predicting the heat demand of objects will help to determine the amount of heat that will be consumed in the coming periods of time. Each object has a static characteristic that describes its thermal load. This characteristic is static in the sense that it cannot be changed quickly. Therefore, it is very informative for various types of heat demand analysis.

Mathematically, this characteristic is described by the functional dependence: $Q = f\ (T_{outdoor})$, where Q is the amount of thermal energy consumed (MWh) and $T_{outdoor}$ is the outdoor air temperature (°C), allowing us to find a straight line as close as possible to the data points from the heat metering unit. With a high degree of approximation accuracy, it is possible to use a linear function to solve the forecasting problem. To construct and analyse this dependence, one should use the instantaneous demand data from the remote reading system of heat meters.

2.2. Demand-Side Management

The demand-side data for each substation was measured and collected by smart meters every hour for the entire distribution network (730 buildings), which is shown in Figure 1. An automatic system evaluates data outside a meaningful range and fills them in via interpolation. The automatic evaluation of the curve characteristics of all consumers is used to simplify the hourly evolution of the next day's thermal request to easily predict the thermal request.

Outdoor temperature and heat demand are measured every hour for each substation. Examples of this dependence for three selected substations using data collected during the 2020/2021 heating season (October–April) are shown in Figure 2.

As can be seen from the above diagram, this dependence is nearly linear. An important area of application of this model is the solution of forecasting problems. To predict the generation and consumption of thermal energy and heat losses for a short-term period of 24 h, the first task is to understand the variability of each consumer. To do this, we must calculate the demand-side of hourly demand for each consumer via a histogram, an example of which is shown in Figure 2. The y-axis in the graph represents the various hourly demand points and the x-axis represents the outdoor temperature. Based on the consumption data, we have linear characteristics for each object of thermal energy demand. The second task is to understand the influence of the outdoor air temperature on the heat demand of each consumer.

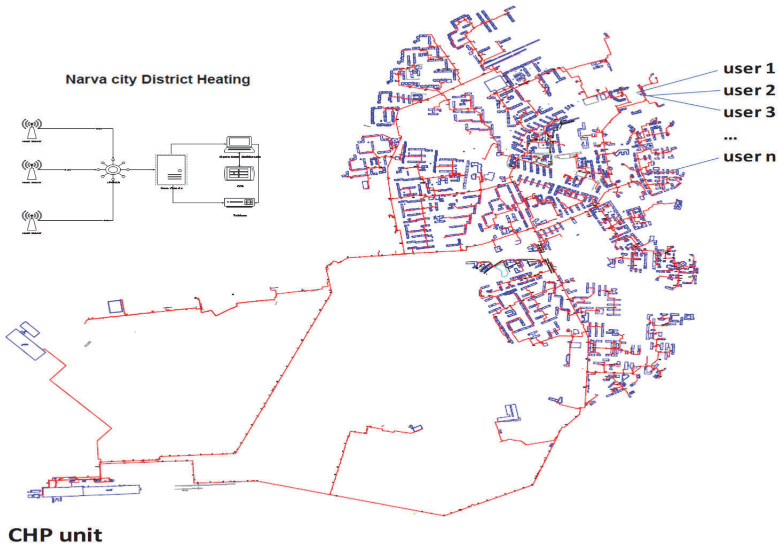

Figure 1. Narva district heating network.

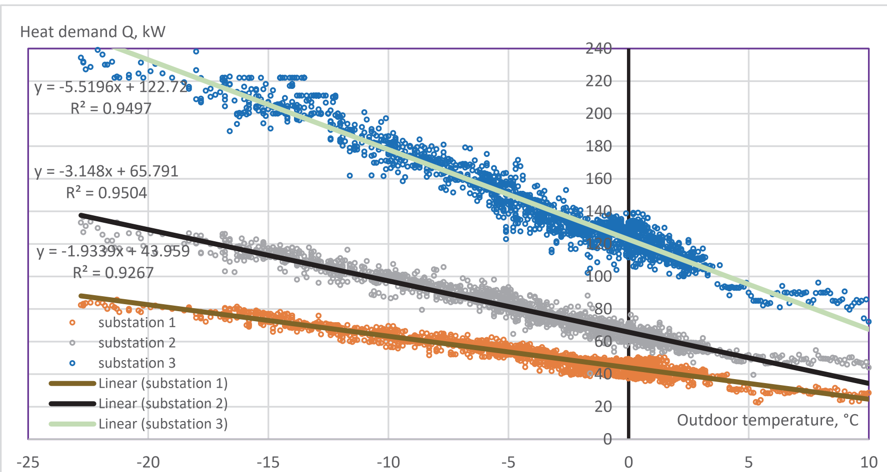

Figure 2. Dependence of the heat demand on the outdoor air temperature.

The final step of the algorithm for the next day's daily profiles is to extract the daily demand hours that occur regardless of the outdoor air temperature. To do this, we use the periodic autoregressive algorithm for time series data from a fragment of an hourly demand time series for all consumers over a period of several days. We are only given the total hourly demand, but the purpose of the algorithm is to determine, for each hour, which load does not depend on temperature and which additional load is temperature related.

The demand-side management approach considered in this paper has x users and y heat sources as the research objects, and the set of all users is represented as $X = (1 \ldots x)$. The number of heat sources Y is denoted by numbers $1 \ldots y$. The relationship between the heat produced by heat source y and its users is represented as $f(y) = (y_1 \ldots y_x)$, where $f(y_x)$ indicates that the heat is supplied to user x over time T. If the heat loss in the system is not taken into account, then the heat supplied to user x by the heat source is equal to the heat dissipated by user x (see Equation (1)).

$$H_{user}x = c \times (t_{1x} - t_{2x}) \times m_x \times T; \sum_{x=1}^{n} (H_{user}) = H_{demand} \quad (1)$$

where t_{1x} and t_{2x} are the supply and return temperatures of user x (°C). m_x is the flow rate of user x (kg/h); c is the water mass/specific heat of water mass (4.19 kJ/(kg·°C))

The heat supplied by heat source y is

$$Qs_y = c \times \left(t_{1y} - t_{2y}\right) \times m_y \times T \quad (2)$$

where t_{1y} and t_{2y} are the water supply and return temperatures of heat source y (°C). m_y is the circulating flow rate of heat source y (kg/h).

The demand-side data collection system allows us to identify the optimal set of user heating system turn-on times, which is necessary to assess the expected thermal profile of each building. Temperature sensors collect temperature data at the inlet and outlet of heat exchangers, and mass flow meters measure the current mass flow rate. These data can be used to estimate the change in heat demand for a monitored consumer at different outdoor air temperatures. This way, it is possible to estimate the consumer's heat load profile for different outdoor air temperature levels.

It is always necessary to satisfy the heat demand, even if the electrical load and the heat load of the CHP unit are interrelated. A typical profile of the average load for a CHP unit before the application of the model and after optimisation with more accurate consumption data is shown in Figure 3.

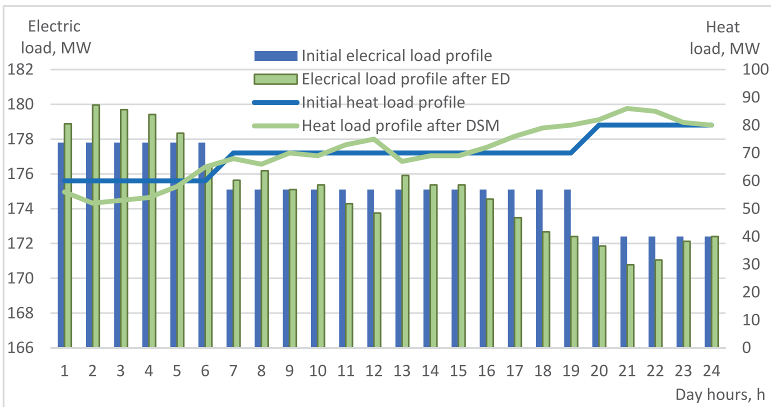

Figure 3. Electric and heat load profile before and after economic dispatch according to demand-side management.

Based on the assessment of all possible combinations of electrical and thermal loads, it is possible to find the general optimum for each mode of operation of the unit. It is necessary to minimize the consumption of primary energy of the CHP or its overall efficiency at the given electrical and thermal loads of the unit for more accurate planning. Economic Dispatch is applied at each settlement hour by optimizing the distribution of heat and electrical loads based on heat demand-side data.

2.3. Combined Heat and Power Generation

The model used in this article was based on the CHP plant and district heating network in the city of Narva (in north-eastern Estonia). The district heating company supplies heat to about 60,000 residents. Narva's district heating network is 78 km long and connected to 730 buildings. Heat is generated at the Balti Power Plant (CHP unit), which consists of two circulating fluidized bed boilers, including one reheat and steam turbine, which is a three-casing reheat condensing impulse reheat turbine with uncontrolled extraction for seven stages of feedwater heating. The fuel used in the Balti Power plant is local fossil fuel oil shale mixed with wood chips [35]. The DH circulating water is heated in a district heater using steam from the crossover pipes between the intermediate-pressure and low-pressure parts of the turbine. Extra steam from the hot reheat steam line is supplied to the peak load and the auxiliary steam is supplied to an external auxiliary steam header. The maximum DH load of the facility is 160 MW and the maximum water outlet temperature is 130 °C. The DH inlet water temperature ranges from 40 °C to 60 °C. The annual heat demand in Narva is about 450 GWh. The unit's annual electricity production is approximately 1300 GWh. The main inputs for these analyses are electricity and heat production and process efficiency as per the data available.

The efficiency characteristic of a CHP unit depends not only on the electrical load, but also on the amount of heat supplied. The electrical efficiency dependence on the electrical load of the CHP unit for different heat loads is shown in Figure 4.

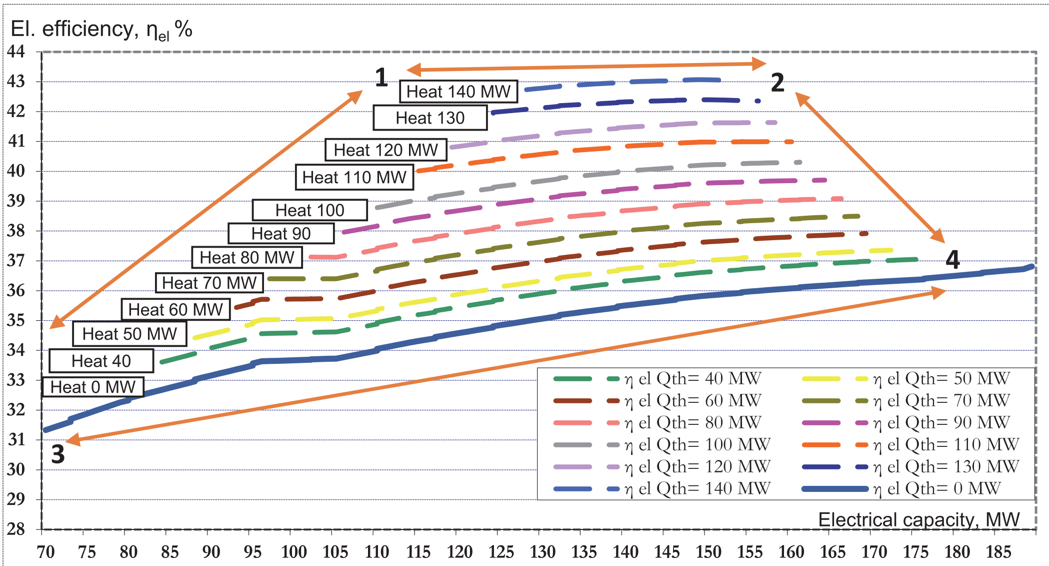

Figure 4. Electrical efficiency of the CHP unit based on the heat load.

Points 1, 2, 3, and 4 have been added to Figure 4 for more clear presentation of CHP operation modes:

1–2—CHP operating at 100% heat load;

3–4—CHP operating without heat extraction;

3–1—limitation on the minimum electrical load to ensure the parameters of heat supply;

2–4—limitation on the maximum electrical load to ensure the amount of heat supply.

It can be seen that electrical efficiency is increased when the heat load becomes larger. When the heat load is maximum, the electrical load is lower (150 MW_{net}). The maximum electrical load (190 MW_{net}) is possible when there is no heat load, but in this case, electrical efficiency is the lowest.

The mathematical optimisation model of a CHP establishes the dependence of primary energy consumption B_i on the value of heat (H_i) and electrical (E_i) loads when operating according to an electrical schedule: $B_i = f\ (E_i)$. When operating on a heating schedule, the electric power depends on the heat load, so the objective function takes the form of $B_i = f(E_i, H_i)$. Short-term optimisation has a horizon of one day, discreteness $\Delta i = 1$ (one hour), and timestamps i.

In accordance with the above methodology, we can determine the energy efficiency of a CHP plant based on the demand-side management algorithm of a heating network. The algorithm is shown in Figure 5. Based on the consumption data, we then determine the electrical loads. We then input the data on the current distribution of the generation of heat and electrical loads. Based on the loaded data of the current operating mode of the CHP, we can calculate the efficiency of heat and electricity generation.

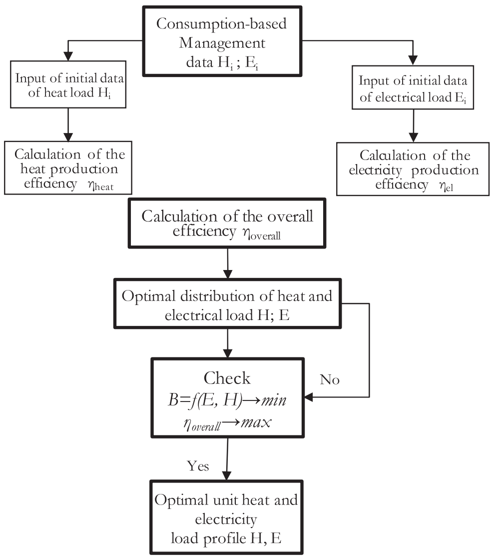

Figure 5. Flowchart of the application of the demand-side management algorithm to solve the economic dispatch problem of the CHP unit.

The data from the graphs of the electrical and thermal loads of the CHP plant is entered into the model and the efficiency is calculated in the case there is a transition to a new electricity supply mode in accordance with the provision of heating network modes. The optimal operating mode of the power unit and effective redistribution of loads are determined, and, if necessary, further data are gathered on the optimised operating mode of the heating network, which is then used to calculate and select the optimal mode of the future load. The introduction of the structure for optimising energy production at CHP plants will ensure competent and correct decision-making by the CHP personnel concerning technical, economic, and organisational aspects related to the efficient management of heat and electrical equipment.

Let us consider the unit's consumption of primary energy B, since primary energy is converted into electrical energy E and into thermal energy of a different potential: $B = B(E, H)$, where the increment in the primary energy consumption per unit associated with the change in the unit load can be represented as

$$dB = \frac{\partial B}{\partial E}dE + \frac{\partial B}{\partial H}dH \quad (3)$$

Then, add the total differential (3) in

$$dB = p\left(\frac{dE}{v} + dH\right) \quad (4)$$

$$p = \frac{\partial B}{\partial H} \tag{5}$$

$$v = \frac{\frac{\partial B}{\partial E}}{\frac{\partial B}{\partial H}} \tag{6}$$

Physically, the coefficient p represents the response of the power unit in terms of primary energy consumption to a change in heat supply to consumers while maintaining the electrical load, and the coefficient v characterises the relative efficiency of heat supply to consumers compared to the supply of electricity. Let us find the coefficient v, considering the two variants of the transient process in the system at E_i, H_i, and B_i in the initial state, and E_i, H_{ji} in the final state as a sequence of two transitions:

- I. Changing H from $H_i \rightarrow H_{ji}$ while maintaining B_i;
- II. Changing the electrical power to the initial E_i.

Let us analyse a direct relationship between electric and thermal power and the use of primary energy:

$$\eta_i = \frac{Ei + Hi}{Bi \cdot Q_f} \tag{7}$$

where Q_f is the calorific value of the primary energy (fuel).

In the first variant of the transient process (I), the utilisation factor of the primary energy of the power unit changes to a value of η_{ii} in accordance with the change in E_i and H_i after the transition to the load H_{ji}.

$$\eta_{ji} = \frac{E_i + (H_i - H_{ji}) \cdot v + H_{ji}}{B_i \cdot Q_f} \tag{8}$$

where H_i is the thermal power in the initial mode with electric power E_i and the efficiency value η_i, H_{ji} is the thermal power in the current Economic Dispatch mode, and B_i is the primary energy consumption for the initial operating mode.

The result of this optimisation is represented by an objective function that establishes the dependence of efficiency on both heat and electrical loads when operating according to the electrical schedule. When operating on a heating schedule, the electrical power depends on the heat load. The criterion for the optimality of one of the options of the distribution of unit loads at a given value and parameters of the heat supplied is the minimisation of the fuel component considered as the maximum efficiency. The coefficient v in Equation (8) reflects the efficiency of energy-to-electricity conversion in the CHP unit for a specific change in heat load based on Economic Dispatch.

From Equations (7) and (8) we get:

$$\eta_{ji} = \eta_i \cdot \left(1 - \frac{\Delta H_i}{E_i + H_i} \cdot (v - 1)\right) = \eta_i - \frac{\Delta H_i}{B_i \cdot Q_f} \cdot (v - 1) \tag{9}$$

where $\Delta H_i = H_{ji} - H_i$. Additionally, let us consider the relationship between the parameters:

$$\eta_{ij} - \eta_i = b \Delta H_i \cdot \frac{\partial \eta}{\partial B} \tag{10}$$

where b is a constant characteristic of a given power unit that does not depend on E, H, or v.

In the second variant of the transient process (II), the electric power $E_i + (H_i - H_{ji}) \cdot v$ is restored to the initial value E_i by changing the primary energy consumption from B_i to B_{ji}.

As a result of transformations of Equations (9) and (10), we get a ratio for determining the change in efficiency Equation (11), i.e., primary energy consumption ΔB at ΔH_i and $E = const$:

$$\frac{\Delta B}{\Delta H_i} = \frac{1}{\frac{E_i + H_i}{B_i} + \frac{1 - v}{b}} \tag{11}$$

The average value of the coefficient $p = \frac{\partial B}{\partial H_i}$, where E_i = *const* for an arbitrary range of heat loads, can be represented as:

$$p = \left[\frac{E_i + H_i}{B_i} + \frac{1 - v}{b}\right]^{-1} \tag{12}$$

The coefficient p in Equation (12) corresponds to the new state of heat supply, which led to an increase in ΔH_i.

In the initial mode (before the application of Economic Dispatch), the electrical E_i and thermal H_i power correspond to the initial value of the operating efficiency, and when switching to a new load from Equation (3), we get:

$$B_{ji} - B_i = p \times \left[\frac{E_{ji} + E_i}{v} + H_{ji} - H_i\right] \tag{13}$$

Let us determine the coefficient p using the parameters of the initial mode and Equation (13) for this mode:

$$p = \frac{B_{ji} - B_i}{\frac{E_{ji} - E_i}{v} + \left(H_{ji} - H_i\right)} \tag{14}$$

The coefficient p is determined by two ratios, Equations (14) and (12), describing the transition process from the original mode to the Economic Dispatch mode:

$$p = \frac{1}{\left[\frac{E_{ji} + H_{ji}}{B_{ji}} + \frac{1 - v}{b}\right]} \tag{15}$$

The above method for determining the unit's consumption of primary energy B makes it possible to change the practical approach to using the efficiency characteristics of CHPs in managing the equipment operating modes and, using the *Bji* parameter, create a simplified characteristic with qualitative information on the efficiency of the planned heat and electricity generation modes at the CHP.

2.4. Economic Dispatch

Economic Dispatch is a nonlinear optimisation problem with several constraints. The objective function is to minimise the total primary energy consumption with constraints, or in other words, to maximise the overall efficiency. The consumption characteristic curve is a functional dependence of the hourly consumption of primary energy on electric power for various heat loads. We must also consider the minimum and maximum limits for electrical loads as constraints that are determined by technical conditions for different heat loads.

From a mathematical point of view, the problem of Economic Dispatch can be formulated concisely. That is, the objective function, B, must be equal to the overall energy efficiency to supply the indicated heat and electrical load.

The main demand characteristic for a unit on the market is the relationship between primary energy consumption B_i and electrical and thermal power E_i; H_i is a characteristic of consumption or efficiency. The objective function of the problem of short-term optimisation of the CHP operation has the optimisation horizon n = 24 (one day), discreteness Δi = 1 (one hour), and time stamps i. Essentially, the dispatch problem can be formulated as an optimisation problem with a quadratic objective function and linear constraints. The challenge is to find the heat and power generation for each hour so that the objective function defined by the equation is a quadratic polynomial:

$$B_{ji} = \sum_{i=1}^{n} B_i = \sum_{i=1}^{n} \alpha_i + \beta_i B_i + \gamma_i B_i^2 \tag{16}$$

where α_i, β_i, and γ_i are constant regression equations for hour i. Generation output should be placed between the maximum and minimum limits according to heat production. The corresponding inequality constraints for each generator are.

$E_{i,min} \leq E_i \leq E_{i,max}$ where, $E_{i,min}$ and $E_{i,max}$ are the minimum and maximum power output limits of electrical capacity (MW). In order to establish the necessary conditions for the extreme value of the objective function, add the constraint function to the objective function after the constraint function has been multiplied by an undetermined multiplier.

Various methods are used both individually and in combination to optimise power dispatch. These methods include the Lagrange method, the lambda(λ) iteration method, the first- and second-order gradient methods, coefficients of sharing, linear programming, neural networks, and fuzzy algorithms. This model is based on the Lagrange method because it offers an accurate, reliable, and conclusive solution. Compared to other methods, the convergence rate for this model is acceptable. All of this makes it a suitable choice for solving the problems of Economic Dispatch.

The above constrained optimisation problem is converted into an unconstrained optimisation problem. The Lagrange multiplier is used when a function is minimised (or maximised) with a side condition in the form of equality constraints. In this method, the Lagrangian function is formed by adding equality constraints to the objective function using the appropriate Lagrangian multipliers. Using this method, the augmented function is defined as:

$$L = B_i + \lambda \left(B_{ji} - \sum_{i=1}^{n} B_i\right) \quad (17)$$

Thus, the Lagrange multiplier λ is the cost of one extra MW with an optimal solution. The necessary conditions for the extreme value of the objective function are obtained when we take the first derivative of the Lagrangian function with respect to each of the independent variables and set the derivatives to zero. Now, this Lagrangian function needs to be minimised without any constraints.

To find the minimum, the function with the constraint in the form of Equation (17) is differentiated with respect to all variables (n + 1), and then its derivatives are equated to zero. The minimum of this unconstrained function is at the point where the partials of the function to its variables are equal to zero:

$$\begin{cases} \frac{\partial L}{\partial B_i} = \frac{dB_{ji}}{dB_i} - \lambda = 0; \\ \frac{\partial L}{\partial B_i} = 0 \\ \frac{\partial L}{\partial \lambda} = 0 \end{cases} \quad (18)$$

The first condition given

$$\frac{\partial L}{\partial B_i} = 0, \text{ results in } \frac{\partial B_{ji}}{\partial B_i} + \lambda\,(0 - 1) = 0 \quad (19)$$

therefore, the mathematically obtained condition for economic dispatch is:

$$\frac{\partial B_{ji}}{\partial B_i} = \lambda \quad (20)$$

or

$$\beta_i + 2\gamma_i B_i = \lambda \quad (21)$$

The linearized characteristic of the power unit is a straight-line segment in a two-dimensional regime space for various heat loads. The minimum and maximum electric power, E_{min} and E_{max}, (the beginning and end of the straight-line segment), set the power unit control range. The linear functions of electrical efficiency are shown graphically in Figure 6.

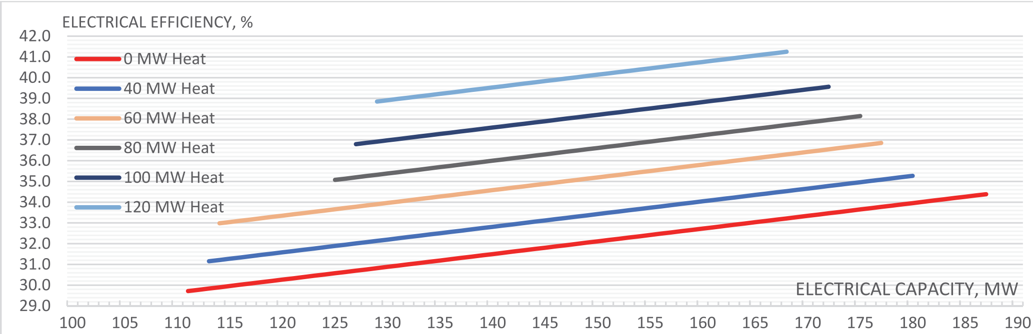

Figure 6. Linear function of electrical efficiency based on the heat load.

Thus, the necessary condition for the existence of the maximum efficiency operating condition for the CHP unit is that the incremental cost rates for the entire capacity must be equal to some undetermined value λ. Of course, to this necessary condition, we must add the constraint equation, according to which the sum of the power outputs must be equal to the power required by the load.

$$\begin{cases} \frac{\partial B_{ji}}{\partial B_i} = \lambda \text{ for } E_{i,min} < E_i < E_{i,max}; \\ \frac{\partial B_{ji}}{\partial B_i} < \lambda \text{ for } E_i = E_{i,max} \\ \frac{\partial CB_{ji}}{\partial B_i} > \lambda \text{ for } E_i = E_{i,min} \end{cases} \quad (22)$$

The expression $\beta_i + 2\gamma_i B_i$ is the incremental production efficiency of hour i. When solving economic dispatch, the incremental production efficiency of each hour is equal to the Lagrangian parameter λ;. The most economical option is to operate at equal incremental production costs, which can be found as follows:

$$B_i = \frac{\lambda - \beta_i}{2\gamma_i} \quad (23)$$

These inequalities indicate that any capacity with an incremental cost higher than λ is inefficient and should operate at the lowest level of capacity.

On the other hand, for each heat load, it is necessary to calculate the incremental costs at the maximum and minimum output for the heat load. Then, set λ_{min} to the smallest value among the incremental costs at unit E_{min} values, and then set λ_{max} to the largest value among the incremental costs at unit E_{max} values. If $\lambda = \lambda_{min}$, then the lambda search algorithm is $E = E_{min}$, and if $\lambda = \lambda_{max}$, then the lambda search algorithm is $E = E_{max}$.

$$\Delta\lambda = \frac{\lambda_{max} - \lambda_{min}}{2} \quad (24)$$

If the value λ is less than the incremental cost at E_{min}, then just set the unit output to E_{min}, and if the value λ is greater than the incremental cost at E_{max}, then set the generator output to E_{max}. Otherwise, calculate the E value for the unit from the incremental cost function. A simple procedure to allow the unit to generate $B(E)$ consists of adjusting λ from λ_{min} to λ_{max} in specified increments, where:

$$\lambda^{min} = min\left(\frac{\partial B_i}{\partial E_i}\right);\ \lambda^{max} = max\left(\frac{\partial B_i}{\partial E_i}\right) \quad i \text{ for each Heat demand} \quad (25)$$

At each increment, calculate the total primary energy consumption and the total power output for all heat loads. These points represent the points on the $B(E)$ curve or efficiency curve. The incremental cost is the cost of one additional MW per hour. This equality means that the best distribution is achieved in the case of an increase in the primary energy consumption dB_i with an increase in power dE_i. Expression (25) determines the order of distribution of heat and electrical loads at the CHP. Thus, the order of priority of electric power is determined by the principle of equality of relative gains; if equality is unattainable, then we use the order of increasing relative gains.

3. Discussion

The district heating network and CHP plant considered in this analysis were based on an actual district heating network located in Narva, Estonia [23] and the Balti Power Plant CHP unit that supplies heat to the Narva DH network. The CHP unit with an extraction-condensing turbine at the Balti Power Plant produces heat and electricity [28]. Figure 7 shows the actual average relationship between thermal and electrical power for the CHP of Narva city during the past five years. This relationship is used for further calculations. As can be seen from the figure, in the operating range of powers, this dependence can be approximated by a linear function with sufficiently high accuracy.

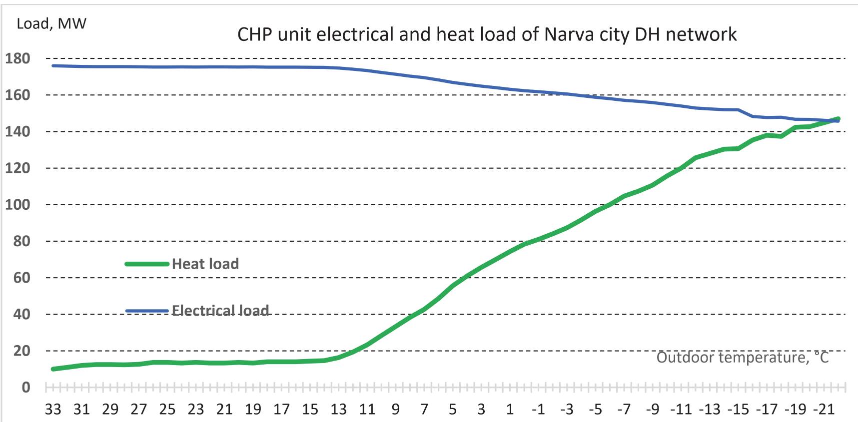

Figure 7. CHP unit electrical load and heat load according Narva city DH network.

The actual operating data of the CHP unit in September-November 2020 at the minimal thermal loads of 30–70 MW confirm the statistical and calculated characteristics of the unit. The calculations in this paper are based on these data and are shown in Figure 8.

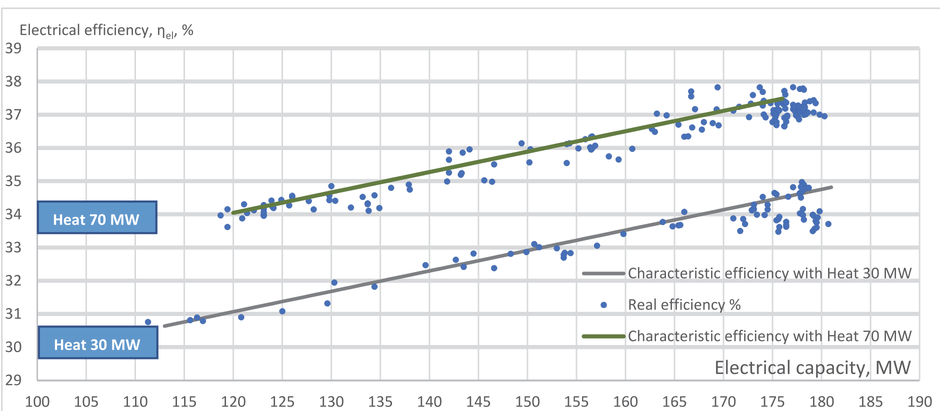

Figure 8. Electrical efficiency of the unit for heat load 30 MW and 70 MW.

The overall efficiency of a CHP unit refers to the sum of electricity production and useful heat output divided by the amount of fuel used to generate heat in the cogeneration process. The total production efficiency for the scheduled period is the sum of electricity and heat efficiency. In general, the problem of overall efficiency is given as follows:

(1) Maximising the overall operating efficiency of the CHP unit:

$$\eta_{overall}(P_i) = \sum_{i=1}^{n} (\eta E_i + \eta H_i) \tag{26}$$

where $\eta_{overall}$ is the overall efficiency of the CHP unit; ηE_i is the efficiency of electricity production of the CHP unit at hour i; ηH_i is heat production efficiency of the CHP unit at hour i; n is the total number of hours.

Let us note the key feature of the cogeneration technology for the generation of electrical and thermal energy, namely the fact that in this case, the physical meaning has a general (overall) efficiency. ($\eta_{overall}$)—the use of the fuel's primary energy. The value of the overall efficiency depends on the share of the types of energy generated during cogeneration in their total dimension. The values within which the value ($\eta_{overall}$) can vary depending on the operating mode of the cogeneration plant. Typical limiting modes include (a) the mode with minimum heat production and maximum electricity generation, with efficiency at the minimum value (η_{min}) and (b) the mode with minimum electricity generation and maximum heat production, with efficiency at the maximum value (η_{max}).

The qualitative dependence of the change in overall efficiency on the change in heat load is shown in Figure 9.

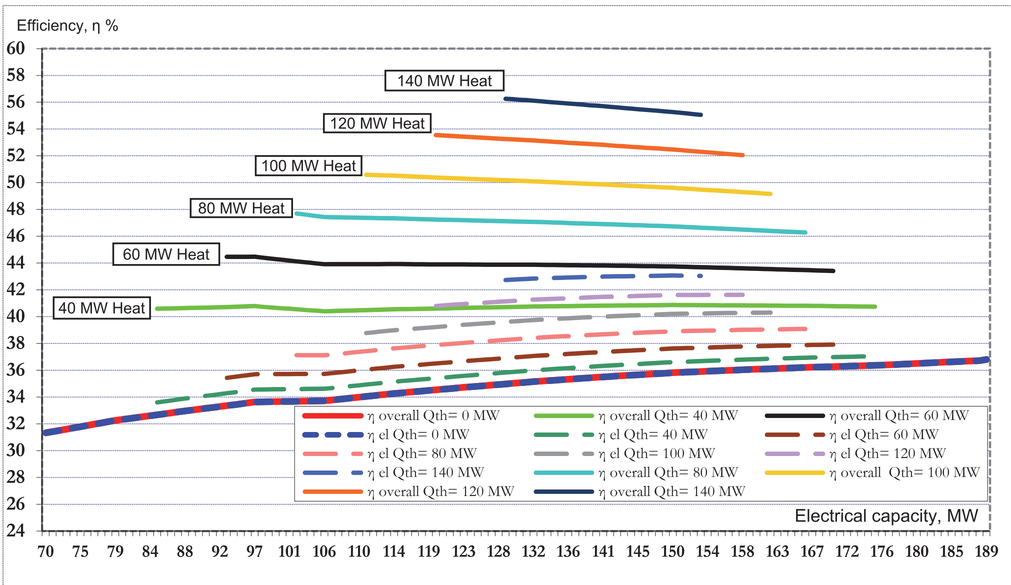

Figure 9. Overall and electrical efficiency of the CHP unit based on the heat load.

Hourly system balance. The total heat generation must be equal to the heat load demand, H_D, at all hours.

(2) Heat demand balance constraint:

$$\sum_{x=1}^{n} (H_i) = H_D \tag{27}$$

where H_i is the heat load demand at hour i.

(3) The minimum and maximum rated capacities of the unit must not be violated:

$$E_{i,\ min} \le E_i \le E_{i,\ max} \tag{28}$$

where $E_{i,\ min}$ and $E_{i,\ max}$ are the minimum and maximum electricity capacity according to heat demand.

The efficiency curve of a conventional heating unit can be approximated by a quadratic function. A CHP unit has a convex cost function for both power and heat. The bi-objective economic dispatch problem is converted into a single optimisation problem by introducing the maximum overall efficiency as follows:

$$\max \eta_{\ overall} = \left(\eta E_i\left(a_i P_i^2 + b_i P_i + c_i\right) + \eta H_i\left(d_i P_i^2 + e_i P_i + f_i\right)\right) \tag{29}$$

-Electricity production efficiency per hour at maximum power output is determined as

$$\eta E_i\left(P_{Ei(\max)}\right) = a_i P_{Ei(\max)}^2 + b_i P_{Ei(\max)} + c_i \tag{30}$$

-Heat production efficiency per hour at demand supply is determined as

$$\eta H_i\left(P_{Hi(demand)}\right) = d_i P_{Hi(demand)}^2 + e_i P_{Hi(demand)} + f_i \tag{31}$$

The operating efficiency determined by the above quadratic Equation (32) is obtained by approximating the power in MW. The incremental efficiency is then calculated as

$$\frac{d\eta E_i}{dP_{Ei}} = a_i P_{Ei} + b_i \text{ and } \frac{d\eta H_i}{dP_{Hi}} = d_i P_{Hi} + e_i \tag{32}$$

4. Study Results

4.1. Comparison at the Minimum Heat Load of the Heating Network

In the first stage of calculations, the optimisation criterion is the maximum generation of electrical power in terms of heat consumption. Based on statistical data, a regression model has been built, reflecting the dependence of the efficiency of power generation and the overall efficiency of the CHP unit with a minimum heat load of 40 MW (Figure 10).

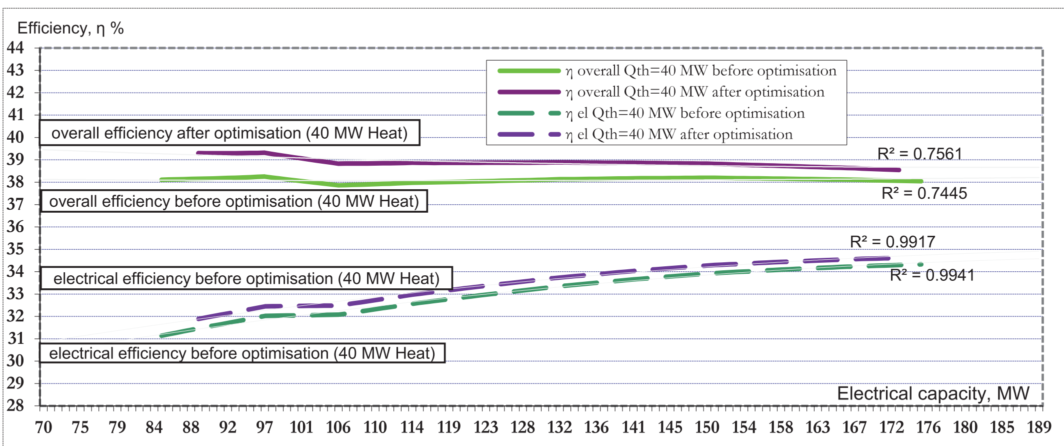

Figure 10. Efficiency optimisation result for minimum 40 MW heat demand.

The CHP unit is loaded more optimally, which increases the efficiency of electricity up to 0.5%, and the overall efficiency of the unit up to an additional 1.0% with a heat supply of 40 MW. A statistical relationship was found between the efficiency of electricity generation by CHPs and a fixed minimum supply of heat. By differentiating this function, we can find the characteristic of the relative increase in efficiency, which will be about 1%.

4.2. Comparison at the Maximum and Average Heat Load of the Heating Network

Based on statistical data, a regression model has been built that reflects the dependence of the efficiency of power generation and the overall efficiency of the CHP unit with an average heat load of about 90 MW, and a maximum heat load of 130 MW. A similar calculation based on statistical data was used to build a regression model that reflects the dependence of the efficiency of power generation and the overall efficiency of the CHP unit with a heat load of 90 MW and 130 MW (Figure 11).

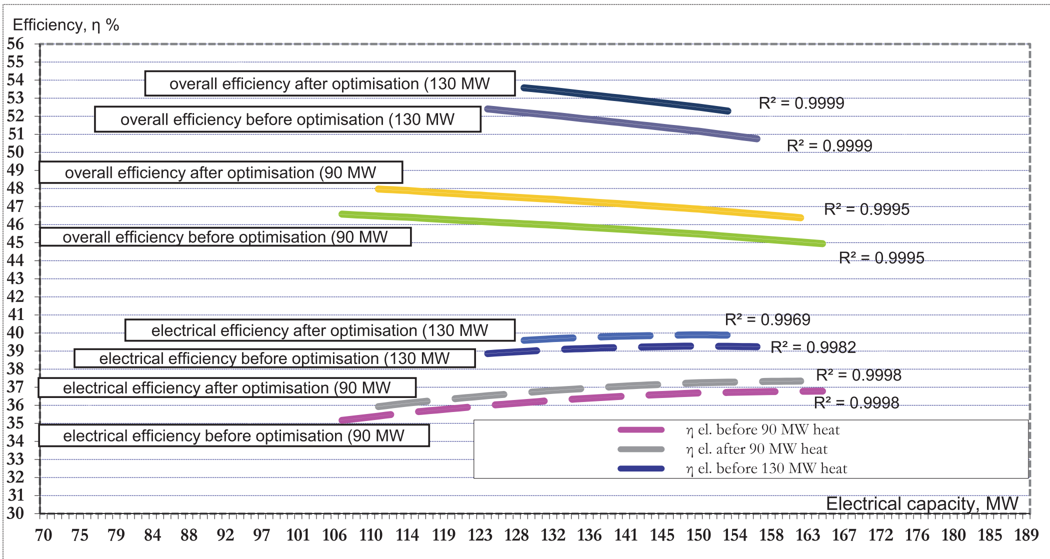

Figure 11. Efficiency optimisation result for an average 90 MW and maximum 130 MW heat demand.

One can observe that with a clear reflection of the heat load, based on the demand data, the CHP unit is loaded more optimally, which increases the efficiency of power generation by about 0.7%, and the overall efficiency of the unit up to an additional 1.5% with a heat supply of 90 MW. It should be noted that heat release was recorded to depict the dependency, which greatly simplified the construction and search for a statistical model, and as a result, it was possible to find a sufficiently high-quality characteristic showing that with a clear reflection of the heat load, based on the demand data, the CHP unit is loaded more optimally, which increases the efficiency of electricity by up to 1.0%, and the overall efficiency of the unit up to an additional 2.0% with a heat supply of 130 MW.

4.3. Summary

From the viewpoint of power unit loading in the wholesale market, this optimisation can be interpreted in such a way that the power unit loading is advisable as long as the relative increase in the cost of electricity generation at the power plant is lower than the market price at which the additional generation is sold, and only then the power plant obtains the maximum economic effect from operating in the wholesale market. A similar effect can be achieved if the price offer on the market matches the relative increase in production efficiency.

Thus, an error in heat supply forecast can lead either to an unreasonably high load of the power plant and sales at a price below the relative increase in the cost of fuel equivalent consumption, or to underutilisation of capacities and a decrease in electricity sales.

However, in most cases, statistical data do not allow for obtaining probabilistic models of characteristics and influencing factors; therefore, the most realistic is the use of heat demand-side management.

At the same time, under conditions of uncertainty, predicting these characteristics is a rather difficult task, which can lead to lost profits when operating on the open electricity market. In particular, the heat supply mode significantly affects the characteristics of the CHP unit.

5. Conclusions

5.1. Summary Model Validation

When distributing the CHP unit load using heat demand-side management, optimisation tasks were formulated, namely the minimisation of primary energy consumption and maximisation of the total useful electrical load of the CHP unit at a given electrical load of the unit and at a given heat load of consumers.

A method based on DH demand data was proposed to optimise the operation of a cogeneration plant and to determine the energy savings of the primary fuel and/or an increase in the efficiency during the cogeneration of electric and thermal energy compared to the traditional method.

The methodology is based on an analytical expression that determines the dependence of the consumption of thermal energy of the primary fuel for the production of electrical and thermal energy during the cogeneration process, taking into account the corresponding efficiency values.

The use of the proposed method was illustrated by an example that shows that the maximum effect of primary energy savings during the cogeneration of electrical and thermal energy under the assumed design conditions is about 2%, compared to the energy consumption of primary fuel for the production of the same amount of electrical energy and thermal energy using the traditional production planning method.

The results obtained and the analysis performed indicate that the proposed methodology provides logical results and can be used to calculate the efficiency indicators of the cogeneration of electrical and thermal energy.

5.2. Summary Calculation Results

The analysis of the calculation results showed that with more optimal planning of a portion of the load at the CHP, the primary energy savings for the heating period due to the difference in the efficiency of the supply will be about 10,000 MWh per year. In addition, fuel savings for the heating season will reach around 18,000 tons of CO_2 per year. The results obtained can be used to increase the effect of energy saving measures and to optimise the operation of the CHP system.

Simulating a real CHP unit with a district heating network shows that demand-side management can improve the overall economic efficiency of the CHP plant and increase the unit's operating range.

As a result, the problem of optimising the operating mode of the CHP unit was solved, which allows us to determine the optimal additional increase in the unit's electrical load at a given heat load of consumers, which, on average, increases the CHP unit's efficiency up to an additional 1.5%.

5.3. Summary Study Result

The practical value of the work is experimental calculations on the data of the CHP unit of the Balti Power Plant—showed the practical suitability of the developed tools. The results obtained served as effective information support and can be used to substantiate the distribution of heat and electric energy at CHPs.

In conclusion, it should be noted that the format of this research did not permit a discussion of all the problems of CHP units that arise when operating in the wholesale electricity market, for example, the issue of forced generation at minimum loads, the problem of accounting for the need to turn on peak hot water boilers to ensure electrical generation, and so on. However, these problems should be the subject of a separate discussion and solutions.

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Nomenclature

Abbreviation	
CHP	combined heat and power
ED	economic dispatch
DH	district heating
DHN	district heating network
DSM	demand-side management
Parameters	
H	heat, MW
Q	heat supply, MW
B	primary energy (fuel heat), MW
E	electrical energy, MW
C	unit production cost function
L	Lagrange function
η	efficiency, %
λ	Lagrange multiplier
v	coefficient of relative efficiency of heat.
p	coefficient of primary energy rate of heat
t	temperature, °C
T	time period
x	heat user
y	heat source
m	flow rate, kg/h
c	specific heat of water 4,19 kJ/(kg °C)
n	24 h—one day
i	time stamps Δi = 1 one hour
Subscripts	
a, b, c	electrical efficiency coefficients
d, e, f	heat efficiency coefficients
α, β, γ	unit efficiency coefficients
1	supply
2	return
min	minimum
max	maximum
i	initial state
ii	current state

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Publication III

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energies

Article

Comparison of District Heating Supply Options for Different CHP Configurations

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Abstract: The article discusses the evaluation of potential heat production options for a large-scale district heating system in Narva (Estonia). Heat is currently generated at the Balti Power Plant's CHP unit using local oil shale mixed with biomass. The CHP unit consists of two circulating fluidised bed boilers and a reheat steam turbine. According to the development strategy, the district heating system is expected to achieve carbon neutrality in the future. Various options and parameter variations should be analysed. The following scenarios were compared: (1) baseline scenario featuring an existing CHP extraction steam turbine; (2) alternative Scenario I featuring a CHP backpressure steam turbine; and (3) alternative Scenario II featuring a CHP gas turbine. To evaluate the above scenarios, a comprehensive energy/exergy analysis was performed, and economic indicators were calculated. The primary energy consumed, as well as the heat and electricity generated, were all taken into account. Based on this analysis, a scenario was selected using multiple-criteria decision-making that will improve energy efficiency and reliability of the system.

Keywords: district heating; CHP; efficiency; electrical and thermal loads; efficiency; exergy; heat; turbine; demand; scenario

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1. Introduction

Rising energy prices, the effects of the pandemic on the social and economic lives of all countries, and global energy transition processes characterised by a massive increase in the use of green energy sources and the transformation of global energy markets are currently affecting the energy industry. This resulted in a decrease in cogeneration electricity production in terms of heat consumption during periods of lower spot prices in the electricity market, especially during the global pandemic, and created conditions for unbalanced production and consumption of heat and electricity according to optimal parameters. However, during the energy crisis of winter 2022, there was a significant demand for the production of both power and thermal energy. Furthermore, the war in Ukraine has significantly exacerbated the issue of improving the reliability of electricity and heat supply.

Centralised combined heat and power (CHP) plants have been identified as a priority for meeting the European energy sector's decarbonisation targets. Increased use of CHP and renewable energy sources is widely recognised by the EU administration as an effective way to improve the overall energy efficiency of energy systems, reduce CO_2 emissions, and minimise dependence on imported fuels. The heating sector is often characterised by old, inefficient equipment that loses a lot of heat. According to [1], the heating sector accounts for the majority of energy consumption and carbon emissions in Germany.

The purpose of this study is to analyse the possibilities of using various turbine modifications for the existing CHP and to determine the best scenario. Furthermore, the paper establishes the primary comparisons of the characteristics and performance indicators of the scenarios and calculates the ratios of thermal load fuel consumption and fuel savings for various scenarios. The practical value of the paper is in the implementation of methodological provisions for selecting a rational option for CHP plant renovation. This will improve the efficiency of heat supply system sources and aid in the selection of the most effective directions for their transformation.

Estonia's energy sector is one of the most carbon-intensive in the EU. According to the EU climate and energy framework, the EU aims to reduce Estonian CO_2 emissions by at least 70% compared to 1990 (6500 t/a) or reach a new target of 55% compared to 1990 (9800 t/a) by 2030. By 2050, it is planned to reduce emissions by 80–90% compared to 1990 [2]. In Estonia, the target has been raised to 81% (9800 t/y) in 2021. It is expected to further increase to 85% (3300 t/y) by the end of 2022 in order to reach zero emissions by 2050 [3]. The transition from the 2050 target to 100% renewable energy in the EU has been analysed as a series of steps in [4]. Each step represents a significant technological advancement. At the same time, the decline of the oil shale industry threatens the local economy of Narva, a city in eastern Estonia.

Narva has a CHP plant with a maximum heat capacity of up to 160 MW_{DH} and an electrical capacity of up to 215 MW_{el} (depending on the heat capacity). In addition to the CHP unit, heat can also be supplied via the boiler house in the event of the unit's failure or during maintenance. The emergency boiler house has three boilers with a total heat capacity of 240 MW. Average district heating production in Narva is approximately 450 GWh/a, peak demand in winter is approximately 160 MW_{th}, and summer supply is only approximately 15 MW_{th}.

To increase the efficiency and flexibility of the heating sector, European regulators are looking into combining different generation systems, particularly cogeneration plants [5]. Through energy and exergy analyses of the cogeneration mode, it is possible to increase electricity generation, improve heat load, and reduce heat loss in the DH network [6]. A review of the literature explores technical solutions aimed at improving the flexibility of CHP plants, considering the potential transition to 4th generation district heating, which improves efficiency and balances the thermal and electrical loads of CHP plants [7]. The importance of CHPs in the integrated energy sector was analysed in [8]. The use of low-carbon capacities after system integration, as well as the installation of heat pumps and electric boilers, was described in [9]. The heating system's energy and exergy efficiencies were investigated, with the energy and exergy flow diagrams presented in [10]. The importance of identifying appropriate methods and reference parameters was discussed in [11], with a particular emphasis on applications that require the determination of allocation factors and potential effects, followed by the selection of a renovation scenario. In [12], exergy and economic analyses of CHPs were performed in order to determine the specific exergy-economic rates and CO_2 emissions of end products. Much better indicators of economic and environmental sustainability, demonstrated using actual project inputs, were noted in [13], implying that similar concepts can be developed for other networks in accordance with the approach leading to a flexible modular DH solution based on CHP. According to the review of the literature, various modelling approaches are focused on optimisation algorithms for the integration issue of the electric power industry and thermal power industry [14].

2. Methodology

This paper compares different heat production scenarios in Narva's district heating network. The following methodologies use the basic principles of analysis: thermal efficiency analysis, exergy analysis, and the concept of energy conservation. Based on the second law of thermodynamics, the efficiency factor is the most basic indicator of a system's (or process's) efficiency in relation to the energy used. Efficiency is defined as the ratio of useful energy used in the system (useful work) to total energy supplied. Process energy efficiency analysis for various process improvement options and selection of the most efficient option can be used to justify the adoption of energy efficiency improvement methods. This paper compares different heat supply scenarios for Narva's heating network during operation and different values of specific power generation for heat consumption, which characterise the power/thermal energy generated ratio. In this article, the efficiency indicators of various types of heat supply sources are calculated using the ratio of generated types of energy, and the following heat supply technologies are compared:

1. Baseline scenario—a CHP extraction steam turbine.
2. Alternative scenario I—a CHP backpressure steam turbine.
3. Alternative scenario II—a CHP gas turbine.

2.1. Baseline Scenario: A CHP Extraction Steam Turbine

This scenario reflects the existing heat generation process in Narva's district heating network. A CHP extraction steam turbine requires replacing the existing CHP unit with 70–100% wood waste-based biomass CFB boilers that use the same steam turbine to supply heat to Narva. The plant is expected to be able to operate without a heat load.

The CHP plant will cover the full load of Narva. The CHP plant consists of a biofuel boiler (a mixture of oil shale and biomass, and in the future only 100% biomass) that generates high-pressure steam, a steam turbine, and a set of heat exchangers that recover heat from the turbine's exhaust steam [15].

Figure 1 depicts the analysed baseline scenario for a CHP steam turbine. The district heater uses steam from crossover pipes between the intermediate and low-pressure parts of the turbine to heat the DH circulating water. The peak load receives extra steam from the hot reheat steam line. The facility's maximum DH load is 160 MW and the maximum outlet water temperature is 120 °C. The DH water temperature at the inlet ranges from 40 °C to 60 °C. Narva's annual heat demand is approximately 450 GWh [16]. Simplified models demonstrated the relationship between fuel input and heating plant output.

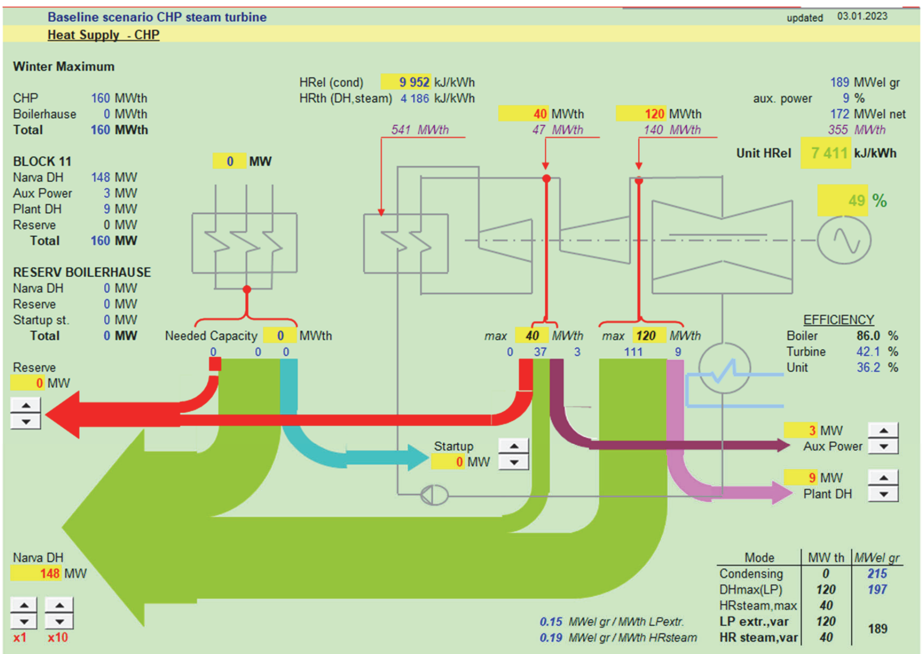


Figure 1. Simplified process flow diagram of the CHP extraction steam turbine in the baseline scenario.

2.2. Alternative Scenario I: A CHP Backpressure Steam Turbine

A combined heat and power plant with backpressure turbines in which electricity generation is entirely dependent on heat demand is referred to as a CHP backpressure steam turbine. The low demand for heat in the summer complicates the operation of CHP plants using this type of turbine.

The flow rate of live steam in the case of a backpressure turbine is equal to the flow rate of steam discharged from the turbine to the network heater. Figure 2 depicts a schematic diagram of a CHP plant with backpressure turbines.

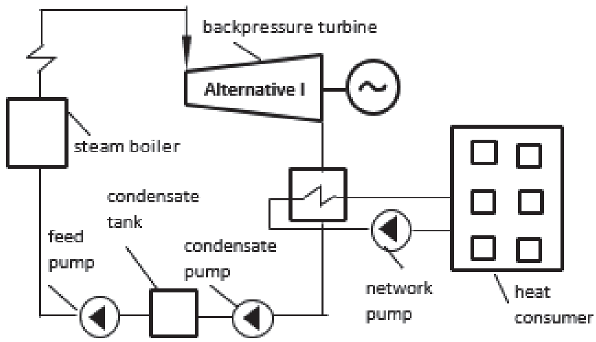


Figure 2. Schematic diagram of a CHP plant with a backpressure turbine.

The generation of electricity at CHP plants with backpressure turbines is entirely dependent on the demand of industrial and municipal enterprises for thermal energy. In the summer, when there are no thermal loads, steam from the turbine is only used to cover the load of hot water supply and is thus consumed in a limited amount. The bulk of the steam flow enters the condenser. In the winter, the network heater receives the most steam from the heat extraction, while the condenser receives the least.

2.3. Alternative Scenario II: A CHP Gas Turbine

A gas turbine-based CHP plant is one that operates by converting the heat of combustion products from gaseous or liquid fuel into mechanical work performed in a gas turbine. Figure 3 depicts a schematic diagram of a CHP with gas turbines.

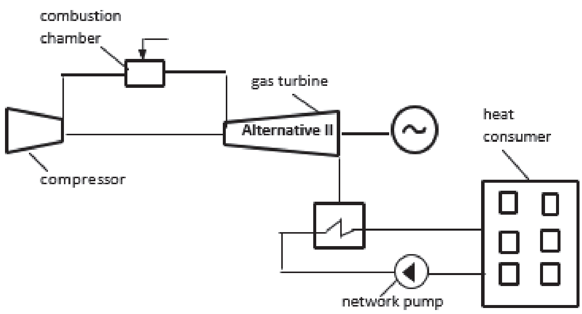


Figure 3. Schematic diagram of a CHP plant with a gas turbine.

Internal losses accompany the compressor and gas turbine's compression and expansion processes the value of which is estimated using the internal relative efficiency of the gas turbine and compressor.

If the gaseous byproducts of combustion exhausted in the gas turbine are routed to the heat recovery steam generator (HRSG), the resulting steam can only be used in the steam turbine cycle for additional electrical energy generation (combined steam-gas cycle power plant), or additional electrical and thermal energy generation (steam-gas cycle CHP).

Purified atmospheric air enters the gas turbine through the air intake and then into the compressor, where adiabatic compression occurs. The compressed air then enters the combustion chamber, where fuel is constantly supplied and burned. The combustion products then enter the gas turbine and expand, completing the useful work of the gas turbine cycle. The compressor, which is located on the same shaft as the gas turbine, consumes a significant portion of the useful work.

3. Case Study

3.1. Heat Demand Characteristics

Narva's district heating network follows a 120/70 °C temperature schedule. The actual temperatures at the district heating network's inlet and outlet are based on the outdoor temperature in 2021 (see Figure 4) and the demand for district heating (see Figure 5).

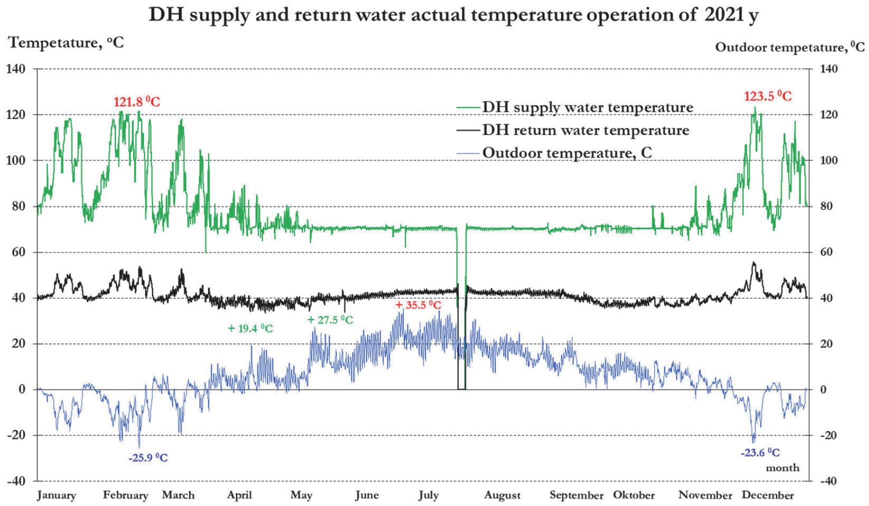


Figure 4. Actual supply and return water temperatures for the Narva district heating system in 2021.

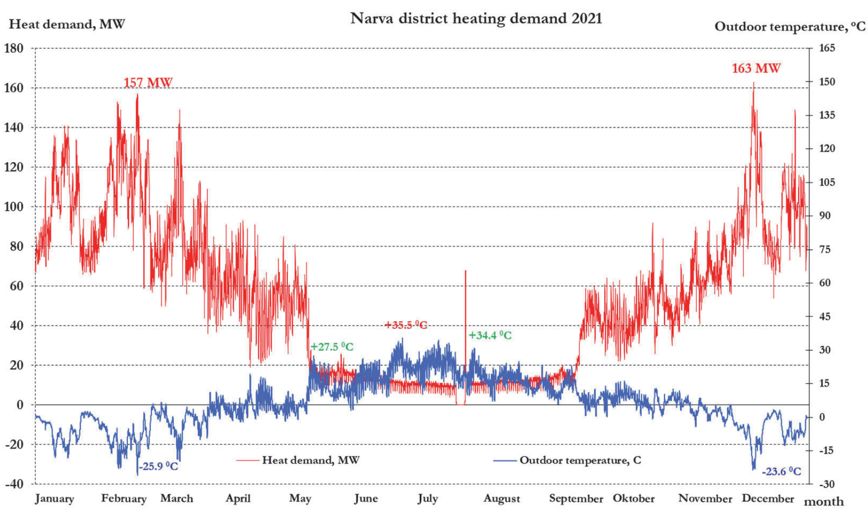


Figure 5. Actual heat demand for the Narva district heating system in 2021.

Because so-called qualitative control is commonly used in Estonian district heating systems, the supply temperature to the district heating network is determined by the outside temperature, while the flow in the district heating pipeline remains constant.

The temperature of the return water changes with qualitative control, but this cannot be controlled directly by the heat producer.

The temperature curve of the supply and return network water affects the consumption of network water (kg/s), which transfers the necessary amount of heat to the heating systems (Equation (1)).

$$G_{DH} = \frac{Q_H}{C_p(t_s - t_r)} \quad (1)$$

where Q_H is the thermal load of the district heating heater, MW; c_p is the specific heat capacity of water, J/kg·K; t_s is the supply temperature, K; t_r is the return temperature, K.

In the case of qualitative control, the supply and return temperatures of the district heating system depend on the ambient air temperature, but in order to heat domestic hot water to the required temperature (55 °C), the flow temperature must be maintained around 65 °C. If the supply temperature is regulated at the heat producer, the return temperature is calculated for each temperature regime and is determined by consumer behaviour and the settings of the heating units (Figure 6).

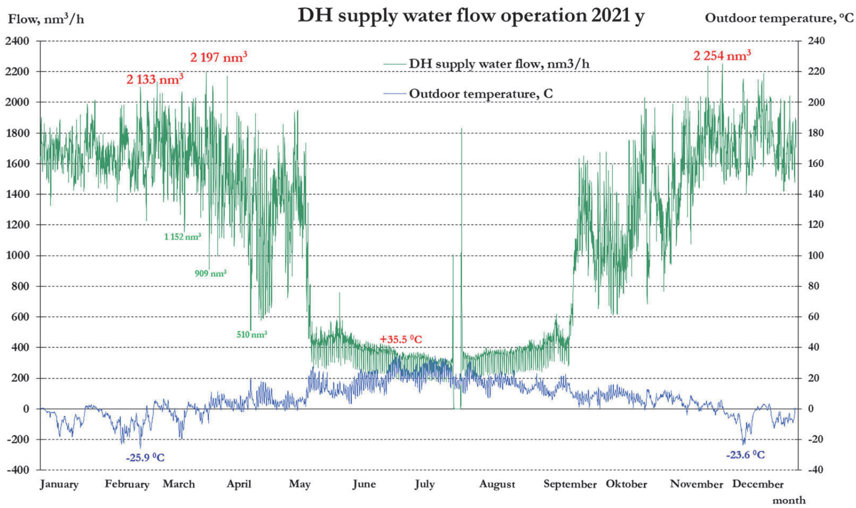


Figure 6. Supply water flow rate of Narva's district heating network in 2021.

The heat balance equation for a network heater allows us to determine the heating steam flow rate needed to cover the heat load (Equation (2)).

$$D_H = \frac{Q_H}{h_H - h'_H} \quad (2)$$

where h_H is the enthalpy of the steam coming from the turbine to the district heating heater, kJ/kg; h'_H is the enthalpy of the condensate at the heater outlet, kJ/kg.

In the absence of heating loads during the summer, steam from heating extraction is only used to cover the load of hot water supply (Figure 7) and is thus taken in a limited amount. In the winter, the network heater receives the most steam after the intermediate pressure turbine cylinder (120 Mw_{th}), and peak load steam is taken from the hot reheat steam line before the intermediate pressure turbine cylinder (60 MW_{th}) to cover the full heat load of up to 180 MW, as shown in Figure 7.

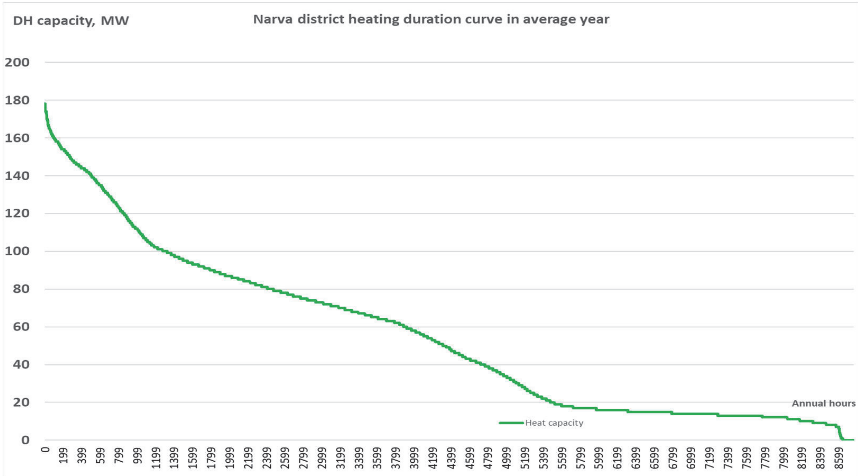


Figure 7. Narva district heating average annual duration curves.

3.2. Optimal Scenario Indicators

3.2.1. Energy Efficiency

The efficiency of power production is calculated using electrical efficiency:

$$\eta_{el} = \frac{N_T}{B_f \cdot Q_{LHV}}, \tag{3}$$

where B_f is fuel consumption, tonnes; Q_{LHV} is the lower calorific value of fuel, MWh/tonne; N_T is the electrical energy of extraction turbine/backpressure turbine/gas turbine, MWh;

A CHP unit's overall efficiency is the sum of its electricity generation and useful heat output. The efficiency of a CHP plant producing electricity and heat can be calculated using the following energy efficiency equation (Equation (3)):

$$\eta_{CHP} = \frac{N_T + Q_H}{B_f \cdot Q_{LHV}} \tag{4}$$

where Q_H is the thermal energy of district heating, MWh.

The fuel consumption at the CHP plant can be determined using the heat balance equation of the steam generator (Equation (5)).

$$B_f = \frac{D_0\left(h_1 - h_{fw}\right)}{Q_{LHV} \cdot \eta_b} \tag{5}$$

where η_b is boiler efficiency, %; h_{fw} is the enthalpy of feed water at the inlet to steam generators kJ/kg; h_1 is the enthalpy of superheated steam, kJ/kg.

Since these scenarios consider a mix of fuels (oil shale and biomass), the term 'standard fuel' (coal equivalent) with a lower heating value Q_{LHV} = 29.31 MJ/kg is used in this paper.

3.2.2. Exergy Efficiency

Exergy efficiency is calculated using unequal types of energy, which are summed up in the numerator of Equation (6), i.e., the previously determined ratio of electric power to heat load can be used as a more objective indicator of the heat supply source's efficiency. It can be determined as follows:

$$\eta_{ex} = \frac{N_T + L_{DHw}}{B_f \cdot Q_{LHV}} \tag{6}$$

where L_{DHw} is the useful work of network water, MWh;

If the value of the exergy efficiency, which is the ratio of thermal work to the energy of the consumed fuel, is used to evaluate the quality of boiler hot water, then the efficiency of a hot water boiler or boiler must be evaluated using the value of the exergy efficiency, which is the ratio of thermal work to the energy of the consumed fuel.

$$\eta_{ex} = \frac{L_{DHw}}{B_f \cdot Q_{LHV}} \tag{7}$$

During the entire operation of the heat supply system, the temperature of the network water passing through the heating devices is maintained at a higher level rather than dropping to the ambient temperature. The temperature of the network water in the return pipeline is determined by the heating network's temperature schedule. This means that in heating systems, not all exergy is spent on doing the heat work necessary to raise the temperature of the heated outdoor air. This portion of the exergy is returned to the hot water boiler. The quality of the heat supply source (hot water boiler/hot water boiler house) is evaluated using its thermal efficiency (the ratio of heat supplied with network water to the energy of fuel consumption; boiler efficiency, heat consumption for auxiliary equipment, and heat loss in the DH heat exchanger are all taken into account).

$$\eta_{TH} = \frac{Q_H}{B_f \cdot Q_{LHV}} \tag{8}$$

The ease and efficiency with which the heat from the burned fuel is transferred to the network water characterises the operation of a hot water boiler. The boiler has an efficiency of 90% or higher. At the same time, the hot water boiler's exergy efficiency does not exceed 20–40%. Such a significant discrepancy in efficiency values makes it difficult to fully assess its effectiveness because focusing on one or more efficiency factors leads to radically different conclusions.

Water in the district heating network is heated to 70–120 °C in a hot water boiler, transferring a significant amount of thermal energy but little working energy or exergy. This means that only the exergy portion of the transferred heat is capable of performing thermal work, i.e., raising the temperature of a heated body (air). Except for boiler losses, all energy from the combusted fuel is transferred to heated water as a heat flow. Nevertheless, the working portion of this flow, or its exergy, is negligible. The majority of the energy in the burned fuel is converted into anergy, which is a non-working state. Thermal work is only performed as a result of network water exergy in the heating devices of the heating system during thermal interaction, which is then used to raise the temperature of the heated air.

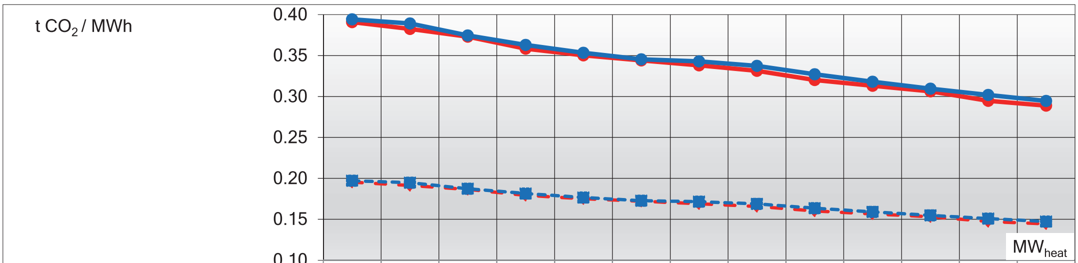
3.2.3. CO_2 Emissions

The boilers in each scenario will be capable of burning up to 100% of oil-shale and wood-based biomass. The addition of biomass to the mix allows for maximum CO_2 savings and the potential elimination of all emissions from fossil fuel systems. Carbon dioxide emissions can be calculated using the formula listed below that takes into account the efficiency of the CHP unit η_{CHP} and the carbon dioxide emission factor of the specific CO_2 emission per MWh of oil shale consumption for an oil shale fluidised bed unit k_{CO2OS} = 0.37 tCO_2/MW_{th}.

$$C_{CO2} = \frac{k_{CO2OS}(1 - s_{bio})}{\eta_{CHP_i}} \tag{9}$$

where k_{CO2OS} is the specific CO_2 emission factor, tCO_2/MWh, s_{bio} is the share of biomass, η_{CHP_i} is the energy efficiency of the i heat load. Because biomass cannot be used in alternative scenario II, this indicator will only be calculated for the baseline scenario and alternative scenario I.

Figure 8 depicts the contribution to reducing the environmental impact of heat and power production using oil-shale and biomass co-combustion 40% and 70% biomass (thermal energy input) for baseline scenario and alternative scenario I.



	40	50	60	70	80	90	100	110	120	130	140	150	160
Baseline scenario - 40%	0.39	0.38	0.37	0.36	0.35	0.34	0.34	0.33	0.32	0.31	0.31	0.29	0.29
Alternative scenario I - 40%	0.39	0.39	0.37	0.36	0.35	0.35	0.34	0.34	0.33	0.32	0.31	0.30	0.29
Baseline scenario - 70%	0.20	0.19	0.19	0.18	0.18	0.17	0.17	0.17	0.16	0.16	0.15	0.15	0.14
Alternative scenario I - 70%	0.20	0.19	0.19	0.18	0.18	0.17	0.17	0.17	0.16	0.16	0.15	0.15	0.15

Figure 8. CO_2 emissions under baseline scenario and alternative scenario I from a mix of oil shale and biomass (40% and 70%).

4. Results

Quantitative indicators of energy use are reflected in the thermal efficiency of processes, but their qualitative aspects are ignored. In this regard, exergy analysis methods have been developed to assess the efficiency of energy-related technological processes. Exergy is the maximum amount of work that any thermodynamic system can do during the reversible transition from a state with specific parameters to a state of equilibrium with the environment. Exergy efficiency is defined as the ratio of usefully absorbed exergy to spent exergy. Although the exergy analysis condition for improving energy efficiency is formulated similarly to thermal efficiency, the exergy analysis produces excellent results. When the exergy efficiency of some power units is compared to the thermal efficiency, the exergy efficiency is 1.5–2 times lower (for example, η_{ex} = 45%, η_b = 90% for a steam generator). The exergy efficiency is low due to significant heat loss from the fuel and heat transfer.

As a result of the exergy analysis, the main approaches to improving the efficiency of energy technological processes, namely combustion and heat transfer processes, can be highlighted.

The transition from a hot water boiler to cogeneration sources of heat supply is accompanied by an increase in electrical energy production while maintaining the same volumes of thermal energy production. If we consider the baseline scenario (CHP steam turbine) as Narva's current heat source, the switch to alternative scenario II (CHP gas turbine) results in a 1.5-fold increase in electricity. To conduct a comparative analysis, the calculation results were summarised in Table 1.

As shown in the table, the commissioning of new highly efficient combined-cycle energy sources under alternative scenario I (CHP gas turbine) will result in a significant increase in electricity generation while reducing heat production. To make up for the lost thermal energy, a heating water boiler must be installed, limiting the most efficient way to generate electricity via heat consumption. Thus, this scenario is characterised as unbalanced in terms of optimal production and consumption of heat and power, leading to significant excess fuel consumption.

As can be seen in Table 1, the share of generated electrical energy in the determination of exergy efficiency far outweighs the share of heat flow exergy. Alternative scenario II (CHP gas turbine) has an exergy efficiency of 42%, while the baseline scenario (CHP steam turbine) has an exergy efficiency of only 33%.

Table 1. Comparison of energy supply source indicators.

	1	**2**	**3**
	Baseline Scenario	**Alternative Scenario I**	**Alternative Scenario II**
	Extraction Steam Turbine	**Backpressure Steam Turbine**	**Gas Turbine**
Max heat capacity Q_H, MW	160	160	160
Max electrical capacity N_T, MW	215	220	450
Thermal efficiency η_{th}	0.78	0.76	0.68
Exergy efficiency η_{ex}	0.33	0.37	0.42
Overall efficiency η_{CHP}	0.55	0.57	0.56

Energy efficiency, which refers to the efficiency of the fuel consumed, decreases as electricity generation increases. This makes it difficult to assess the true quality of the heat supply source. For a comparative assessment of the quality of heat supply sources, it is recommended to use the value of the exergy efficiency. The proportion of generated electrical energy in determining exergy efficiency far outweighs the proportion of heat flow exergy. Alternative scenario II (CHP gas turbine) has the highest exergy efficiency of 42%, while the baseline scenario (CHP steam turbine) has an exergy efficiency of only 33%.

Baseline scenario (CHP extraction steam turbine) has an energy efficiency of 78%, whereas alternative scenario II (CHP gas turbine) has a thermal efficiency of 68%. At the same time, alternative scenario I has a thermal efficiency of 76%.

As a result, alternative scenario II (CHP gas turbine) generates the most useful energy. It's worth noting that the generation of electrical energy at the CHP gas turbine exceeds the thermal energy supplied via the source. When there is a low demand for electricity but a high demand for heat, the question of whether new combined cycle energy sources should be introduced may arise. It is necessary to compare the baseline scenario (CHP extraction steam turbine) and alternative scenario II (CHP gas turbine) as sources of heat and power operating in the Narva district heating system. We will compile a table of performance indicators for the compared energy supply sources to analyse the results of the calculation.

The amount of fuel consumed is a clear and objective indicator of the energy supply source's efficiency. The electrical efficiency in the baseline scenario (0.37) corresponds to the fuel consumption in scenario II (0.37), with the maximum production of the same amount of electricity and heat. However, switching to separate generation of the same amount of electricity (using a CHP gas turbine) and thermal energy (using a hot water boiler), as described in scenario II, decreases efficiency by 4% to (0.33). Given that the capital costs for construction under scenario II (CHP gas turbine) are 30–40% higher than under scenario II (CHP gas turbine), the feasibility is called into question. The renovation of the existing CHP costs two times less under the baseline scenario (CHP steam turbine).

Table 2 provides the energy and exergy balances for all scenarios.

Table 2. Comparative total energy and exergy balances of the boiler unit for all scenarios.

Balance	**Energy**		**Exergy**	
	10^6 kJ/h	**%**	**10^6 kJ/h**	**%**
Flow				
Fuel	629	100	629	100
Consumption				
Received via water(steam)	572	91.0	290	46.0
Flue gases	45	7.0	8.2	1.3
Incomplete chemical combustion of fuel	9	1.5	9.4	1.5

Table 2. *Cont.*

Balance	Energy		Exergy	
	10^6 kJ/h	%	10^6 kJ/h	%
Heat loss to the environment	3	0.5	2.2	0.4
Loss incurred during the combustion process	-	-	152.1	24.2
Loss during heat transfer	-	-	153.7	24.4
Loss due to air suction	-	-	13.4	2.1
Total:	-	100	-	100

According to this exergy balance, the losses consist of losses incurred during the combustion process, heat transfer and air suction.

Under all heat supply scenarios, the same amount of thermal energy is produced (140, 120, 100, and 80 MW_{th}), whereas electricity generation remains constant at a minimum of 44 MW_{el}. The values for the scenarios are given in Table 3.

Table 3. Baseline scenario values for different heat loads.

Heat Load, MW	140			120			100			80		
Scenarios	**B**	**I**	**II**	**B**	**I**	**II**	**B**	**I**	**II**	**B**	**I**	**II**
HPR	3.2	3.2	3.2	2.7	2.7	2.7	2.3	2.3	2.3	1.8	1.8	1.8
B_f, kg/s	8.26	8.46	8.65	7.89	7.73	7.56	7.42	7.19	7.14	6.83	6.67	6.61
b, kg/MWh	161.6	165.4	169.2	173.3	169.6	166.0	185.4	179.9	178.5	198.2	193.7	191.8
h_{th}, %	76.0	74.2	72.6	70.9	72.4	74.0	66.2	68.3	68.8	62.0	63.4	64.0

HPR is heat-to-power ratio (HPR = N_T/Q_{DHw}), B_f is standard fuel consumption (kg/s), b is fuel specific consumption (kg/MWh), h_{th}, % is thermal efficiency.

The amount of fuel consumed is a clear and objective indicator of the energy supply source's efficiency in the scenarios. As shown in Table 3, the amount of fuel consumed at maximum heat generation under all three scenarios is at its lowest in the baseline scenario (8.26 kg/s). When we consider that capital costs during construction under the two alternative scenarios are 40–50% higher than during construction under the alternative scenario, the question of expediency arises. When comparing the considered energy supply sources with a heating coefficient TPR = 3.2 in which the consumption of thermal energy is more than three times that of electrical energy, we see that the efficiency of the baseline scenario, estimated based on the standard fuel consumption for the production of thermal and electrical energy, was 156.9 g/kWh. In alternative scenarios, the minimum specific consumption of reference fuel decreases as the thermal factor decreases, as shown in Table 3.

Relevant features from the standpoint of indicator calculations include the fact that alternative scenario I uses backpressure turbines with tightly interconnected electrical and thermal loads. The thermal load is used as the primary load in the scheme, and the electrical load is calculated from the steam flow through the turbine and thus can be greater or less than that indicated for all schemes, which has an effect on both technical, economic, and financial indicators. As a result, we use a steam turbine CHP plant as the baseline scenario, because the transition to alternative Scenario II is accompanied by a 1–2-fold increase in electricity, whereas the transition to alternative Scenario I comes with a 3+fold increase. A comparison of scenario cogeneration sources reveals that the most thermal energy (140 MW) is generated under the baseline scenario with the least amount of standard fuel consumption.

As the presented comparative analysis of various sources of heat supply has demonstrated, it is more convenient to produce electrical and thermal energy at steam turbine CHP plants; however, such a path for further development of heat supply cannot be recognised as promising because all of the shortcomings inherent in the existing district heating system are preserved. As a result, with the continued development of heat supply, alternative sources and technologies of low-temperature heat supply must be introduced.

It is critical to remember that the feasibility of implementing any scenario must be considered in relation to the conditions of each specific facility, taking into account the thermal scheme's characteristics and the plant's operating mode. The latter is crucial because, when a heat-extraction steam turbine is operating on a thermal schedule, using steam extractions before the thermal is impractical.

The well-known effective strategies to increase the thermal efficiency of the steam-power cycle, namely the regeneration system, are ignored when introducing steam-gas technologies.

Under the baseline scenario, significant thermal efficiency reserves can be realised by making more extensive use of regenerative steam extraction from CHP plants.

Specific CO2 emissions were calculated for variable heat load scenarios with biomass shares of 40% and 70%. The results are depicted in Figure 8.

5. Conclusions and Discussion

Different scenarios of possible heat supply for the Narva district heating network were compared, including a scenario where an existing extraction CHP steam turbine completely replaces fossil fuel with biomass and covers both base and peak loads (with boiler house as backup), a scenario with a CHP backpressure steam turbine, a scenario with a CHP gas turbine. The overarching goal of the various scenarios for power supply solutions is to identify technologies that best meet the needs of DH from a technical standpoint. The system efficiency analysis revealed that the baseline scenario (CHP extraction steam turbine) made the best use of the input primary energy at various heat loads.

In the future, the use of a heat pump to preheat circulating network water should be investigated as the most promising option for improving a district heating system's energy efficiency. Network water is supplied by a network pump to the condensers of parallel-connected vapor-compression heat pumps with an electric drive and then, already heated, to the main heat exchanger, where it is further heated according to the network temperature schedule. It is necessary to select the optimal parameters and determine the maximum water temperature after the HP condenser in order to evaluate the energy efficiency of the combined HP as an additional heat source for district heating. In this scenario, the heat pump's conversion factor must be at least equal to the value that ensures the primary energy costs for heat generation via the combined HP station and the main source are the same.

As a result, in the scenario under consideration, replacing a hot water boiler with a combined heat pump can potentially reduce annual fuel consumption for heat generation by up to 10%. The creation of combined heat pumping stations with electrically driven heat pumps as part of the main operation mode allows for the reduction of total fuel consumption by utilising low-grade thermal energy from renewable and secondary sources.

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Nomenclature

Abbreviations

CHP	combined heat and power
DH	district heating
CFB	circulating fluidised bed

HPR	heat to power ratio
Parameters	
G	network water flow rate, m^3/h
Q	thermal load, MW
c_p	specific heat of water, J/kg·K
D	heating steam flow rate, kg/s
h	enthalpy of steam, kJ/kg
η	efficiency, %
N	electrical energy, MWh
B	fuel consumption, t
Q_{LHV}	calorific value of fuel, MWh/t
t	temperature, °C
L	useful work, MWh
k	carbon dioxide emission coefficient, tCO_2/MW_{th}
s	share of biomass
Subscripts	
DH	district heating
H	heat
s	supply
r	return
T	turbine
f	fuel
fw	feedwater
b	boiler
ef	energy efficiency
ex	exergy efficiency
bio	biomass

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