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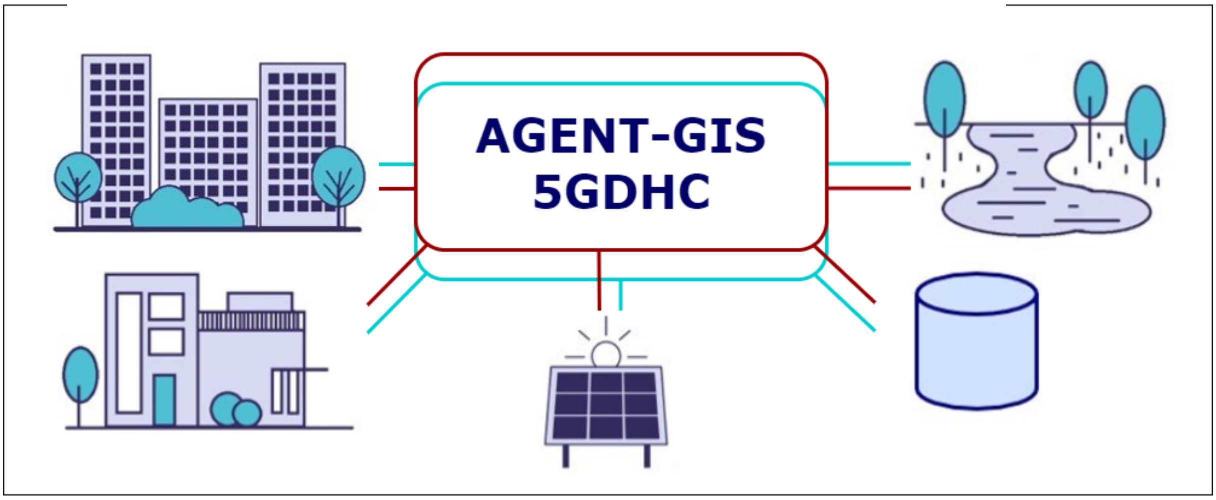

TECHNO-ECONOMIC PERFORMANCE AND FEASIBILITY STUDY OF THE 5GDHC TECHNOLOGY USING AGENT BASED MODELLING AND GIS

FINAL REPORT

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2023

Acknowledgements

This report is the result of collaborative project Joint Baltic-Nordic Energy Research Programme research project „Techno-economic performance and feasibility study of the 5GDHC technology using agent based modelling and GIS“ (106840 – Agent-GIS-5GDHC), jointly funded by Nordic Energy Research and the Baltic States' ministries responsible for the energy sector.

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Abbreviations

4GDH	4th Generation District Heating
5GDHC	5th Generation District Heating and Cooling
AHP	Analytic Hierarchy Process
CAPEX	Capital Expenditures
CO_2	Carbon Dioxide
COP	Coefficient of Performance
DH	District Heating
DHC	District Heating and Cooling
DHW	Domestic Hot Water
DR	Discount Rate
EE	Estonia
EU	European Union
HP	Heat Pump
HX	Heat Exchanger
LCOH	Levelised Cost of Heating
LT	Lithuania
LV	Latvia
MCM	Monte Carlo Method
MFH	Multi-Family Houses
MILP	Mixed-Integer Linear Program
MPC	Model Predictive Control
NERC	National Energy Regulatory Council
OPEX	Operating Expenses
PV	Photovoltaic

SCOP	Seasonal Coefficient of Performance
SH	Space Heating
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution

1. 5GDHC Agents

1.1. 5GDHC Definition

District heating and cooling (DHC) technology is widely regarded as a promising solution for reducing both primary energy consumption and local emissions [1,2]. The 5th generation district heating and cooling (5GDHC) network is the latest concept in district heating/cooling, characterised by low temperature supply (close to ground temperature), bidirectional operation (can provide heating and cooling simultaneously), decentralised energy flows (allows multiple heat sources and heat sinks in the network), and heat sharing (can recover waste heat and share it with different users) [3]. Unlike 4th generation district heating (4GDH), 5GDHC is consumer/prosumer-oriented. It only requires one thermal grid, but it serves multiple purposes for both heating and cooling distribution, including heat and cold storage, and thus provides flexibility in adopting local renewable energy and waste heat resources. As stated in [4], by integrating low-grade heat with photovoltaic arrays, batteries, and vehicle-to-grid applications, 5GDHC systems also support the electrification of both the building and transportation sectors towards the broader concept of 'fifth generation smart energy networks'.

The differences between 5GDHC and 4GDH have been investigated in prior studies. For instance, [5] conducted a systematic comparison of 5GDHC and 4GDH in terms of goals and capabilities. According to their findings, 5GDHC shares five core capabilities with 4GDH:

(i) the ability to supply different types of buildings;
(ii) the ability to distribute heat with low grid loss;
(iii) the ability to recycle heat from low-grade sources;
(iv) the ability to integrate into large smart energy systems;
(v) the ability to ensure proper planning and cost-effective investment.

The main differences between 5GDHC and 4GDH are a strong emphasis on combined heating and cooling, as well as the use of a collective network at close to ground temperature as a common heat source or sink for heat pumps (HP). They also concluded, after reviewing various literature, that 5GDHC can be viewed as a technology with distinct advantages. It does not have to replace other 4GDH technologies. Instead, it can coexist with them. Reference [6] compared the levelised costs of heat for both 4GDH and 5GDHC in Denmark and the UK. According to the results of this study, 4GDH is more cost-effective than 5GDHC in both of these countries under current cost scenarios.
This is due to three key factors:

(i) central HP economies of scale;
(ii) access to cheaper energy;
(iii) simpler building interface units.

These factors can offset the additional cost of the insulated piping network and the associated distribution heat loss in 4GDH systems compared to 5GDHC. The key barrier and difference between 5GDHC and 4GDH is HP's reliance on the power supply system, as they must raise temperatures to meet the needs of end users. Therefore, an increase in the price of electricity will significantly raise the cost of 5GDHC.

Several studies have examined 5GDHC from various perspectives. Grzegórska et al. (2021) looked into the current state of district heating (DH) systems in several Baltic countries in terms of application, solutions, and novel approaches to smart asset management (i.e. maintenance approaches based on asset control, prediction, optimisation, and selective refurbishment using novel hardware and software solutions) [7]. They compared the traditional maintenance system to smart asset management solutions in terms of optimal design, operating conditions, and management of the DH network. According to their findings, integrating smart management tools into DH systems can help to solve issues in existing DH networks while also ensuring profitability for both heat providers and consumers. Buffa et al. (2019) [3] conducted an in-depth analysis of 40 thermal networks operating in Europe that can provide both heating and cooling to buildings. They conducted a drawback-benefit analysis to investigate the pros and cons of 5GDHC. They also examined the challenges of implementing 5GDHC, such as a lack of guidelines for designers and planners, a lack of a local heat atlas, and a lack of new business models and tariff mechanisms. Model predictive control (MPC) algorithms based on recurrent artificial neural networks were developed in [8] to improve the performance of energy transmission stations in buildings. The results showed that MPC can effectively shift electricity consumption of energy transmission stations from peak to off-peak hours by up to 14%, suggesting that the use of advanced control in 5GDHC can promote the coupling between the heat and power sectors. They also stated that the potential weaknesses of 5GDHC include complex seasonal load balancing and increased complexity in terms of both distribution network management and energy transmission stations at customer sites.

There are a number of studies covering the techno-economic analysis of the 5GDHC network. For example, [9] developed a mixed-integer linear program (MILP) control method for short-term network temperature optimisation in 5GDHC systems that took into account the integration of waste heat and free cooling. Their 5GDHC system consisted of a heat pump, a chiller, and thermal storage in a central generation unit, as well as pumps, chillers, electric boilers, and a thermal storage unit in 17 agent buildings. The results showed that such temperature control can reduce network operating temperatures, as well as cut operating costs by 10-60%. Another study [10] proposed an assessment framework for determining the economic, operational, and carbon benefits of HP-driven 5GDHC energy sharing networks in urban areas. They developed a load matrix to determine which energy loads (from various building types) were suitable for energy sharing. Using the proposed assessment framework and load matrix, they conducted parametric studies of various scenarios for different combinations of heat tariffs, energy sharing, thermal storage, and carbon taxes. The study's findings revealed that the financial benefits of 5GDHC are more dependent on factors such as thermal storage size and time-of-use tariffs, whereas the carbon savings of 5GDHC are more dependent on system alternatives such as natural gas boilers. Energy sharing has virtually no effect on these metrics. A bibliographic analysis of 5GDHC system modelling and co-simulation was conducted in [11]. Because proper advanced control strategies for 5GDHC operation are still lacking, the study concluded that the co-simulation of the district energy system and building energy models could help reduce oversized space heating and cooling systems. They also stated that 5GDHC systems address two of the main challenges faced by the 4GDH, including the need for separate pipes to provide both heating and cooling, as well as centralised energy generation, which limits the expansion area of the network.

In 5GDHC, different players can be viewed as agents interacting with one another through pipes: consumers, suppliers, and prosumers. Consumers represent end users of heat and cold, such as residential buildings. Suppliers represent heat producers, such as the existing DH network, excess heat, or solar thermal energy. Prosumers represent heat users that can sometimes produce heat, such as data centres and shopping centres. Potential agents in 5GDHC include office buildings, shopping centres, data centres, electrical transformers, and other facilities that can add low-temperature heat to the network. The agents draw water from the loop at temperatures ranging from 5 to 30°C to cover their heating or cooling demand and re-inject it into the same loop. HPs can be used to meet a variety of heating and cooling needs in a network at different temperatures. Renewable energy sources, such as wind farms and photovoltaic (PV) power stations, can be used to power HPs. In this regard, the use of HPs by agents can also provide flexibility in balancing fluctuations in the power grid caused by intermittent renewable energy sources (RES) [12]. Danfoss, as practitioners, emphasise that 5GDHC has a significant dwelling spatial impact as well as medium dwelling noise levels due to the use of individual HPs [13]. There is a significant resident risk for the same reason that HPs are used. Geothermal energy can also be integrated into 5GDHC as a potential agent [14]. The legal framework for shallow geothermal energy use in 14 European countries was discussed in detail in [15]. This article revealed significant differences in legal provisions, regulations, standards, and institutional support across the European countries. These differences are barriers to the further integration of geothermal energy into 5GDHC. 5GDHC is also subject to similar barriers, which prevent 5GDHC from being implemented on a larger scale.

1.2. 5GDHC Agent Identification

The identification of agents will allow the potential of their use in 5GDHC. This potential is one of the most important criteria for evaluating the concept's implementation. The preliminary potential of the following agents has been determined: shopping centres, electrical transformers, and data centres. Each 5GDHC agent has slightly different properties that are described further below. Temperature is the most important parameter for excess heat. Another important factor is whether the heating agent is liquid or gaseous, as this determines the conditions for the use of excess heat.

1.2.1. Electrical Transformers

Electrical transformers have the potential to be 5GDHC agents [16]. In Milan (Viale Gadio), there is a demo project consisting of a newly built low-temperature DH network that uses excess heat from an electrical transformer as a waste heat source. Throughout the year, excess heat from electrical transformers is available at a temperature of 30°C [17]. Excess heat in electrical substations is generated as a result of substation power loss. In older electrical transformers, mineral oil was used to cool the transformer. Mineral oil has an autoignition temperature of around 300°C, but to avoid premature ageing of the insulation, the temperature should not exceed 90°C. In the case of substations, there are two modes of operation: normal operation and maximum load operation. During normal operation, the power output of the transformer is lower, and thus the excess heat temperature is also lower [18]. Modern power transformers have dry insulation, which means that the transformer windings are cast in epoxy resin and completely isolated from the outside environment. They have a lower oil content, so their risk of autoignition is reduced [19]. The operation of the transformer, on the other hand, generates a significant amount of excess heat that must be cooled, and this heat can be used as a 5GDHC agent. The use of electrical substations as heat sources in Danish DH networks was discussed in [20]. The article suggests replacing the substation's cooling radiator with a heat exchanger connected to the DH network or a heat pump. The case study demonstrates that, while power transformers cannot cover a substantial portion of the DH load, the amount of heat supplied can be significant at the local level. Although [20] suggests reducing transformer oil circulation to obtain higher excess heat temperatures, it should be kept in mind that efficient cooling is crucial for a power transformer to prevent autoignition of the mineral oil and premature ageing of the insulation.

1.2.2. Retail Stores

According to [3], supermarkets and warehouses can play an important role in the development of new 5GDHC projects. Retail stores as potential sources of low-grade heat were investigated in [21]. Large cooling systems used for ventilation in retail stores and other public buildings create a flow of urban excess heat that can be utilised as an agent in the 5GDHC network. The temperature of excess heat flow in retail stores is typically in the 30-40°C range [22]. Heat recovery should be performed via a heat pump unit connected to the condensation circuit of the cooling generation plant. The heat pump captures and thermally improves the heat rejected by the chillers [23].

Retail stores are the most common type of public building that can be found in any part of the city. It should also be noted that they have a high excess heat potential due to the large number of daily visitors, which creates a demand for proper ventilation, resulting in excess heat flow. Although utilising excess heat from retail stores can benefit both the store and the DH network, profitable business models are still required.

1.2.3. Data Centres

Data centres consist of data halls, or buildings, containing rows of IT server racks, which are used to store, process, and transmit information from connected computer networks. To cool the data centre, various types of air conditioners are used, which are located throughout the facility [24]. Chilled water is also used to generate cooling.

Excess heat from data centres is a readily available and accessible low-grade heat source that heat pumps can easily utilise. Excess heat from data centres will become more available in the future as electrification of energy systems and industries continues [20]. The number of data centres is expected to triple by 2050 [22].

To keep our day-to-day information systems running, servers and computers require a stable and uninterrupted power supply. Most of the electrical energy supplied to the IT equipment turns into heat, which must be cooled down in order for the equipment to function properly. This heat is typically not used, but is instead cooled in cooling towers or similar devices. Because the amount of energy needed to cool the IT equipment in a data centre is substantial, utilising excess heat has significant economic and environmental benefits [25]. Since data centres require continuous power supply throughout the year, the amount of useful excess heat does not vary significantly [22].

Data centres are low-grade heat sources in 4GDH systems and can also serve as agents in 5GDHC systems.

The temperature of the air leaving hot aisles is often 25-40 °C [22], and there are several methods for recovering excess heat. The feasibility of the chosen method depends on the current state of the data centre [25]. Using the data centre's excess heat for DH will also reduce operating costs because the data centre's cooling demand will decrease. Reference [26] presents a case study where excess heat from a liquid-cooled data centre is used to heat a local swimming pool, with profitable business models described for both parties.
There can be all sorts of barriers to utilising excess heat in a data centre. The majority of the barriers are non-technical in nature and related to a lack of information and profitable business models [22].

1.3. Database and GIS Map

1.3.1. Data Collection

One of the project's goals was to create a high-resolution GIS database for the digital mapping of 5GDHC agents. All potential 5GDHC agents and their locations were compiled into a database and classified according to their source and excess heat potential. Data collected during the study allowed us to update the interactive map created during the previous project of the Joint Baltic-Nordic Energy Research program, "Heat Pump Potential in the Baltic States". The following layers have been added, containing data on three 5th generation district heating and cooling agents:

- data centres;

- retail stores;

- electrical substations.

To assess the excess heat potential of electrical transformers, a database of electrical substations has been created. Transformer location and voltage data were obtained from [27] for Estonia, [28] for Latvia, and [29] for Lithuania. Substation locations for 330 kV and 110 kV were also obtained. Unfortunately, there was very little information on transformers, so the substations were divided into two types: 110 kV and 330 kV. According to previous studies on the potential of electrical transformers in Denmark [30], a 330 kV transformer can generate 18,400 MWh/y of excess heat, and a 110 kV transformer can generate 560 MWh/y. Substations located in the DH regions have also been classified.

It was decided to gather locally available information on retail stores in the Baltic States, such as the total area and the exact location of each store. The list of retail stores and shopping centres in Estonia was compiled using the websites of major retail chain stores and additional information obtained from companies. Most retail stores' construction year and total area were obtained from the Estonian Register of Buildings [31]. For Latvia, data on the total area were collected from large retail chain stores and supplemented with additional information from the data distribution portal of the State Land Service of the Republic of Latvia [32]. The majority of information for Lithuania came from large retail chains. The gathered retail store data was added as a GIS map layer. The next step was to identify the stores that were within the DH regions and could be connected to the DH system. It was possible to merge the GIS map layer with retail stores with the DH region layer.

Public data on data centres was collected for each country. As in [21], it was assumed that 65% of all electricity consumed by data centres can be classified as ’excess heat’. All data centres identified are located in DH regions.

A GIS map containing all of the collected 5GDHC agents can be found at https://www.arcgis.com/home/webmap/viewer.html?webmap=5db84d09f1724ff4a05f404a54d59b1b

1.3.2. Potential Calculation

The ReUseHeat report calculation results [33] were used to estimate the relative excess heat from retail stores in each country. Based on these results, the following average estimated excess heat amounts were determined: 0.555 MWh/m^2 in Estonia, 0.547 MWh/m^2 in Latvia, and 0.469 MWh/m^2 in Lithuania. Table 1.1 shows the possible amount of excess heat from retail stores in the DH region and beyond in the Baltic countries.

Table 1.1. Excess heat potential of 5GDHC agents

	Estonia		Latvia		Lithuania	
	total (MWh)	within DH (MWh)	total (MWh)	within DH (MWh)	total (MWh)	within DH (MWh)
Retail stores	1,050,693	991,307	887,354	795,414	1,285,050	1,157,938
Electrical transformers	212,160	86,000	285,040	202,480	410,960	114,560
Data centres	107,081		53,271		30,903	

2. 5GDHC Technical Performance Analysis in the Baltic and Nordic Regions

Considering the available data, this project has selected Tallinn as a case study for the techno-economic analysis of the 5GDHC system.

2.1. Development of the 5GDHC Simulation Platform

It is important to quantify the energetic and economic benefits of 5GDHC systems. The data used for the analysis, as well as the underlying assumptions and methodology, are described in the following section. The subsections below also include information on meteorological parameters, component sizes, and economic boundary conditions.

2.1.1 Building Loads

The analysed low-temperature grid provides heat to one of the districts in Tallinn, Estonia. This district consists of 14 Multi-family houses (MFH). The utility company provided data for 2021, which was used in the analysis. The hourly value is made up of the existing heating plant's flow rate as well as supply and return temperatures. The load consists of space heating (SH) and domestic hot water (DHW) demand, with annual combined loads of 1,897 and 536 MWh, respectively. The total peak demand of the district is 1.4 MW. Monthly variations in combined SH and DHW demand are depicted in Figure 2.1., indicating seasonal variations in space heating demand with nearly constant DHW demand throughout the year.

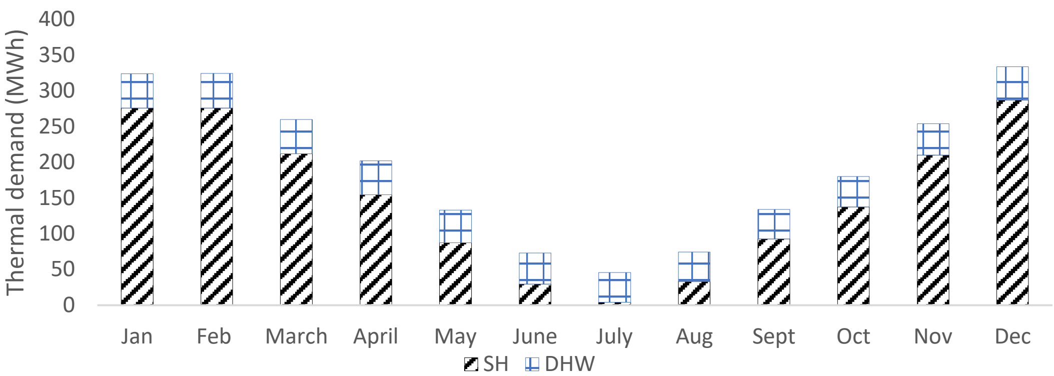


Figure 2.1. Monthly variations in SH and DHW demand for the combined heat load of the analysed district

2.1.2. TRNSYS System Model

Because the dynamic performance of an HP substation is important in any 5GDHC system, it was simulated in this study. Previous research has shown that the electricity consumed by HPs is a major contributor to the overall heating cost of a 5GDHC plant. Since HP performance is affected by source and sink temperatures, mass flow rate, and partial load conditions, the dynamic characteristics of the HP model must be considered. As a result, a detailed TRNSYS model was developed to simulate the performance of HPs and other system components for each APB under changing boundary conditions.

The network side of a 5GDHC system consists of a distribution system that serves as a heat source for various heat pump substations. After the heat is received, the HP generates a temperature suitable for SH and DHW on the consumer end. Step 1 involves using the TRNSYS model to simulate the consumer's side, assuming that the HP has a nearly constant supply temperature. Control valves ar each substation manage temperature drops across the evaporator, which are assumed to be 5°C in this study. As shown inFigure 2.2., one substation was considered for each MFH.

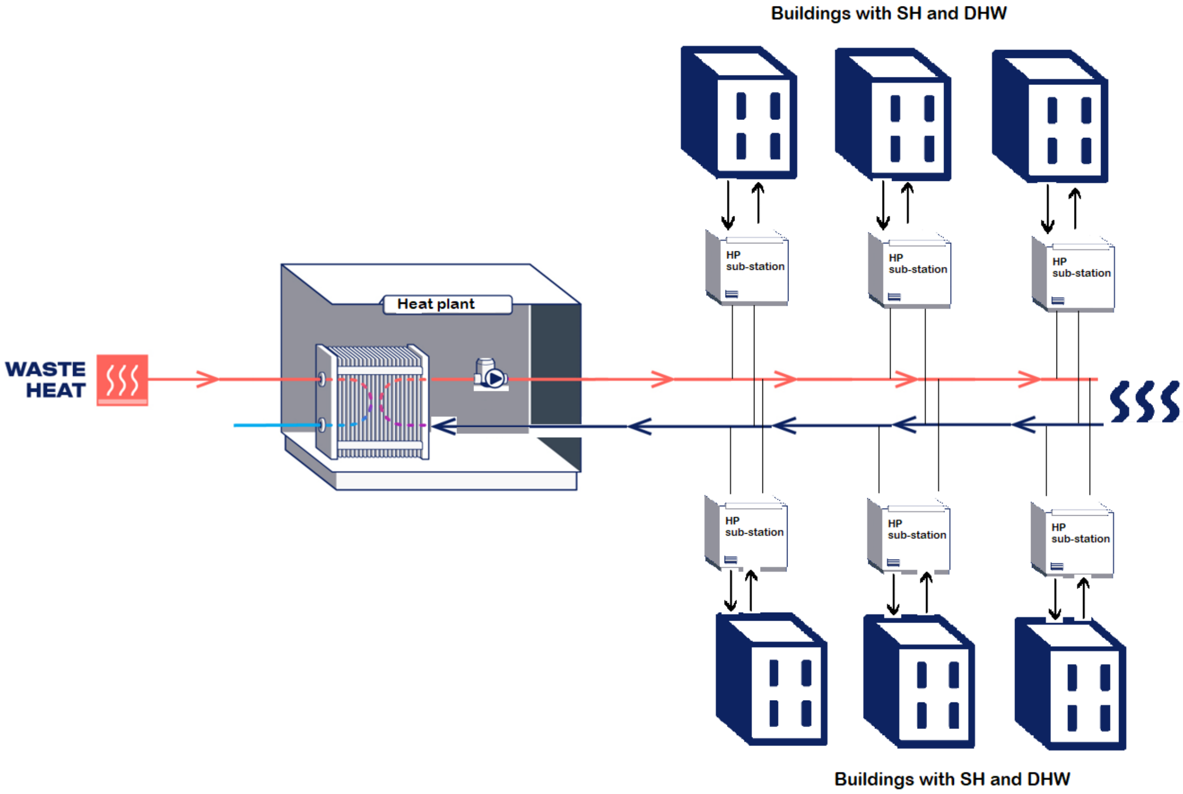


Figure 2.2. Schematic of a 5GDHC system considered for analysis

The HP substation is used on the consumer end to deliver SH and DHW to each group of MFH. A standardised substation configuration was selected for each building group, as shown in Figure 2.2. Depending on the level of the DHW tank, the HP operates in either SH or DHW mode. The hot water from the HP outlet is routed to either the SH circuit or a 1 m^3 storage tank connected to the DHW system. The DHW circuit is designed to provide the consumer with hot water at 55 °C. The hot water is prepared using an external plate heat exchanger unit together with a variable-speed pump. The design supply/return temperatures of the SH circuit are 55/45 °C, respectively, and they vary according to a climatic curve. Heat is distributed to individual apartments via wall-mounted radiator units. The control of the HP based on the charge level of the DHW tank, which is managed by a differential controller. The top priority is to fully charge the DHW tank using the peak capacity of the HP. When the HP is in DHW mode, a small 0.3 m^3 storage tank is connected to the SH circuit and used to cover SH loads. The electricity used to power the heat pump and auxiliary devices comes from the grid. Because the heat pump is designed to cover the peak heating demand of a single building, it does not require a backup system.

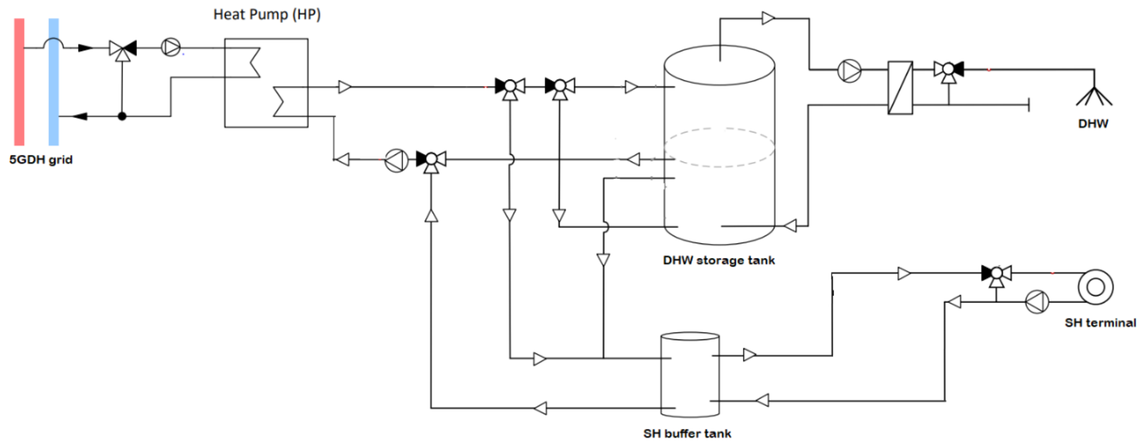


Figure 2.3. Configuration of substation simulated in TRNSYS

The system was simulated for a year at a time step of 5 minutes. The simulated HP is of the water/water type, and it was modelled using a performance map based on lab testing measurements. The rated COP of HP is 3.3 at 5°C source and 35°C sink fluid temperatures. The output of the TRNSYS model is a time series of condenser heat loads for each MFH substation, along with COP and electricity consumption of HPs and fluid pumps. This time series is used as input data for the DH grid model, which is created in a separate tool called Fluidit, as described in the following section.

2.1.3. Fluidit Simulation Software

Fluidit is a Finnish company that specialises in fluid dynamic simulations. The company has a wide range of fluid simulation tools such as Fluidit Water (for water distribution systems), Fluidit Heat (for district energy systems), Fluidit Storm (for stormwater systems), and Fluidit Sewer (for pumping stations and sewer systems). Fluidit Heat is used for district energy systems and allows users to design, manage, and evaluate DHC systems.

The tool uses the EPANET hydraulic network simulator and a proprietary in-house energy transfer model. Consumers can use Fluidit to determine the optimal production parameters for their heat sources, such as the sequence of operation, the amount of electricity required, and the temperature and pressure at which they operate. It can simulate current and future scenarios, as well as estimate demand based on weather and consumer conditions. The advantage of this tool is its user-friendly interface, as well as the realistic scenarios, material banks, and system controls found in actual DH plants. This study used the Fluidit tool to develop the network model as described below. This two-step modelling approach using TRNSYS and Fluidit makes it easy to model the entire system in detail, with each tool being used to its full potential to produce acceptable results.

2.1.4. Network and Heat Source

The system is assumed to have a waste heat source to maintain a constant temperature of 25 ℃ at the network’s outlet. The temperature of the heat supply is assumed to be constant throughout the year. Practically speaking, if a large industrial waste heat source (such as a steel mill) is located in close proximity to the network, it is possible to maintain a constant temperature in the grid throughout the year. The heat exchanger (HX) is assumed to transfer heat from the waste heat source to the network fluid.

A centralised pump from HX is used to receive network flow via a two-pipe system. The network is of the branch type, with buildings connected by pipe branches with main supply and return pipes. The total length of the network under consideration is 800 m, so the total length of the pipeline is 1,600 m. The temperature drop across the evaporator is managed by the control valves at each substation and is assumed to be 5 °C in this study.

2.1.5. Pipe and Insulation Sizing

The pipe diameter required in a 5GDHC system is generally larger than in a conventional DH system due to the smaller temperature difference between the supply and return pipes. Despite this, heat loss is lower in the 5GDHC system due to the smaller difference between network fluid and ground temperatures. This allows for a thinner layer of insulation or no insulation at all in some cases. The network pipes used in this study are X series pre-insulated pipes with thermal properties derived from the Flexynets project. The X series is based on commercial pipe series, but it only has one-third the insulation level of standard pipes. The use of insulation is considered appropriate because the ground temperature is significantly lower than the supply temperature.

The pipes are sized considering velocity and pressure drop constraints. A commonly used criterion for determining the optimal flow rate versus diameter relationship is to set the pressure gradient to a constant value, typically in the range of 50 – 150 Pa/m. The pipe size is chosen to provide maximum flow rate at the designed dT of 5K while maintaining a maximum fluid velocity of 2 m/s. The maximum pressure drop is 150 Pa/m. Once the model is created, the Fluidit Heat simulation results can be compared to see if the velocity simulation results for each pipe are within the recommended ranges. The network is thought to have pipes of various diameters, with the location of the building determining the maximum flow rate that each pipe section must provide. The total length of the pipeline is 1.6 km. Table 2.1. shows the pipe diameter and corresponding length in the entire network.

Table 2.1. Pipe size and properties used in the model

Pipe size	Pipe + insulation diameter (mm)	Heat loss coefficient ($U_{pipe+insulation}$) W/mK	Pipe length (m)
DN 220	291	0.61	400
DN 125	196	0.54	600
DN 100	169	0.47	400
DN 80	134	0.46	200

2.1.6. Central Pump Sizing and Operation

Pumps and pump batteries introduce energy into the system by raising the hydraulic head. Pumps are either controlled by their pump curves or modelled as constant power devices. Pump batteries are simplified pumps that allow the modeller to select intuitive control options such as constant flow, constant outlet pressure, constant inlet pressure, and constant generated head.

Pump batteries are hydraulically independent of their pump curves by default, but they can be restricted to operate within their specific curves.

The pump size is chosen so that it can provide the desired flow rate in the network. Using Serghide's method, pressure drop is calculated in order to estimate the total head in the network. The pump is designed for a total network pressure drop of 2 bar, with a 20% safety margin to account for bends, joints, and so on. The network's forward pressure is set at 4 bar. Based on the flow and pressure drop, a commercial pump is selected from the manufacturer's catalogue. Because Fluidit Heat can import pump curves (flow vs. head and efficiency vs. head) to simulate the operating points of a given scenario, these curves were used as input data for the model. The performance curves used in the model are shown in Figure 2.4.

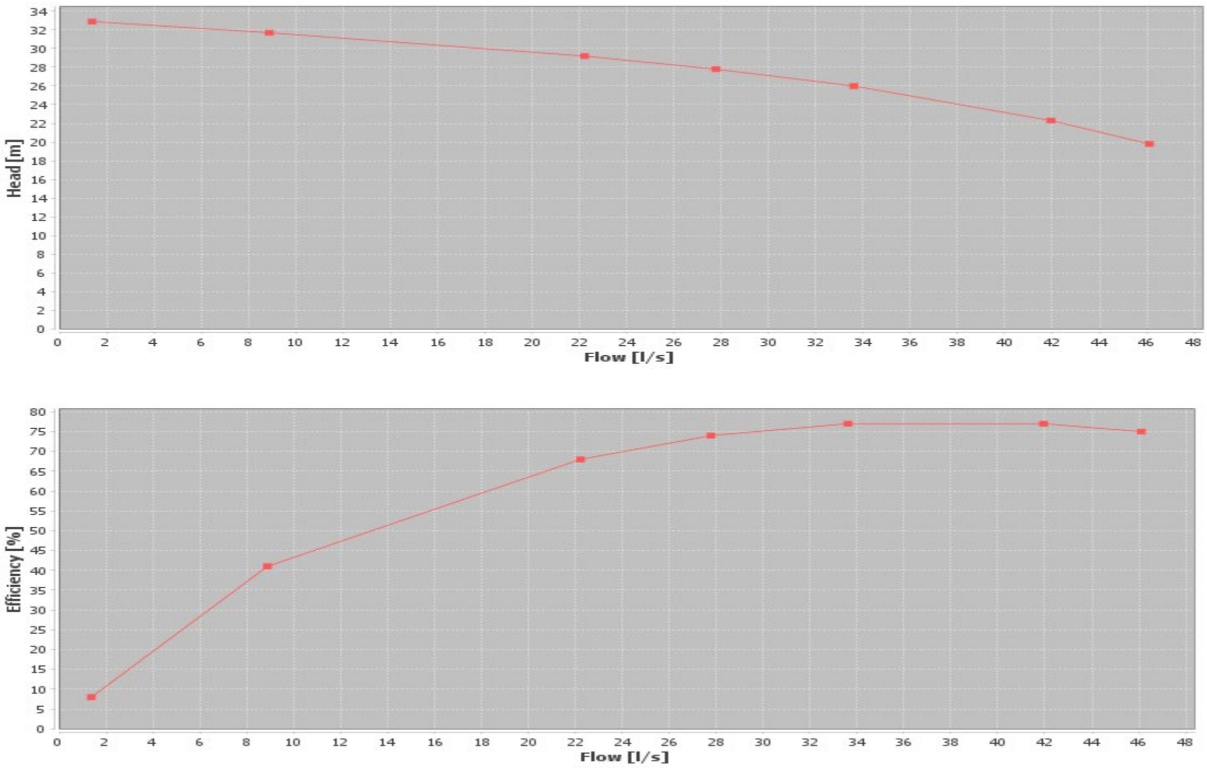


Figure 2.4. Pump performance curves : flow vs. head (above) and efficiency vs. flow (below)

2.1.7. Heat Loss and Ground Temperature Calculation

The network's heat loss is proportional to the heat loss coefficient and the temperature difference between the fluid and the ground. The ground temperature time series was calculated using the Kusuda model, where the undisturbed ground temperature is a function of season and depth below the surface. Equation 2.1. depicts the ratio used in the calculations.

$$T = T_{mean} - T_{amp} \cdot exp\left(-depth\left(\frac{\pi}{365\alpha}\right)^{0.5}\right) cos \qquad \text{Equation 2.1.,}$$

where T_{mean} is the average ambient temperature during the year and T_{amp} is the difference between the average and peak temperatures. t_{now} denotes the day to be calculated, and t_{shift} is the difference between t_{now} and the day denoting the minimum ambient temperature. α is the the soil's thermal diffusivity. It was calculated using Equation 2.2.

$$\alpha = k\rho Cp \qquad \text{Equation 2.2.,}$$

where k is the thermal conductivity of the soil, ρ is the density of the soil, and Cp represents specific heat of the soil. The parameters used in the calculations are given in Table 2.2.

Table 2.2. Ground temperature calculation parameters

Parameter	Value	Unit
T_{mean}	6.51	C
T_{amp}	23.40	C
t_{shift}	12	
k	8.2	kJ/hr.m.K
ρ	2900	kg/m^3
Cp	0.79	kJ/kg.K
$Depth$	1	m

The resulting ground temperature time series was used as input data for the model. The changes in the calculated ground and air temperatures for this area are depicted in Figure 2.5.

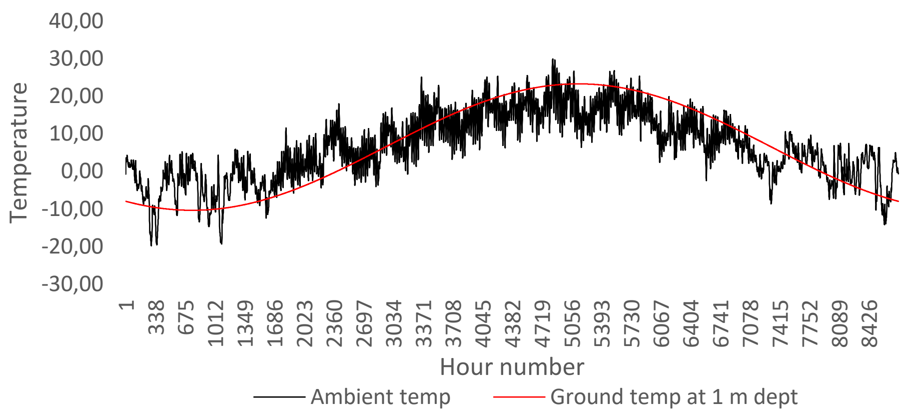


Figure 2.5. Changes in ambient and ground temperatures

2.1.8. Junctions

Junctions are network nodes that connect two links or where a link breaks without connecting. In total, there are 7 junctions in the base model, each of which connects 2 multifamily houses. The junctions are generated from imported pipe segments rather than being imported explicitly. The valve diameters in the junctions are designed to fit the various sections of the pipe. The simulation generates results for junctions that include pressure, temperature, volumetric demand, energy demand, energy deficit, and pressure difference visualisation.

2.2. Performance Analysis Indicators

The simulation results were used to calculate the cost of heating that the designed system could provide. The Levelised Cost of Heating (LCOH), a broad term used to compare different energy systems, was used as an indicator in economic analysis. It includes system investment costs, fixed and variable O&M costs, and the discount rate. Equation 2.3. was used to calculate LCOH.

$$\boldsymbol{LCOH_{HP}} = \frac{\boldsymbol{CAPEX_{sys} + Price_{el} \cdot \sum_{n=1}^{N}\left(\frac{W_{Sys}}{(1+DR)^n}\right) + \sum_{n=1}^{N}\left(\frac{OPEX_{f+v}}{(1+DR)^n}\right)}}{\boldsymbol{\sum_{n=1}^{N}\left(\frac{Q_{Yield}(1-SD)^n}{(1+DR)^n}\right)}}$$ **Equation 2.3.**,

where

$CAPEX_{sys}$ is the total capital cost of the system, including installation and commissioning;
$OPEX_{f+v}$ denotes total system operating costs, including fixed and variable O&M;
$Price_{el}$ is the price of one unit of electricity;
W_{Sys} is the annual power consumption of heat pumps and fluid pumps;
DR is the discount rate [%];
N is the project's lifespan [in years];
Q_{Yield} is the heat demand covered by the DH network.

The estimated costs for the system's various components are based on previous research articles, flexynet guidelines, case studies, and location-specific data. The CAPEX accounted for the various system components are listed in Table 2.3.

Table 2.3. Capital costs for various system components

	Description	Value	Unit
Heating plant	Heat exchanger CAPEX	90	EUR/kW
Network	Pipe + insulation cost (including installation)		
	DN200	534	EUR/m
	DN125	364	EUR/m
	DN100	307	EUR/m
	DN80	191	EUR/m
	Fluid pump CAPEX	35	EUR/(m^3.h)
Substation	Total HP substation installation cost	700	EUR/kW$_{th}$
Consumer side	Total pipeline installation cost (fixed)	200,000	EUR

An interpolation function based on the external diameter (pipe + insulation) was used to determine the cost of the pipeline. It was assumed that pipes were installed in unpaved areas. The cost function is given in Equation 2.4.

$$Cost = 1.7 \cdot 10^{-6} D_{ext}^3 - 0.0037 D_{ext}^2 + 3.28 D_{ext} - 149$$ Equation 2.4.

In addition to CAPEX, there are O&M costs, which are divided into two categories. The first involves fixed O&M costs that must be paid regardless of how the plant is operated. They includes various taxes, insurance, diplomatic fees, service charges, and so on. Variable OPEX costs, on the other hand, are parameterised based on the amount of heat supplied by the system to the consumer. They include spare parts, maintenance, auxiliary equipment, personnel costs, and so on. Table 2.4. provides the O&M costs for various system components.

Table 2.4. O&M costs for various system components

	Fixed OPEX (EUR/MW/year)	Variable OPEX (EUR/MWh)
Heating plant	150	0.2
Network	50	0.05
Substation	3,500	1.9
Consumer side	100	0.2

Besides, electricity is also consumed by substations and pumps. An electricity cost of 100 EUR/MWh was assumed to be average during the system analysis period. Please keep in mind that the 5GDHC system is primarily operated by a utility company, which has lower electricity costs than residential consumers. Waste heat has a fixed cost of 10 EUR/MWh, which is paid by the utility company to the industry from which it was recovered. A period of 30 years was used for the analysis. The discount rate used was 3%.

2.3. Performance Evaluation Results

2.3.1. Heat Pump Performance

The total heat load of the district is 2,433 MWh. According to the simulation results, the calculated HP seasonal coefficient of performance (SCOP) for the entire district is 3.3. Figure 2.6 depicts the variations in HP COP for one substation as a function of ambient temperature. At higher ambient temperatures, the HP operates more efficiently due to the low SH supply temperature. The lower end of the curve represents the lower COP representing the DHW mode of the HP, which has no change in ambient temperature.

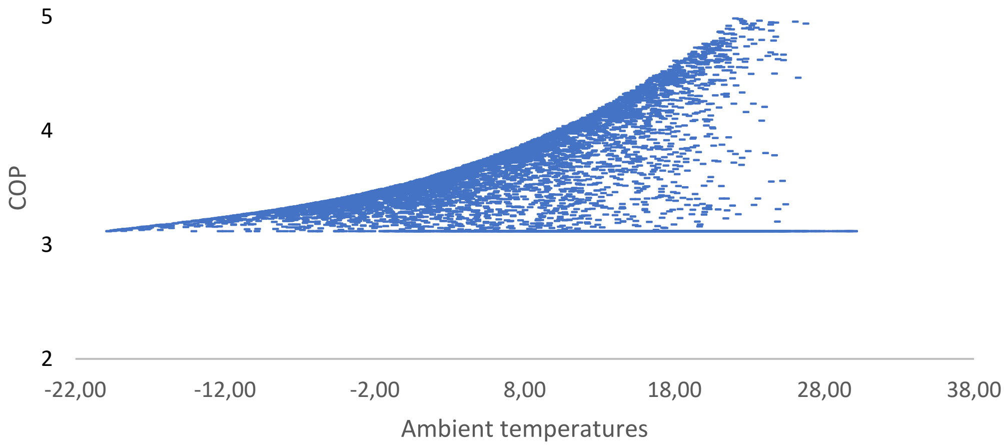


Figure 2.6. COP variations based on ambient temperature for one substation

According to the results, the lowest COP was observed in July, when the HP operated in DHW mode only, resulting in a high condenser temperature. The COP is higher in the remaining months, with the highest value of 4.72 between April and May due to the very low HP temperature in SH mode. The 5GDHC network must supply 1,710 MWh of heat to the heat pump while accounting for COP. The variations in total evaporator load used as input to the Fluidit model are depicted in Figure 2.7.

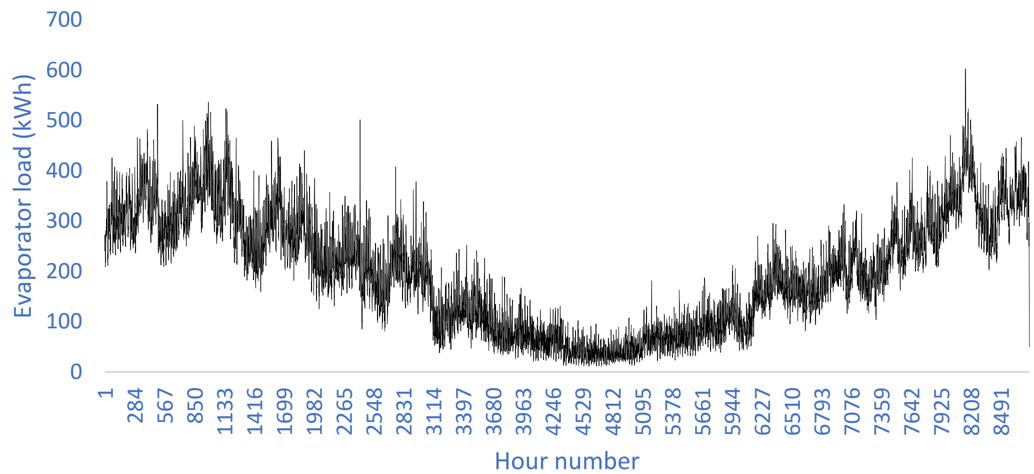


Figure 2.7. Variations in aggregated evaporator load for the district

The total annual electricity consumption by the HP substation to cover the thermal demand is 723 MWh. The electricity consumption of pumps on the consumer and network ends is 37 and 32 MWh/year, respectively.

2.3.2. Network Performance

Once the network is modelled, it is important to make sure that the flow velocity and pressure drop are within the design range (see Figures 2.8 and 2.9). The maximum flow velocity is 1.8 m/s, observed only for one hour per year. The average flow velocity is 0.5 m/s, which is well within the design range.

The head loss per unit length, or unit head loss [bar/km], represents the pressure drop within the pipes between junctions on a per unit length basis. Unit head loss is an essential metric for identifying distribution system bottlenecks. Pipes that are undersized and have a high head loss have an impact on consumer's downstream. The average head loss for the modelled system is 20 Pa/m, with a maximum value of 180 Pa/m for one hour per year.

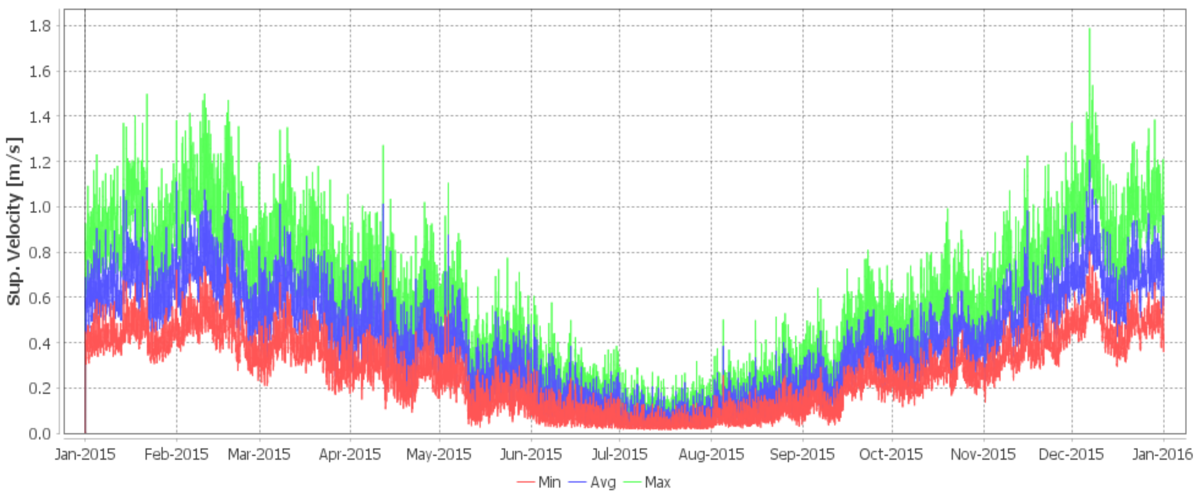


Figure 2.8. Variations in supply pipe flow velocities

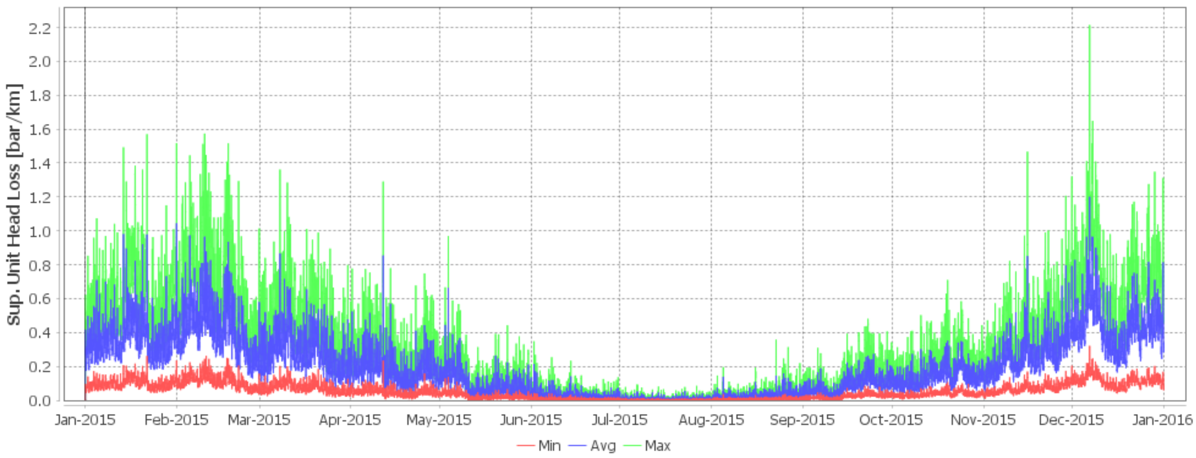
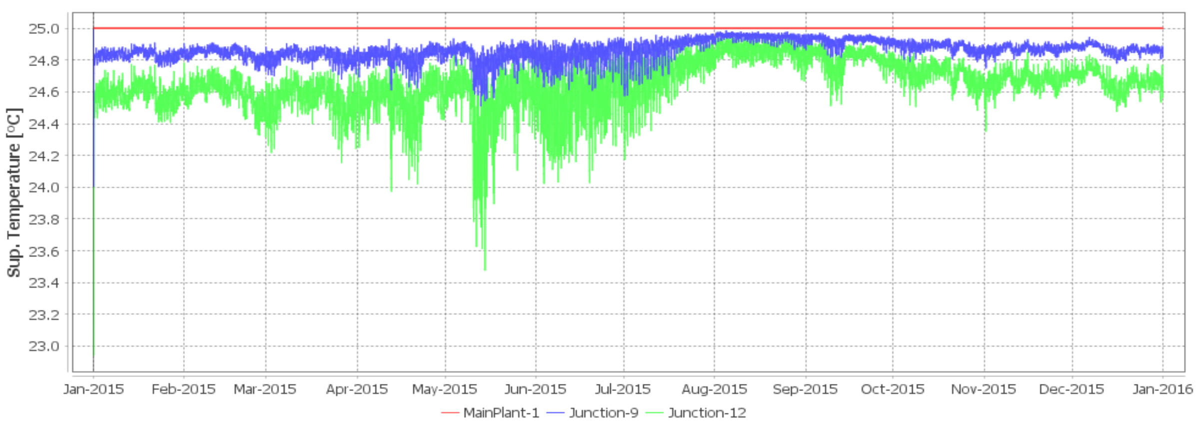


Figure 2.9. Variations in supply pipe pressure drop

Figure 2.10. depicts the variation in the supply and return temperatures at the main plant, the midpoint (junction 9), and the farthest point (junction 12). Due to heat loss, the lowest supply temperatures were naturally at the farthest points of the network. The average temperature drop at junction 9 is 0.15°C. The return flow yielded the same results, with an average return temperature of 19.87°C and an average drop of 0.13°C.



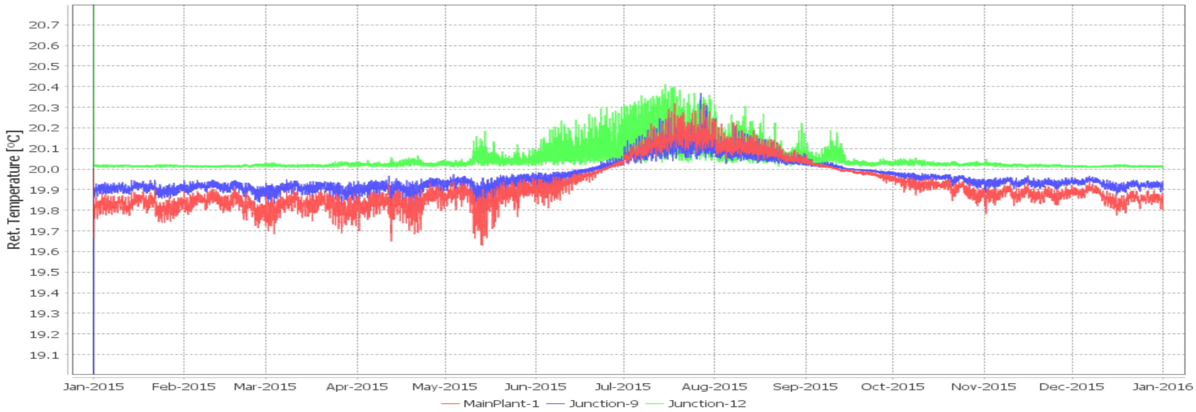


Figure 2.10. Variations in supply (above) and return temperatures (below) at 3 network nodes

Figure 2.11. depicts the changes in heat loss in the pipe network. The rate of the heat loss is greater in winter when the ground temperature is lower. In summer, it's the other way around. Higher ground temperatures cause an influx of heat into the fluid during certain hours of the year. The network's annual heat loss is 107 MWh, which is 4.4 % of the heat supplied. This heat loss percentage is much lower compared to conventional DH systems, resulting in lower primary energy consumption at the plant.

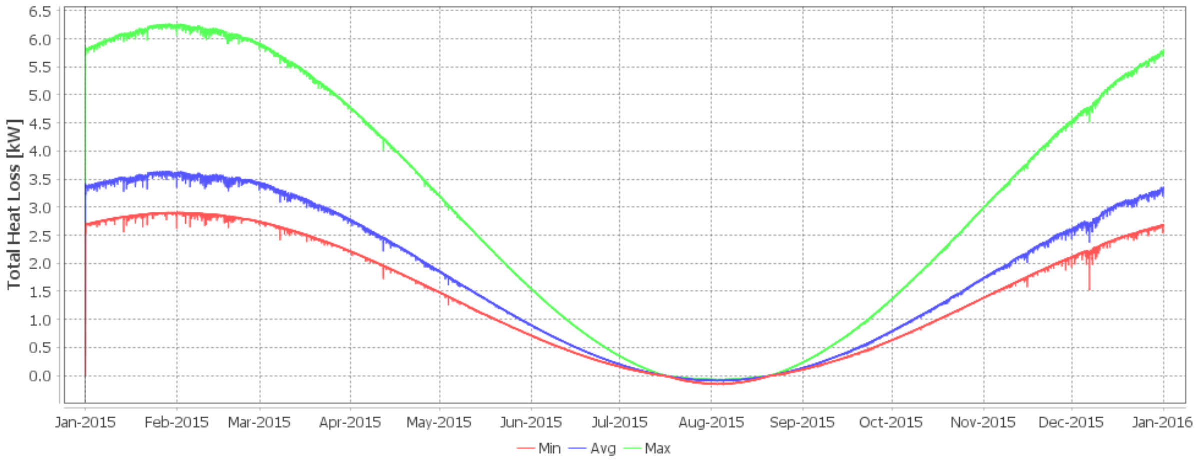


Figure 2.11. Variations in network heat loss

The central pump consumes 32 MWh of electricity per year. Based on the input characteristic curves, the Fluidit tool can calculate the pump's operating points. The model's operating points are depicted in Figure 2.12. The pump's annual average hydraulic efficiency is 45%, with a maximum value of 73%.

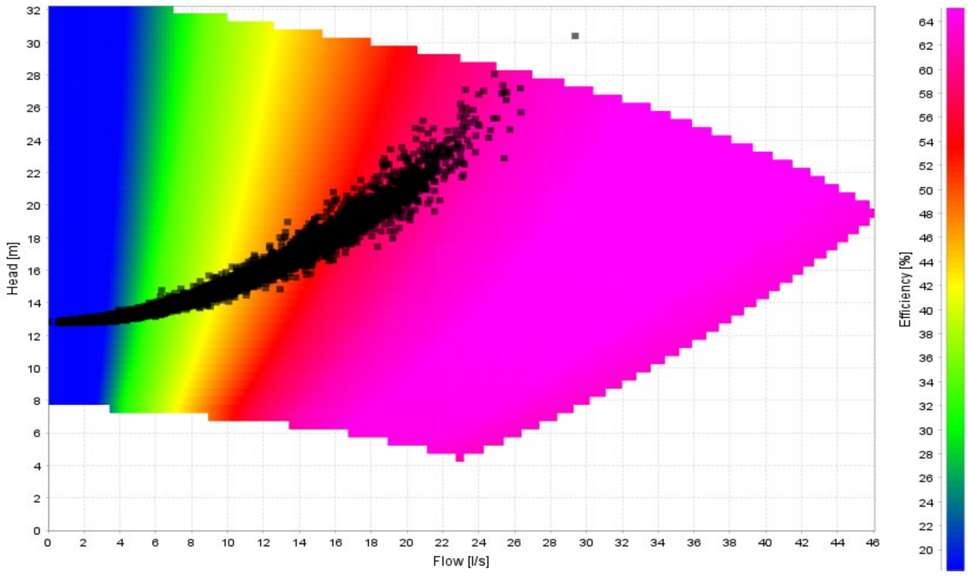


Figure 2.12. Central pump operating point visualisation

2.3.3. Economic Results

To calculate the LCOH of heat supplied to the consumer, CAPEX and OPEX were estimated based on the figures provided in Table 3 and the scale of the various components in the model. The total capital costs for the system are listed in Table 2.5.

Table 2.5. CAPEX for various system components

CAPEX component	Total cost	
Heat pump substation	890,034	EUR
Central heat exchanger unit	54,255	EUR
Pipe + insulation costs, including installation	593,000	EUR
Piping at the consumer end	200,000	EUR
Pump costs (network + consumer)	10,966	EUR
Total CAPEX	1,748,255	EUR

The system's total capital cost is 1.7 Million EUR. Since the peak heat demand is 1.4 MW, the parameterised CAPEX is 1,250 EUR/kW. The system's fixed and variable O&M costs are 105,000 EUR/year, or 6% of CAPEX per year. Based on the results, the cost of heating presented to the consumer (parameterised according to the building's heat demand) is 80 EUR/MWh. The cost of heat parameterised based on heat supplied via the network is 113 EUR/MWh. Heating, in this case, costs more than a typical natural gas boiler in a conventional DH system.

2.4. Monte Carlo Simulation: Uncertainty and Sensitivity Analyses

The Monte Carlo method (MCM) is used to conduct uncertainty analysis. This method is a stochastic optimisation technique that provides significant insight into the influence of independent variables on the proposed objective function, making it useful for making critical decisions. The tool has been widely used for risk analysis in many industries, including energy, finance, and many others.

Several different input variables affecting the LCOH are used to obtain the output result (LCOH). The probability distribution of each independent variable is propagated using a mathematical calculator model. The simulation is repeated several thousand times to generate a pool of random samples associated with specific variables. Therefore, the range and probability distribution of the input variables are necessary for model development. For the optimal implementation of MCM, the input variables must be considered as independent random variables, i.e. they must not be correlated with each other [1]. The number of iterations determines the solution's convergence. Up to 10,000 iterations are usually sufficient to obtain reliable results [2]. The results aid in visualising the change in the LCOH as a result of specific input variables. The results also quantify the uncertainty and refine the future LCOH value.

In this study, the method was implemented using Python. A non-linear model was developed to obtain the LCOH probability distribution for the reference case study. Initially, A sensitivity analysis of the deterministic LCOH model was conducted to rank the model input variables in accordance with their importance to the model's sensitivity. Then seven independent input variables were selected for the model before. The probability distribution for each of these variables was calculated using the 3-point data set representing the minimum, most likely, and maximum value.

The LCOH probability distribution is depicted in Figures 2.13 and 2.14. The most likely LCOH is 85.4 EUR/MWh, which is higher than the reference case value. The most common LCOG has a 4.8% chance of occuring. Changing the variables will almost certainly increase the LCOH for the reference case.

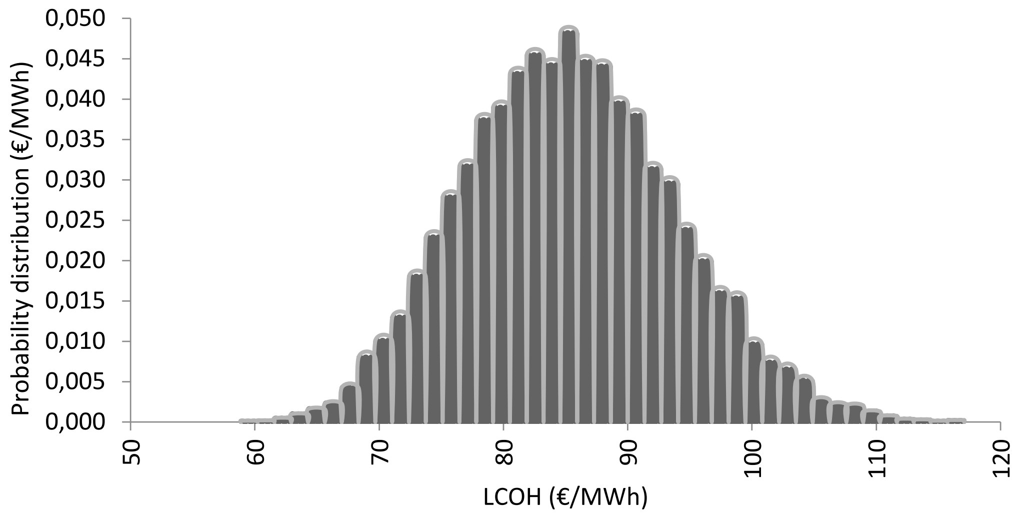


Figure 2.13. LCOH uncertainty analysis results

The minimum and maximum LCOH obtained are 58.8 EUR/MWh and 117 EUR/MWh, respectively. Under certain input conditions, there is zero chance that the value will drop below or exceed this LCOH range. This is further illustrated in Figure 2.14, which shows the probability that the LCOH will not exceed a specific value. When the results are compared to the reference LCOH, the input variables have a 74.5% chance of increasing the LCOH.

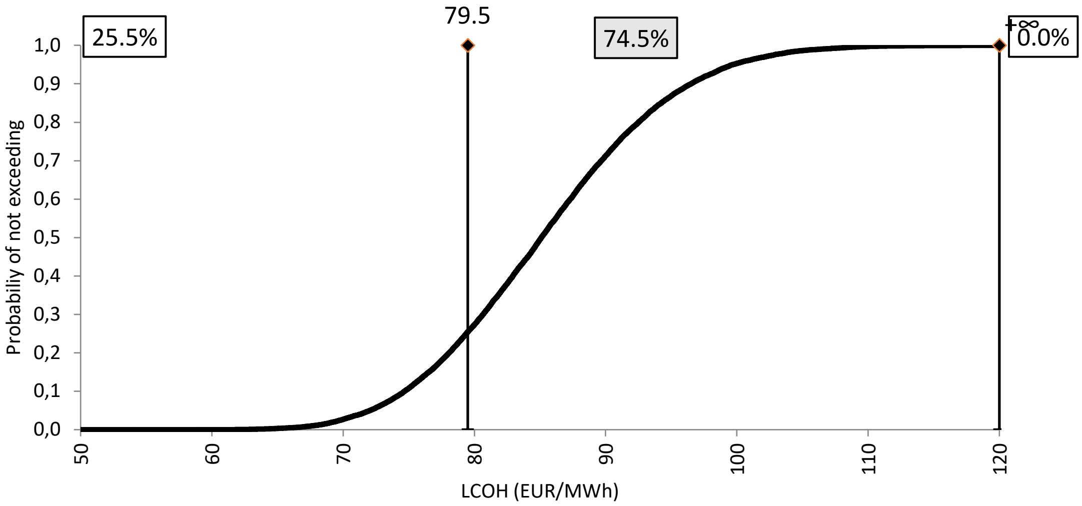


Figure 2.14 LCOH combined probability analysis results based on uncertainty

A sensitivity analysis was performed to determine the effect of the input variables on the LCOH. The results were visualised using Spearman's rank correlation coefficient, as shown in Figure 2.15. The coefficient measures the monotonicity of a relationship between two variables, or how well the relationship between two variables could be represented by a monotonic function. A higher coefficient value in either direction indicates a stronger correlation between the ranked variables.

It is evident that the discount rate variable and the cost of electricity have the greatest and most similar impact on the LCOH. The result shows that the correlation coefficient between the DR and LCOH is 0.58, while the same coefficient for the cost of electricity is 0.57, indicating that both of these variables have a very similar effect on the LCOH. Waste heat and substation cost are the third and fourth most influential variables, with heat loss having the least impact on the LCOH. All other variables, except for years of operation, have a negative correlation with the LCOH (illustrated by positive correlation values on the graph). By increasing the value of each variable by one sigma, the LCOH is increased by its correlation coefficient. As a result, as the number of years the system has been in operation increases, the LCOH decreases, and vice versa.

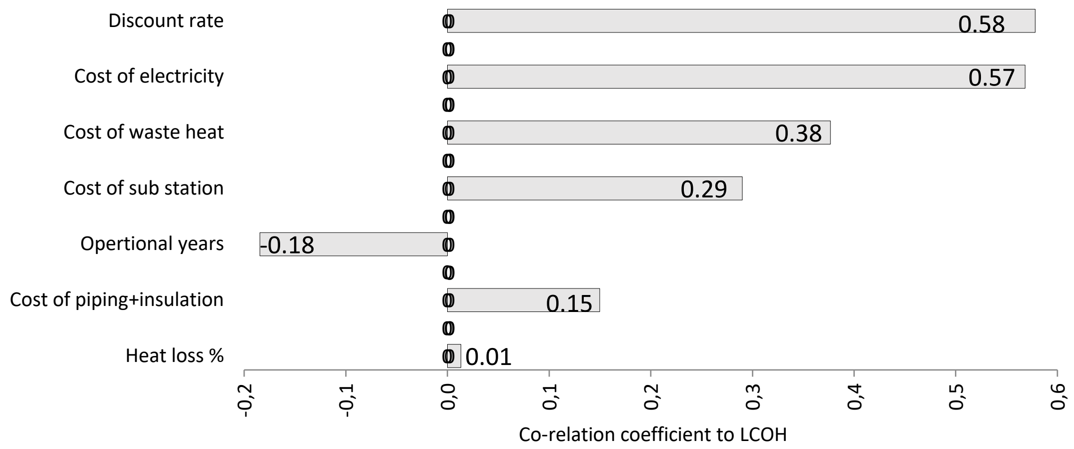


Figure 2.15 Sensitivity analysis of LCOH-influencing factors

The results show that lowering the cost of electricity and waste heat can make a significant difference in reducing the LCOH in the reference case if the discount rate is fixed. This was investigated further by simulating a version of the reference case where PVT collectors are integrated for heat and power generation.

2.5. Discussion on Techno-Economic Analysis

The section presents a techno-economic analysis of a 5th generation DH system using a detailed thermo-hydraulic model of a small district in Tallinn. TRNSYS was used to model HP unit performance, which was then followed by a network model created in Fluidit. The system was designed to cover a total thermal load of 2,433 MWh/year. The heat pump used to meet this demand operates at SCOP of 3.3. The system's total electricity consumption was 762 MWh/year. The network's total heat loss was 4% of the annual heat supply. The system had a CAPEX of 1.7 million EUR and an OPEX of 6% per year. In the designed scenario, the LCOH presented to the consumer was 80 EUR/MWh. At current natural gas prices (up to 150 EUR/MWh), the system is economically viable.

In terms of CO_2 savings, the results are comparable to a traditional fuel-based DH system. Let's assume a conventional DH boiler burns natural gas as fuel and has an annual average efficiency of 90% and an average network heat loss of 20%. The CO_2 emissions from heat production would be around 240-270 kg/MWh. The use of heat pumps increases the heating efficiency of the system by up to three times in the 5th generation system. However, because the system consumes more electricity, the specific CO_2 emissions may be lower or higher than those from the NG-based system, depending on the intensity of CO_2 emissions in the power grid. There is high intensity of CO_2 with about 70% of electricity generated from oil shale (with a CO_2 emission factor of 600 kgCO_2/MWh). The simulated system has a heat emission factor of 180 kg CO_2/MWh.

There is significant opportunity to reduce both the CAPEX and OPEX of the designed system. The cost of the substation accounts for nearly half of the investment, so these costs should be reduced in the future. Given the enormous potential of the HP market, costs are expected to decrease by 40% over the next decade, mainly due to market competition and shrinking margins throughout the supply chain. The expected decrease in LCOH is 0.25% per unit of substation cost reduction (%).

According to the analysis, the competitive advantage of 5GDHC increases if the electricity for HP operation can be obtained at a low cost and with the least amount of CO_2 emissions. In the simulated system, electricity accounted for 55% of the total OPEX. The electricity in question costs 100 EUR/MWh. A 25% decrease in electricity costs would reduce the LCOH by 10 EUR/MWh, bringing it to an absolute value of 70 EUR/MWh, which is comparable to many traditional fossil fuel-fired DH systems. Because of the grid's strong focus on renewable energy, electricity costs and emissions are expected to decrease significantly, which could benefit low-temperature heating networks.

Future studies will explore the effect of cooling load penetration on heat demand. Furthermore, the impact of insulation optimisation on pipeline cost reduction should also be investigated. Finally, the model can be fine-tuned further using a detailed economic analysis, such as a Monte Carlo model, to see how sensitive variables affect the results.

3. 5GDHC Business Models

Currently, 5GDHC solutions are not implemented in the Baltic States. One of the reasons is that these countries have very well developed high-temperature district heating networks, which are based on centralised heat production at boiler houses and combined heat and power plants.

The small scale of 5GDHC is beneficial to communities that are open to collaboration and seeking greater independence from the large-scale energy market. However, due to changes in the infrastructure and the entire technological concept of district heating, the existing business models for district heating will no longer be applicable. Furthermore, these changes require investments that far exceed the financial capacity of the community that is ready to implement such changes. While there are long-term benefits, the actual likelihood that 5GDHC will be used is dependent on the economic justification for the transition. A high-quality, up-to-date study of potential business models that leads to the development of guidelines could help potential shareholders make decisions and motivate them to participate in such innovative initiatives. The business model concept here is based on technology ownership and the interaction of the key participants in the 5GDHC business network.

Because the technology itself is not widely used, there is a lack of data and detailed blueprints demonstrating how it would perform under a given scenario. While consumer engagement, transparency, and reduced energy consumption would benefit rural regions and small towns, these areas are economically vulnerable and have limited resources. Due to the current small market pool and pessimistic future models that predict even higher levels of urbanisation and population decline, these are generally not areas of interest to private companies and investors.

Customised solutions and technological improvements typically reach such communities through individual cases, such as via residents with higher income; for example, it is not unusual to see a house with expensive up-to-date solar panels in a remote location, but a simultaneous switch for the entire community is unlikely without some external impact.

A theoretical assessment of potential business models could encourage potential investors. Elements of game theory can fill in the gaps regarding market processes.

Game theory is a field of study that uses mathematical models to assess the behaviour of rational agents and predict their interactions. Rational agents are any system participants who can make decisions based on the available information. It could be a person, company, or even a computer algorithm, especially if machine learning is implemented. It is widely used in business analytics to assess market conditions and choose the best strategy. It simulates real-life events through sequential games to predict the most likely and best actions of the players [34].

Project management uses a variety of tools when it comes to decision-making. Many of them are based on mathematical models such as investment analysis tools, force field analysis, life-cycle cost analysis, internal rate of return, prospect theory, Net Present Value method, Monte Carlo analysis, linear programming, queueing theory, etc. Whatever project management strategy is chosen, game theory would help choosing the right course of action in each interaction with customers or partners. It does, however, focus on the company's strategy as an individual player. Game theory is particularly useful when multiple players compete or cooperate for the same outcome and can make decisions independently [35].

Business and project management can benefit from game theory. This implies that many interdependent factors are closely related; decisions cannot be isolated from other decisions made by players or competitors [36, 37].

The dominant strategy is the one that benefits the player the most, regardless of the choices of the other participants. However, the best outcome for all will often be a collaborative scenario where all players are ensuring mutual success, i.e. the Pareto optimum. Nevertheless, in most cases, lack of trust and general negotiation tactics prevent players from choosing it, forcing them into a loop of bad decisions that harm both the provider and the customer [38].

The most popular example is the prisoner's dilemma. It involves two prisoners, A and B, who are each asked to admit or deny their crime without being able to communicate with each other. If one of them confesses while the other does not, the one who confessed will receive the minimum sentence while the other will serve the maximum sentence. If both confess, both serve a lesser sentence. If neither confesses, they are free to go. Either both can confess, or only one can confess, or neither can confess; all combinations produce different results. The best outcome for both would be to refrain from confessing. However, if A confesses, B faces the maximum sentence, and vice versa. To avoid this, both are likely to confess. The game assumes that the participants will act strategically in their own self-interest, resulting in a less-than-ideal outcome for both parties.

In a business setting, this often means that competitors must choose a marketing strategy that is detrimental to both of them. In business, lowering prices to gain an advantage forces the competitor to do the same, resulting in lower profits for both companies [34, 38].

Another business case is that companies may force consumers to participate in a game in which the business, not the consumer, wins. If players A and B are both participating in a lottery with the same odds and the organiser offers them the chance to buy an extra ticket, if A accepts, B is forced to follow suit, bringing them back to even. So, both players are back in their original positions, but they have both spent more money [39, 40].

Would the people in the prisoner's dilemma change their testimony if given the chance to cooperate? Not necessarily, because it carries a higher risk and a higher likelihood of the worst possible outcome.

The Nash Equilibrium refers to non-cooperative games that involve strategic interaction between players where no one reconsiders their decisions after learning about the decisions made by others. Even if this is not always the best possible outcome, it is still a win-win situation for all parties involved [41]. Using the necessities and infrastructure required to meet the needs of the population, such as heating systems, regulatory mechanisms are needed to ensure the best possible price and avoid a situation in which all participants, especially customers, lose. In many business situations, it is the responsibility of legislators explore options and implement regulatory frameworks that aim for the Pareto optimum in order to protect the interests of end-users.

Project management methods must be used to evaluate business processes and interconnections. Political, environmental, legal, technological, social, and economic factors all have an impact on the size of business organisations and people, information and technology, partners, suppliers, value streams, and processes. Together, these factors influence the products and services that a company can offer to customers – the value created [42].

The business responds to societal opportunities and demands to create value; a positive outcome eliminates costs and risks for the client. Customer engagement aids in the planning and development of service improvements, as well as their delivery to consumers, with the process being repeated iteratively. Variations are possible in any customer interaction or partner relationships, meaning they can be influenced by other parties.

Interactions in a business network establish service relationships: an agent serves as both a client and a service provider; for example, a heat provider is a consumer of an infrastructure manufacturer. The best solutions must be evaluated to ensure continuous improvement with each interaction, and this is where game theory can help [42, 43].

Co-opetition is a concept in business and economics that is based on game theory. It investigates how company synergy can create added value even when they compete in some areas. To summarise, competitors are organisations that reduce your market share by offering a similar product. At the same time, complementors are agents outside of the company who benefit your customers. Balancing player interaction, added values, rules, tactics, and scope leads to equilibrium among business network participants and growth [37].

Previously, [44], [45], and [46] used game theory in the energy sector, primarily to develop numerical models of the effects of different tariffs.

In the study, the game theory approach was used to evaluate various cooperation models for the implementation of innovative 5GDHC solutions. Three different local market business models for 5GDHC have been tested at the community level:

- Heat Purchase Agreement. The district heating operator finances and owns the 5GDHC network before selling heating and cooling services at agreed-upon prices to end users;
- Local Heat Provider. Real estate companies invest in and run the 5GDHC network by purchasing heat from a variety of sources;
- Local Heating Community. The 5GDHC network is owned and operated by the local community, with different participants sharing ownership.

The purpose of this report is to develop, test, and evaluate three local market 5GDHC business models at the community level. This study investigates the possibility of deep cooperation and energy sharing among various participants. Business models for various actors are being explored in order to create a new sustainable market for the future energy sector.

3.1. Suitable Business Model Selection

At the community level, three local market business models for 5GDHC were analysed. This project considers the possibility of extensive collaboration and energy sharing among various participants. Business models for various actors are being investigated in order to create a new sustainable market for the future energy sector. The goal was to design, test, and evaluate three local market business models for 5GDHC at the community level. The links between market participants were then identified using conceptual diagrams, and their differences and strong points were analysed.

Elements of game theory can be found in any interaction that involves different probabilities; it also reveals any cognitive biases or actions that players typically take (Figure 3.1).

The literature review connects the three main topics: game theory, business management, and 5GDHC. The theoretical foundation is improved in response to the needs identified during the evaluation of results, making the process iterative.

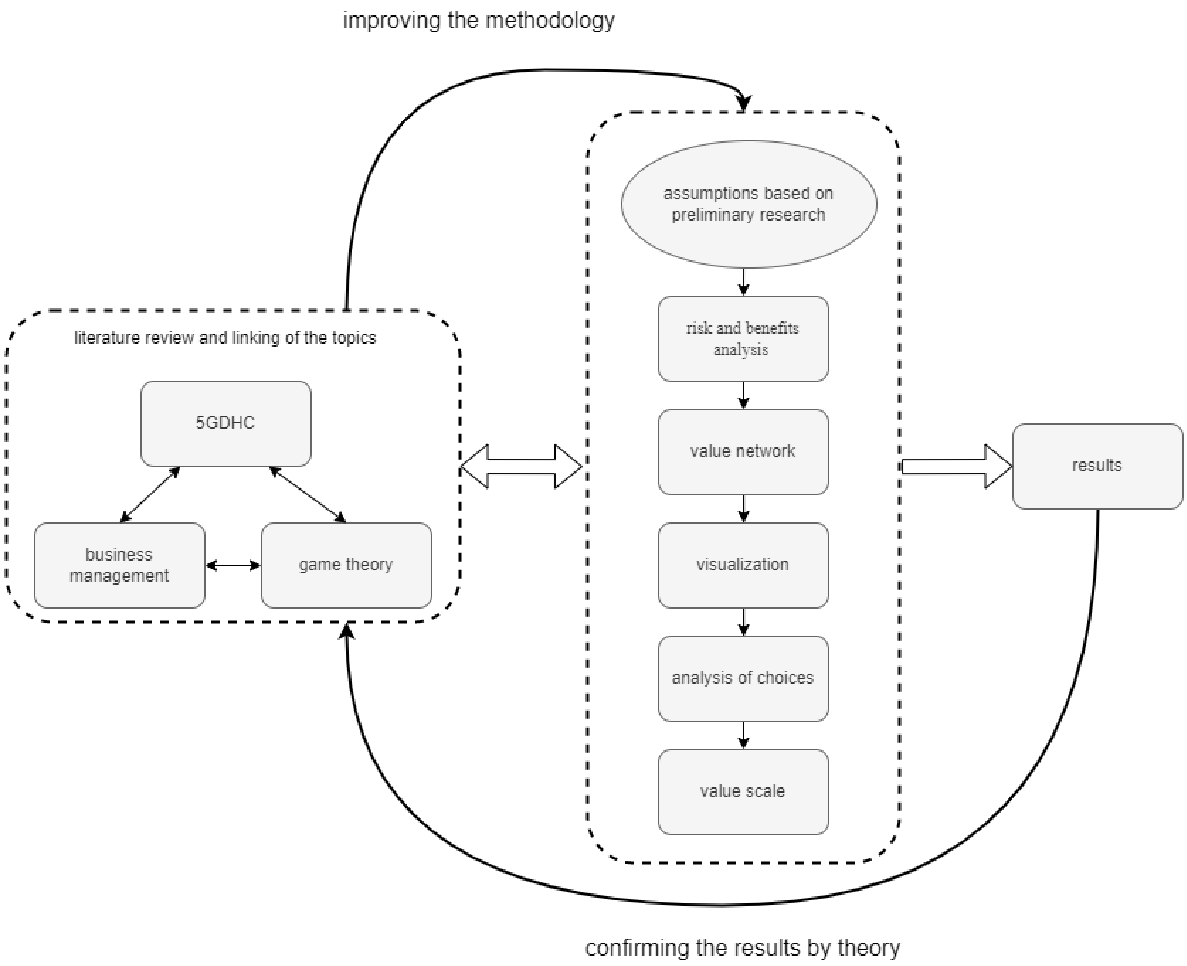


Figure 3.1. Research workflow

The study's first step was to conduct a risk-benefit analysis to determine what kind of 5GDHC is preferable to participants. The overall preliminary assessment was performed to link, identify, and weigh the factors affecting the process in order to create a sustainable strategy and minimise risks. It is based on the previously published SWOT matrix for 5GDHC [47]. Once the players' connections are established, other algorithms such as value networks can be created. The SWOT matrix was created for the implementation of 5GDHC, and the interconnections were examined through the co-opetition value network from the perspective of each rational agent.

Table 3.1. SWOT analysis of common questions across scenarios

Strengths	***Weaknesses***
• Positive effect on health • Reduced price volatility • Increased access to affordable, reliable, and sustainable energy for heating and cooling • Ability to recycle waste heat • Possible excess heat from shopping centres • Possible excess heat from transformers	• Dependence on the power system • High initial costs • New infrastructure is required • Not suitable for rural areas • Requires high building energy efficiency • Separate pipes for heating and cooling are required • Centralised production of energy, which restricts network expansion area • Household spatial impact and noise • Specific building heat consumption
Opportunities	***Threats***
• Possibility of achieving climate goals • Reduced use of imported natural gas • Possibility of implementing innovative business models • Possibility of promoting RES • Increasing energy security • Increased local economic value and job creation • Available support measures for possible 5GDH implementation	• Increased price of electricity • Lack of adequate funding • Lack of skilled personnel • Lack of public acceptance • High resident risk • DH tax rates • Regulatory and policy barriers

The second step was to develop a value network, which included interconnections and action variations. According to the principles of business co-opetition [37], the value network shows the interconnection of rational agents in business. This aids in understanding the links that affect the supply chain. The links were analysed from the perspective of each rational agent.

According to Daniel Kahneman [48], the optimistic bias suggests that the main reason new ventures fail is that they do not view competitors as equal market participants. The reason a business fails may not be due to a lack of competence or quality of service, which entrepreneurs and investors typically pay attention to, but simply because the alternative, already implemented options are good enough.

A general overview of the 5GDHC business chain was evaluated to forecast possible development directions. Although the initiator is primarily motivated by potential profit, the business process cannot be launched successfully unless other parties benefit. Assessing the needs of each player helps to see how to achieve Nash equilibrium, or a situation that is good enough for everyone. In this state, no player changes their actions, despite knowing what the other parties are doing.

In the third step, conceptual schemes were created to identify the connections between market players, their differences and strengths, and the money flow.

Next, the primary and backup options had to be specified—who would start the game? Each scenario has a separate owner who is in charge of maintenance; they bear the greatest risk, and are responsible for involving all other players in the process. The initiating party influences the process and the options available to other players. A process flow diagram was created to test the various processes and the parties that influence them. The possibility of project failure and cancellation was also considered.

The final step was to evaluate the scenarios. First, it was necessary to identify the factors affecting the commercial value of the system for the sample unit. The neighbourhood in the example had three apartment buildings with an average living space of 1,500 m^2 and four commercial buildings with an average area of 2,000 m^2. The 5GDHC network may not include all buildings in the area, especially single-family houses, might not be included in the 5GDHC network. Still, it is better for everyone if there are more participants. Based on the literature review, approximate prices were estimated for the entire process for the technology life cycle.

Because prices fluctuate rapidly, vary by region, and are dependent on multiple business processes, using numbers is impractical as they cannot be kept up to date. Specific costs are associated with procurement outcomes, delivery options, business interests, and all-party negotiations. As a result, the prices from the literature were compared proportionally instead. Each parameter was assigned a coefficient ranging from 1 to 10 based on the correspondence with other parameters. For each scenario, 12 parameters were used, plus three more for the case with an external operator.

After that, each scenario was evaluated based on the respective coefficients' point gains and losses. Furthermore, in all three agreement options, the possibility of the process occurring without any of the parties involved was investigated.

3.2. 5GDHC Business Model Comparison

This section provides an in-depth analyses of suitable business models as well as a simplified numerical comparison of the selected scenarios. The current DH solutions were used to assess the implementation of 5GDHC.

The key difference between the models is who controls the 5GDHC network, that is, the owner. In each business model, there were producers who ran the cooling and heating system that produced all the heat needed or provided the necessary cooling, compensating for the missing energy through prosumers. The equipment can be owned by the regulator of the 5GDHC network or another external party that entered into an agreement with the network owner.

Prosumers are system participants who require cooling and can provide leftover heat to the system. These are primarily shopping and data centres. Consumers are households and public buildings that use the system's energy for heating. Each of them requires a heat pump that is linked to the transmission pipe. Furthermore, investors and government affect the way the market operates.

3.2.1. Risk-Benefit Analysis

Participants are less likely to switch to new technologies in the case of widespread connection to traditional district heating due to high initial costs. However, conventional DH can indicate readiness for centralised solutions [49]. Most of the 5GDHC system's capabilities are associated with greater levels of independence from the external system. The issue of spending is most urgent in rural areas and small towns.

Because the system's implementation affects the participants in different ways, an opportunity for one may pose a threat to another. This is evident when the coefficients below are compared. Overall, the main strengths of 5GDHC are the ability to utilise waste heat, provide cooling and heating at the same time, and significantly reduce energy loss. Reducing energy consumption through heat recovery and achieving higher energy efficiency levels will result in fuel consumption, health, and environmental benefits.

However, switching systems is expensive. A significant initial investment is required, which participants are unwilling to make, especially if the existing DH system works well. Electricity consumption for the operation of local heat pumps is on the rise. If any stakeholders are not ready for the change, the entire system loses value quickly.

Making the right decision when developing a new business model is critical because it is both an opportunity and a threat. Reduced reliance on imported natural gas can result in increased energy independence and security, as well as achievement of climate goals.

Additional investments are required to reap financial benefits. Participants will be unable to fully cover the cost of changes to the DH system on their own, especially in remote areas.

3.2.2. Value Network: Interconnections and Action Variations

The key difference between the models is who runs the 5GDHC network. In each business model, there were producers who ran the cooling and heating system that produced all the heat needed or provided the necessary cooling, compensating for the missing energy through prosumers. The equipment can be owned by the regulator of the 5GDHC network or another external party that entered into an agreement with the network owner. In the value network, these two functions overlap.

Figure 3.2 shows how the main actors fit into the created value chain. Prosumers will not be a part of the chain in the case of individual heating or traditional district heating. They will become regular consumers instead. In the case of 5GDH, they play an important role in the value chain by contributing excess heat. The main co-opetition processes take place between a rational agent and a complementor. In the case of 5GDHC, this also means that they are a necessary part of the entire business process to exist, because not only will the prosumer become a regular customer if 5GDHC is not implemented, but the entire network cannot exist without the prosumer. At the moment, it is difficult to predict how prosumers' participation in the market will be taken into account, given that existing market regulation in many countries prohibits different heating tariffs. Prosumers may push for equal prices for heat and cooling, making heating more expensive than it otherwise would be.

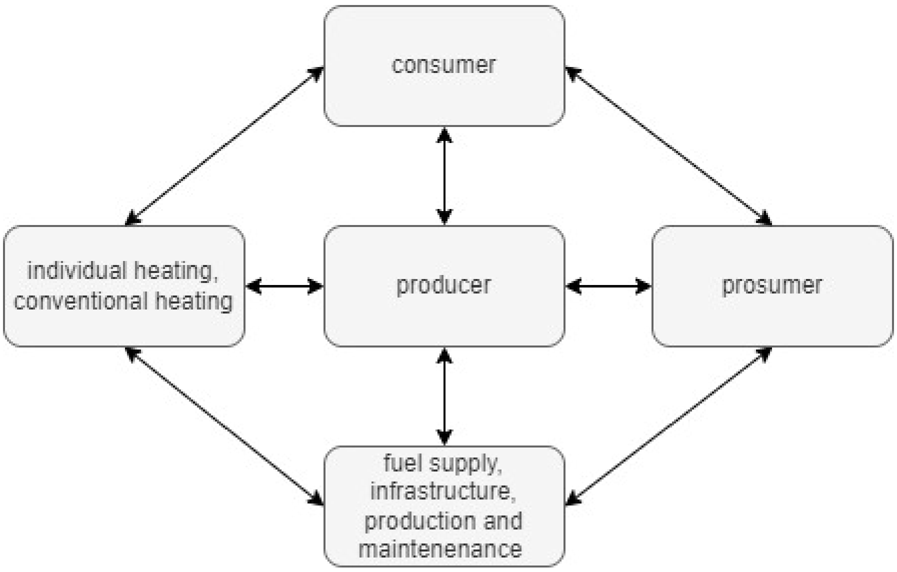


Figure 3.2. Conceptual diagram of the value network created for the 5GDHC system

Construction companies, ESCO, and insulation manufacturers can be considered complementors for 5GDHC implementation since it works best as a heat supply for energy-efficient buildings with low heating needs.

3.2.3. Proposed 5GDHC Business Models

Three different scenarios were considered as potential business models for the 5GDHC system.

Scenario 1. Heat Purchase Agreement

According to the scenario, the district heating operator finances and owns the 5GDHC network before selling heating and cooling services to end users at agreed-upon prices. The owner is responsible for the entire infrastructure and ensuring that everyone's needs are met. They may or may not own the production technology, but the operator is responsible for ensuring that the necessary heat is supplied to the consumers. The operator serves as the hub for all financial transactions. Clients and prosumers pay them for the services they provide. They receive all investments and grants associated with a specific project. The operator must, however, take on all the risks.

At this point, two subscenarios were developed. In addition to the previously mentioned participants, the operator may act as the network's owner (see Figure 3.3). In this case, the operator is primarily concerned with the commercial aspects of the process and is not directly related to the producer. This could be a company supervising the installation of new heating systems in various locations, signing contracts with the relevant energy producing companies and building owners in the area. Heat pumps can be owned and operated by the operator, with maintenance costs included in the tariff, or owned by network users, with individual operation being the responsibility of the consumer.

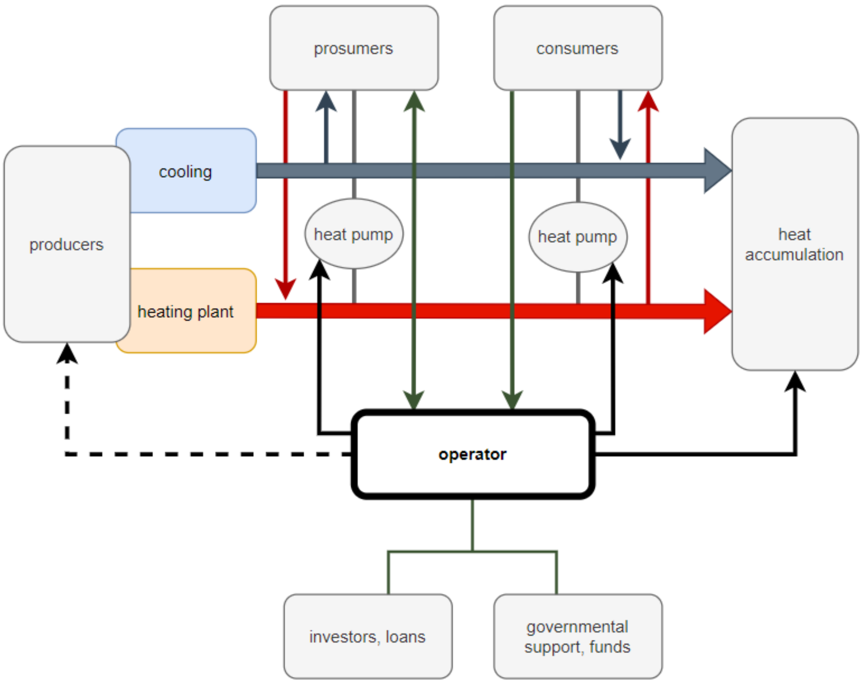


Figure 3.3. Scenario 1a. Heat Purchase Agreement

The owner has the greatest business potential but also the greatest financial risk in this situation. The owner is an outsider who might prioritise their business interests. It is unlikely to be the most affordable option for the consumer, but it will be the most convenient.

Additional contributors always incur additional costs, but a contributor who specialises in a particular job and must have experience maintaining a specific system can ultimately result in an overall win by lowering the risk of implementation errors.

A similar system has been put in place in Sedrun, Switzerland. The system operator must calculate the cost of commissioning and installing the substation for the user, as well as establish a supply limit and total costs, which include a one-time connection fee and a base annual fee calculated in proportion to the substation's reference volume flow rate [50].

Alternatively, it could be a manufacturer who invests in new technology and sells it to customers directly (see Figure 3.4). In this case, the number of participants is smaller. Because the operator has mostly business management value that is not specifically examined here and mostly deals with redistributing the energy produced by the producer and prosumer, in most cases, the operator and producer are assumed to be the same entity in the processes.

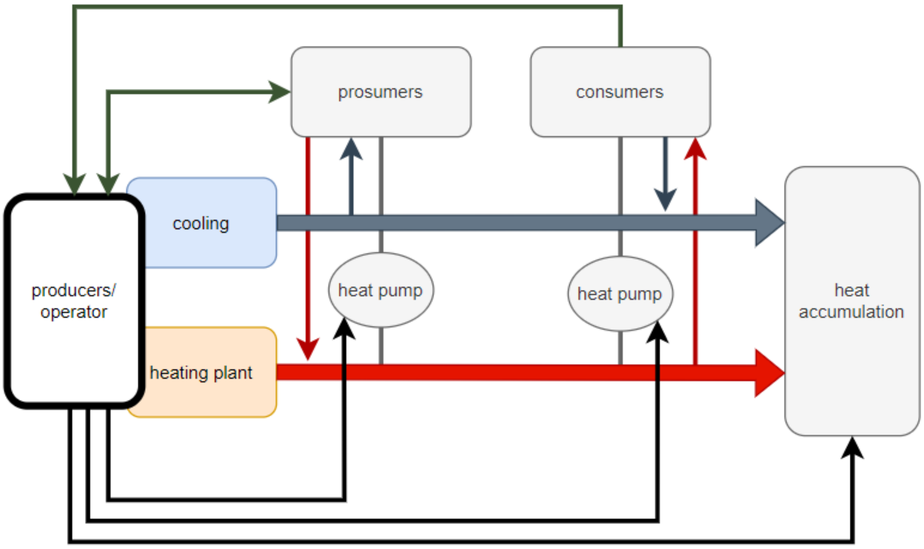


Figure 3.4. Scenario 1b. Heat Purchase Agreement.

Scenario 2. Local Heat Provider

In this scenario, real estate companies invest in and run the 5GDHC network by procuring heat from a variety of sources (see Figure 3.5). This business case is better suited for a small-scale 5GDHC system, where the development of a heating network is a smaller portion of the investment. There is no outside operator; prosumers, such as shopping centre owners, control the energy and value network. Prosumers can own additional energy production facilities, such as power plants and cooling systems, in addition to the 5GDHC system. Alternatively, the company that owns the production system could be the owner; in this case, prosumers sell excess energy to the company.

Because the owner bears the greatest financial risk, the fact that their company is a part of the network and benefits financially and energetically can be another motivator to initiate change. Real estate companies will invest in a specific area, making the situation more stable and less susceptible to changes in economic processes. Excluding additional players may result in lower prices for the consumer.

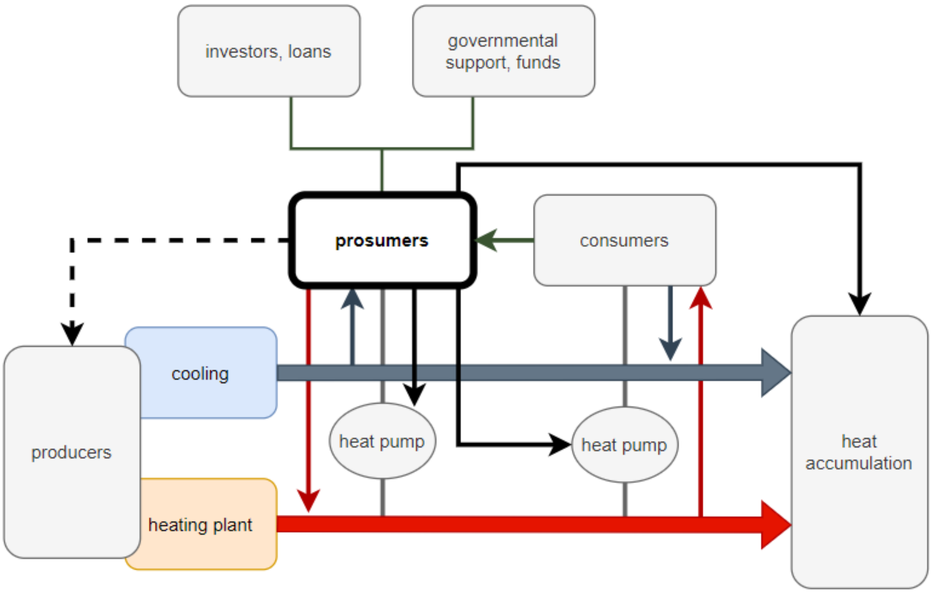


Figure 3.5. Scenario 2. Local Heat Provider.

Scenario 3. Local Heating Community

This scenario involves social initiative and the local energy community. The consumer is the most protected party in this scenario, but there are management risks, as self-organizing organisations with many members may be unsustainable (see Figure 3.6).

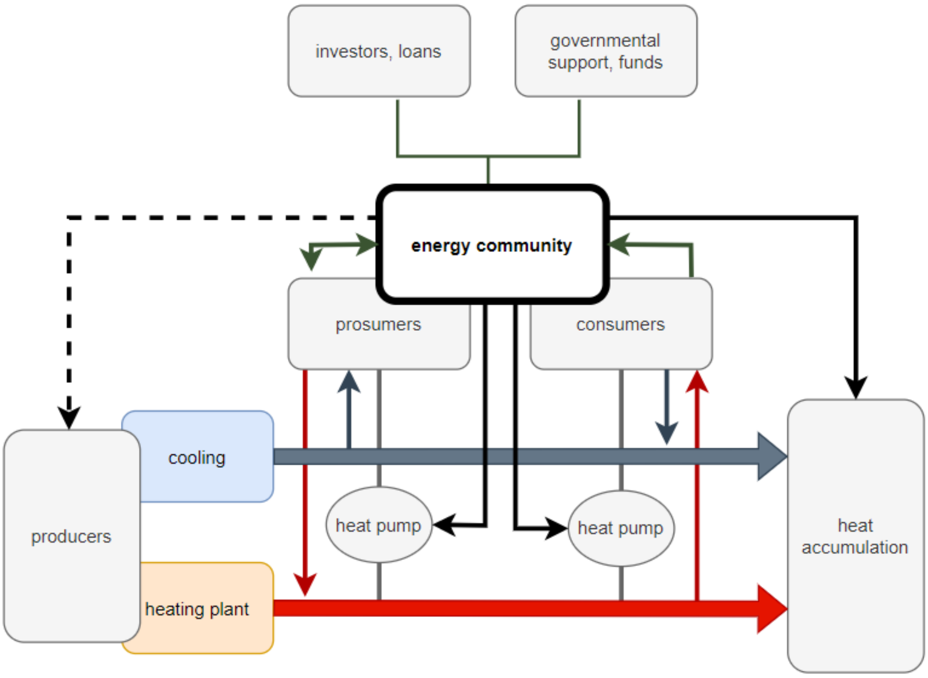


Figure 3.6. Scenario 3. Local Heating Community

As a grassroots self-organising institution, energy communities are preferable in terms of strengthening cooperation within society [51]. Furthermore, this benefit may result in a higher approval rate for projects or governmental funding that may cover a portion of the expenses. In the case of loans, however, banks would prefer to work with long-standing institutions that can prove their viability.

Primary and Backup Options – Who Would Start the Game?

The likelihood of the resulting scenario is heavily dependent on who initiates the process, thus having the upper hand in determining which scenario is most likely. Figure 3.7 shows a detailed assessment aimed at determining the most beneficial business model scenario.

The process can be initiated by an external operator, such as the business owner. An investor may also initiate the change, but administrative responsibilities are ultimately assigned to one of the main players. If the investor retains the management position, Scenario 1 is implemented, and the investor becomes an independent operator.

If consumers and prosumers work together, they can establish an energy community (Scenario 3). The main issue for prosumers and consumers is administrative capacity; they may delegate authority to a competent party, such as a manufacturer or an outside operator (Scenario 1). Prosumers can become owners themselves (Scenario 2) for certain small-scale projects. If none of this works, the project must be cancelled.

If it is a consumer or a prosumer, the first step is to evaluate managerial and administrative capacity, as these are not the primary functions of residents, shops, or commercial building owners. Furthermore, the terms "consumer" and "prosumer" are used as single players who act in concert. In practise, both have multiple owners who must all agree on a common model of the energy supply system.

Another factor that prosumers must consider is the delivered heat, as they will benefit the most if the recovered energy is plentiful. Because of the increased number of consumers with low recovered energy, changing the system would significantly reduce public benefits.

When a preliminary risk assessment is completed and the project appears to be viable, the initial business model is chosen. It can be changed later, after more research and planning. In most cases, all parties involved must reach an agreement.

Now comes the most important part: cost estimation. The 5GDHC system is expensive and requires a large initial investment. Long-term advantages include lower maintenance and energy costs. This isn't much help at the start, when you have to go through an administrative procedure, an environmental risk assessment, buy equipment, do the necessary construction work, switch fuel, and thus change the entire supply chain.

The infrastructure is then built by the player who will become the owner, and the corresponding scenario is implemented. This is where the project is integrated into the public network of heating solutions, and all external agents from the value chain created are linked.

Value Scale and Benefit Assessment for Each Scenario

The game theory method was used to test the selected business models, and different game strategies were tested for each player in order to maximise the overall system gain—lowering the cost of heating and cooling. Each scenario was examined from the perspective of each stakeholder. Estimated costs and revenues were established to evaluate each scenario (see Figure 3.7) to compare the benefits for each player and the total cost in certain business models based on the technical characteristics of the required equipment and the potential earnings from the sale of energy. The total costs and benefits are uncertain and will vary depending on the energy price, region, willingness to collaborate, available investment, and government support. It does, however, highlight the key differences between potential cooperation strategies and monetary flows.

As illustrated in Figure 3.7, Scenario 2 achieves the lowest total heating and cooling costs for residential and commercial buildings when the prosumer initiates system development and manages the heating and cooling of residential buildings. Prosumers in this scenario can reduce the overall cost of heating and cooling compared to other scenarios, but the system's implementation and operation still require additional costs. Scenario 3 is the business model for an energy community. It was assumed in this case that the energy community would develop by involving both prosumers and consumers in the overall development of the 5GDHC system, with no external system operator. Consumers would now be responsible for system administration costs, resulting in higher overall heating and cooling costs when compared to other business models. The highest revenue share was obtained in the Heat Purchase Agreement business model (Scenario 1b), in which the system operator was also the heat producer in order to cover heating and cooling demand shortages. In Scenario 3, investment costs and other additional responsibilities fall on the energy community as a result of consumer and prosumer cooperation.

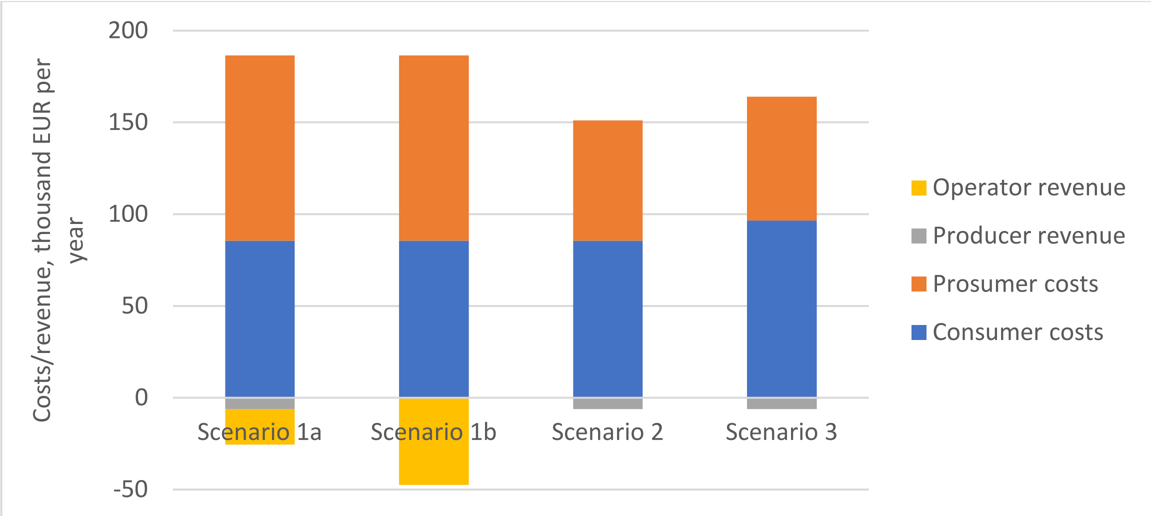
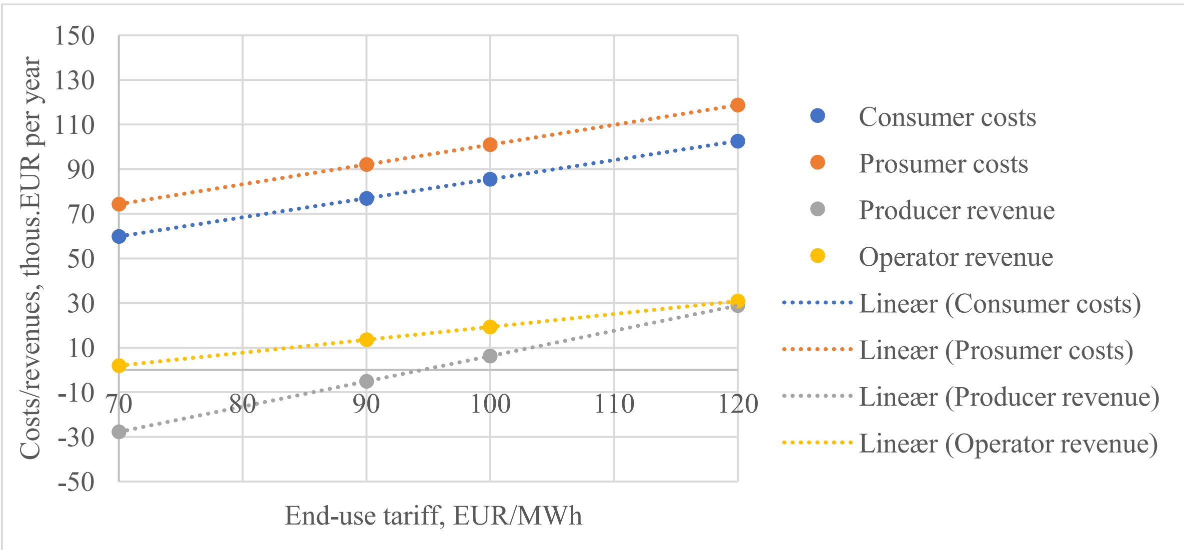
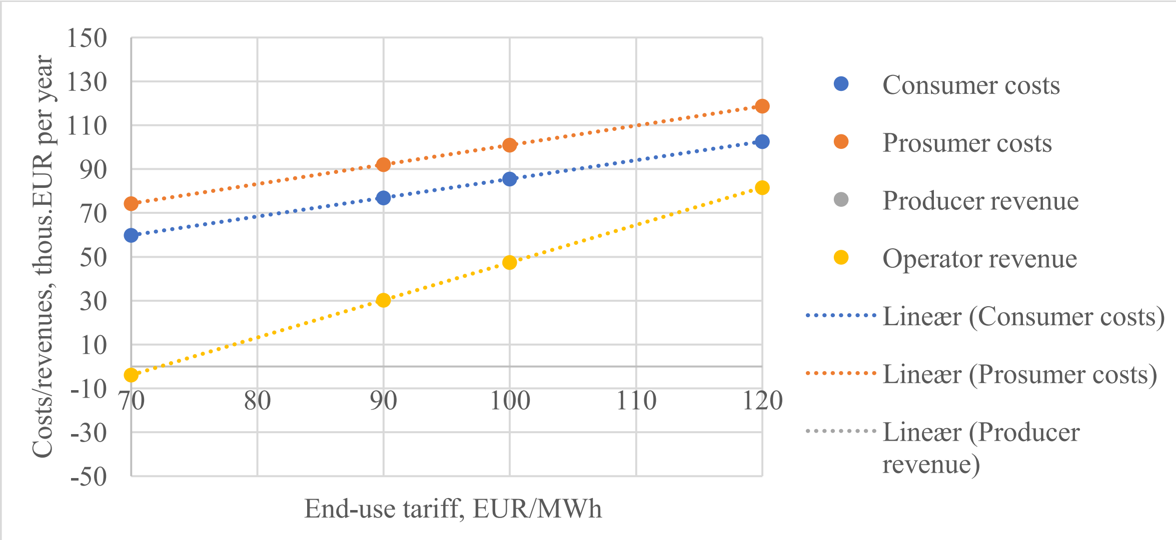


Figure 3.7. Key costs and revenue for stakeholders under different business models

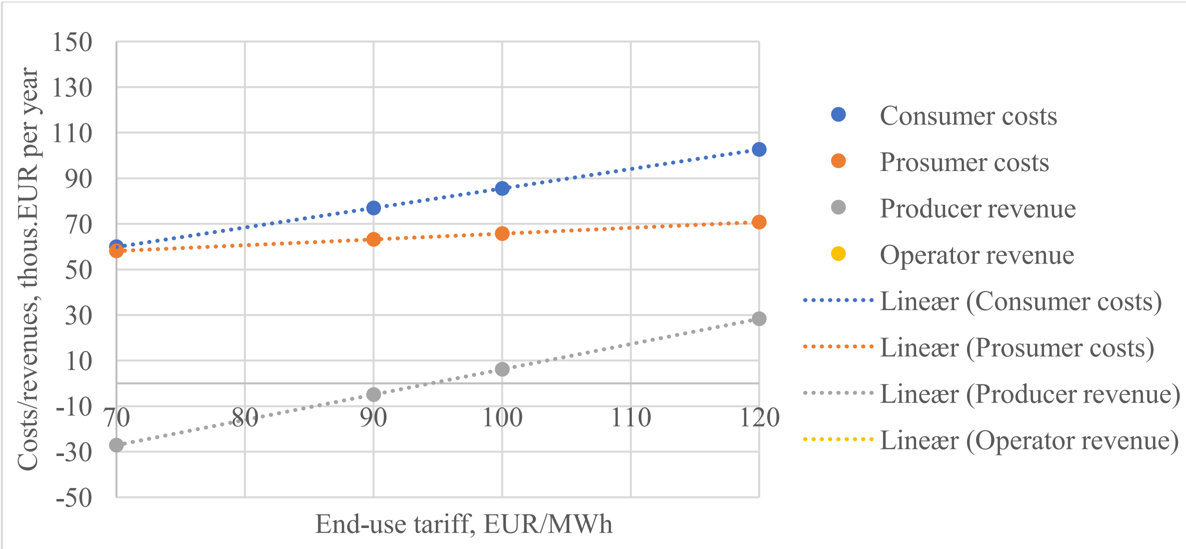
Figure 3.7 depicts the cost and revenue changes for various end-user heat tariffs. The cooling end-user price is linked to the heat tariff and is expected to be 20% higher. As part of the sensitivity analysis, it was assumed that energy and electricity prices would remain constant, resulting in a larger increase in producer revenue. According to Figure 3.7, the business model presented in Scenario 1b can provide the lowest end-user heat tariff that is beneficial to all parties involved.



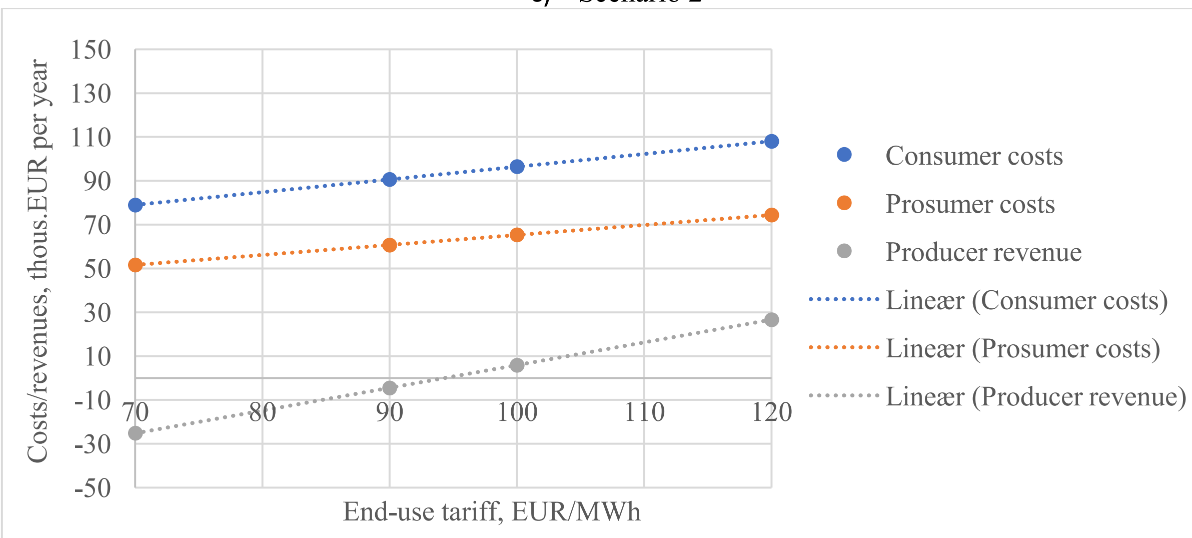
a) Scenario 1a



b) Scenario 1b



c) Scenario 2



d) Scenario 3

Fig. 3.8. Changes in key costs and revenue under various end-user heat tariffs

The most significant changes in profits and costs, according to the analysis, occur for consumers and the external energy producer. As a result, it is critical that these stakeholders be included in the system when planning the implementation of the 5GDHC system.

The main barrier to the development of 5GDHC in the Baltic States is widespread and well-maintained high-temperature DH. Based on this, it is assumed that the existing DH system, as well as individual heating and cooling solutions for each building, will be the main competitors for 5GDHC. Compared to the existing DH system, the new system could have lower operating costs and more room for optimisation, which would greatly increase the return on investment in countries with high wages and expensive labour. However, both approaches interact with the same customers and vendors that 5GDHC developers are attempting to reach, so many technology-related needs will overlap.

Therefore, innovative business models are crucial in areas where the implementation of a 5GDHC system would be beneficial. Although the general technical principles do not change in different business scenarios, changes in cost balance can have a significant impact on consumer prices. It is critical to find the optimal model that is appealing to investors while also allowing for the resolution of urgent energy issues at the consumer level, particularly where price increase contributes to energy poverty.

The study identified three distinct business models for implementing a 5GDHC system, as well as the roles of each stakeholder.In each scenario, the owner of the system receives the funds and the majority of the income and bears the greatest risk. While it is most beneficial to society to lower consumer prices, the lack of professional management is a flaw in the scenario that the energy communities will face.

The operator owns the system in Scenario 1. If this is an independent business, it can exit the project without incurring unnecessary losses. Scenarios 2 and 3 are organised by the players who are directly linked to the specific location, so they have fewer opportunities to quit and are thus more motivated to initiate changes to make it work. The operator's primary motivation is financial gain, so they seek to set prices as high as possible. The risk for rural areas is that independent operators can invest in any location, which means that there may be places that are uninteresting to investors, even if they have great prospects for heat recovery and storage.

The cost-benefit analysis shows that, when all players are considered, Scenario 2 has the lowest costs, but only if the prosumer is willing to administer the system. Furthermore, the energy community option will benefit everyone. However, the administrative risks mentioned previously must be considered. The decision tree's starting point and path to scenario selection are determined by who initiated the transition to 5GDHC. All possible loans and investments should be considered, ideally using governmental and legislative techniques. Regardless of how hard the initiator works, he or she should always be prepared to abandon the project at any stage in order to avoid large losses later on and bias in justifying the effort.

Currently, it is difficult to predict how prosumers will participate in the market because existing market regulations in many countries prohibit different heat tariffs. Heating may become more expensive as a result of prosumers' insistence on equal prices for heating and cooling.

The study assumed that there would be no competition between different providers, such as companies looking to invest in the same location. This approach, however, may become more popular in the future. If heat tariffs and taxes on existing systems are high, 5GDHC implementation is likely to pay off, implying that these economic parameters are critical in balancing the likelihood of changing existing DH systems. Government subsidies and other forms of assistance can significantly alter the equilibrium.

Further research should be conducted to investigate the application of the proposed business models in real-world case studies in order to identify additional benefits and barriers to implementing the 5GDHC system.

4. 5GDHC Implementation and Replication Barriers and Drivers

It is necessary to assess the current situation in order to identify the main barriers and drivers. Because of the cold climate in the Baltic States, the heating sector is extremely important.

4.1. Current Situation

The majority of residents in the Baltic countries have their heat supplied via DH (62% in Estonia, 65% in Latvia, and 58% in Lithuania), which is well above the EU average of 26%. Despite the fact that the share of RES in the heating and cooling sector in the Baltic countries is rather high (52% in EE, 58% in LV, and 47% in LT [52]), there is potential to increase the share of renewable energy in this sector. The heat supply in these countries is mainly based on the combustion process, and the high share of renewable energy can be explained by the combustion of large amounts of wood chips in boiler houses and combined heat and power plants. It should be recognised that the share of energy from low-grade heat sources is minimal and can be significantly increased. The purpose of this section is to assess the feasibility of 5GDHC implementation in the Baltic States. The current situation was assessed, and the major implementation barriers were identified. Based on the 5GDHC definition, the following factors were analysed: stakeholders (DH operators and producers), regulatory mechanisms and DH tariffs, existing DH infrastructure, building stock, pilots, energy policy, and strategic DH energy goals.

4.1.1. Stakeholders

The main difference between DH stakeholders is ownership. In Estonia, DH operators are mostly private companies [53], whereas in Latvia DH operators are mostly municipalities, with some systems owned by private companies. There are both private and public DH operators in Lithuania.

Private DH companies are more experienced with specific DH operating issues and solutions, which is one of the key advantages when DH networks are operated or owned by private companies. Furthermore, because of their profit orientation, private entities as DH owners may be more interested in investing in improvements. In addition, private ownership of the DH network is less dependent as local municipalities do not need to purchase services from private companies. The main disadvantage is that private companies are more profit-driven and are not interested in less viable DH networks [54]. If municipalities own DH, it is possible to implement comprehensive projects for the modernisation of heat supply, including heat supply and public building improvements. For example, the municipality of Gulbene implemented the first small-scale low-temperature DH system in Latvia because it owned both the heat source and the buildings to which heat was supplied. As a result, consumer participation and agreement were not required. Municipalities, on the other hand, may have limited access to adequate investment funds, modern management practises, and new technologies. Furthermore, municipal DH systems are subject to public and political scrutiny, which can slow the adoption of innovative solutions. 5GDHC has viable options for both private and municipal property. Existing case studies show that private companies are more interested in developing 5GDHC technology alongside 4GDH [54].

4.1.2. Regulatory Mechanisms and District Heating Prices

The DH network in Estonia is regulated by the District Heating Act [55], while in Lithuania the DH sector is regulated by the Law on the Heat Sector. Only Latvia has no specific laws for the DH sector [56]. However, the DH sector in Latvia is regulated by the Energy Law, which governs Latvia's energy sector, including heating as a sector of the economy that covers the extraction and use of energy resources. There is also a regulation on the Supply and Use of Thermal Energy, which establishes the procedure for the supply and use of thermal energy, as well as defines the obligations of the supplier and consumer of heat. In addition, the regulations on Energy Efficiency Requirements for Centralised Heating Supply Systems set out energy efficiency requirements for centralised heating systems, specifying the maximum heat loss in the DH network and the minimum requirements for the efficiency of heat production for various technologies.

All Baltic countries have DH price regulators. The main difference between the three countries is the market situation. The DH monopoly exists in Estonia and Latvia, whereas heat production in Lithuania is based on heat producer competition [53, 57]. In order to ensure competition between heat producers, the Lithuanian National Energy Regulatory Council (NERC) approves a set of conditions for the use of heat transmission networks, which are mandatory for all persons involved in energy activities in Lithuania’s heating sector. Lithuania has a unique market mechanism for the DH sector. Each month, different DH suppliers compete in price level auctions. This is the only competitive market model in European DH. Moreover, Lithuanian DH companies participate in the biomass market and the purchase of biomass depends on the market price. A third of biomass power plants have been built by independent heat producers. Monthly heat sale auctions are used to initiate competition among heat producers. Lithuania has BALTPOOL, a national biomass and heat energy exchange, where all heat producers are required to buy biomass and sell heat in individual municipalities. Foreign politicians and officials are interested in the exchange. BALTPOOL is planning to expand its operations to other countries.

DH prices in the Baltic States are set in accordance with national legislation. In Estonia, the DH price cap must be justified, cost-effective, and allow the company to fulfil its legal obligations. Only justified sales volumes and profitability expenses may be taken into account when approving the heat energy price for the period of regulation. The validity of the costs included in the heat limit price and their cost-effectiveness are assessed. The maximum area price is set by the Competition Authority in accordance with technical indicators [58, 59]. The Lithuanian National Energy Regulatory Council (NERC) sets the base price for heat. The municipal council determines the specific components of the heat price, submits documents to NERC for base price harmonisation, and provides feedback on the draft base price. The heat supplier calculates the changed fuel prices and the changed prices for purchased heat and publishes the final heat prices, taking into account the established components of the heat price. Heating tariffs in Latvia depend on many factors, including the size of the system, the fuel used, the technical condition of the system, and even political considerations. Heat production, transmission, and distribution are public services that are regulated by the Public Utilities Commission in Latvia. Small DH systems (up to 5,000 MWh per year) are not subject to regulation [60].

For 5GDHC, strict DH regulation can be a major disadvantage due to the inability to make a profit and pay banks for the investment necessary for a new low-temperature network.

4.1.3. Existing DH Infrastructure

The DH infrastructure in all three Baltic States is well-developed and widespread in many cities and towns. High-temperature DH is only in its third generation at the moment, but heat generation sources used are mostly renewable (Figure 4.1).

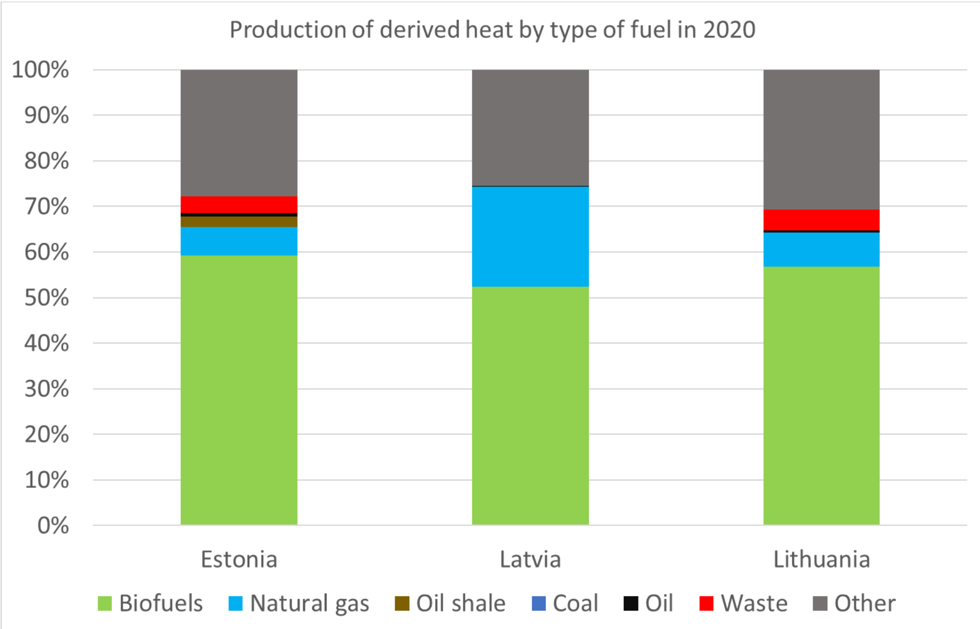


Figure 4.1. Heat production by fuel type in 2020 (based on [61])

Lithuania has a well-developed DH system. The share of DH in the overall heating sector has remained stable in recent years, averaging around 58% in the country and around 76% in cities. DH companies operate in all 60 municipalities of Lithuania. These entities are regulated by the NERC. Smaller heat supply companies are regulated by the municipalities. Municipalities own approximately 90% of DH companies, with the remaining 10% leased to foreign and domestic investors. Private capital entered the Lithuanian DH market in 2000. In the Lithuanian DH sector, RES (primarily biomass) and municipal waste account for nearly 70% of heat production [62]. The share of heat from natural gas in the fuel mix is less than 30%. Up until 2014, natural gas was the main fuel in the DH heat generation structure. The rapid replacement of imported natural gas with local renewable biomass has benefited the local economy, created new jobs in the regions and expanded new industries. The introduction of biomass into the Lithuanian DH sector was made possible thanks to EU support.

Natural gas has historically been the dominant DH fuel in Latvia. Between 2014 and 2019, the share of heat produced using natural gas at CHPPs decreased from 75% to 53.5%, while the share of heat produced using natural gas in heat-only boilers decreased from 42.4% to 29.6%. This is primarily due to policies that encourage the use of renewable fuels, particularly biomass fuel such as wood chips. Thus, biomass-based heat production at cogeneration plants increased from 19% in 2014 to 29% in 2019 and from 50% to 66% at heat-only boiler houses [63].

The total length of heating networks in Latvia is approximately 2,000 km, with the majority of heating pipelines being outdated and subject to significant heat loss. However, there is a gradual renovation and optimisation of heating networks, and average heat loss has been on the decline since 2009, reaching 11% in 2020. The heat supply temperature in heating networks is around 80-90ºC during cold winter periods and around 70ºC during most of the season when the outdoor temperature is around 0ºC [64].

Oil shale is the main source of energy and the main fuel in Estonia's energy mix. On the one hand, the substantial use of oil shale as a domestic fuel guarantees energy security. On the other hand, oil shale energy production emits a substantial amount of greenhouse gases due to its high carbon intensity, which has a negative impact on the environment. As a result, the Estonian economy produces more than twice as much carbon dioxide (CO_2) as the EU average. The Estonian government is gradually decommissioning existing power plants and developing new technologies to drastically reduce CO_2 emissions and harmful environmental impact. Estonia exports electricity because its production slightly exceeds consumption. The total electricity output in Estonia in 2019 was 7.615 TWh, and while the total electricity demand was 8.257 TWh. Oil shale was used to generate more than half of all electricity (56%), followed by biomass (17%), wind power (9%), and renewable waste (1%) [65].

There are over 200 DH networks in Estonia, with DH accounting for more than 60% of total heat production. Since 2014, with the EU's assistance, numerous small DH network boilers have been refurbished, and new biomass boilers have been deployed to replace ageing gas and oil-fired boilers. Oil and natural gas consumption in Estonia has been declining since 2010 [66]. In 2018, biomass accounted for 46.8% of the Estonian DH energy mix and natural gas for 25.6%. Oil shale (9.2%), municipal waste (6%), shale oil gas (6%), fuel oil (3%) and peat (2.8%) make up a small part of the DH energy mix in Estonia.

The main barrier to 5GDHC is the existing well-developed and widespread 3rd generation DH infrastructure in all three Baltic countries. As a result, 5GDHC development can be carried out primarily in newly built areas, in addition to the existing DH network.

4.1.4. Building Stock

According to Statistics Estonia, there are 23,600 apartment buildings in Estonia. Most of these apartment buildings were built during the period of industrial construction between 1960 and 1990. Apartment buildings in Estonia are mainly heated by DH and have a single-pipe heating system with hydronic radiators and no thermostats. The indoor temperature is regulated only at heating substations [67]. The annual energy consumption of residential buildings remains relatively stable at 10 to 12 TWh. Heating accounts for about 85% of consumption (~9 TWh) and electricity accounts for ~15% (~2 TWh). The share of electricity consumption in residential building energy consumption has grown steadily over the years. The final energy consumption of non-residential buildings has also increased. In 2004, non-residential buildings consumed 4 TWh of energy. By 2017, their consumption has increased by 50%, reaching 6 TWh. Around 50% of non-residential building consumption is for heat (~3 TWh) and the remaining 50% is for electricity (~3 TWh). A reduction in final energy consumption of about 7 TWh/y would be possible if the buildings were fully renovated. It would be possible to reduce heat consumption by up to 70% (~6.4 TWh/y) and electricity consumption by up to 20% (~0.5 TWh/y). The slight reduction in electricity consumption is due to buildings that do not have an appropriate indoor climate, but this can be achieved by installing appropriate utility systems that use electricity [68].

According to the Real Property Register, there are more than 41,000 apartment buildings in Lithuania. Most of these apartment buildings (90%) were constructed before 1992 with very low energy efficiency. Only 2% of buildings in Lithuania are owned by the state (state or municipal property), with private ownership accounting for 98% (individuals or legal entities). Therefore, the main obstacle to renovation is the persuasion of private owners of the buildings. The annual consumption of thermal energy by the building stock is about 20 TWh for heating and 8.5 TWh for hot water supply. Residential buildings consume 17.5 TWh of thermal energy and only 1.7 TWh of electricity.

Data provided by the State Land Service show that there were 39,000 apartment buildings in Latvia in 2019. The total housing stock is 91.08 million m^2, and the total area of non-residential buildings is 115.50 million m^2 [69]. The total consumption for space heating in 2019 was 10.24 TWh. Most existing buildings have a high heat consumption and significantly lower thermal properties than can be provided by currently available technologies. The average rate of depreciation for residential buildings is 38.9%. The average energy consumption for space heating among all types of buildings is 138-139 kWh/m^2 per year. In recent years, however, step-by-step measures have been taken to improve energy efficiency, resulting in a reduction in specific heat consumption. In apartment buildings, for example, the decrease between 2016 and 2019 is 13.8 kWh/m^2.

5GDHC ultra-low temperature regime requires high energy efficiency in buildings. A large proportion of old buildings that consume large amounts of thermal energy are not suitable for 5GDHC implementation.

4.1.5. Low-Temperature DH Pilots

DH operators mainly provide space heating and domestic hot water, while some also generate electricity in all three Baltic countries. The existing DH infrastructure is represented only by 3rd generation DH [70]. The first steps toward lowering the temperature are expected to begin in Vilnius, Lithuania, in 2022. A small low-temperature DH was also introduced in Latvia, in a parish of the Gulbene Municipality, which is more focused on the optimisation of the existing heating network in the village [71]. In Estonia, no 4th generation DH networks have been deployed. District cooling is implemented only in Estonia (Tallinn, Tartu, and Pärnu) [72, 73].

4.1.6. Energy Policy

The electricity generation mix is diverse and unique to each of the Baltic countries. Estonia is the only country where more than 70% of oil shale is used to generate electricity. Latvia is the country where natural gas (50%) prevails over hydropower (33%). Since the shutdown of the Ignalina nuclear power plant in 2009, Lithuania has had a unique situation in the electricity market, with about 70% of electricity imported. The rest of Lithuania's electricity is generated primarily by wind (38%) and hydropower (24%), but hydropower generation in Lithuania is quite low compared to Latvia due to a substantial share of imported electricity. Electricity production can be seen in Figure 4.2.

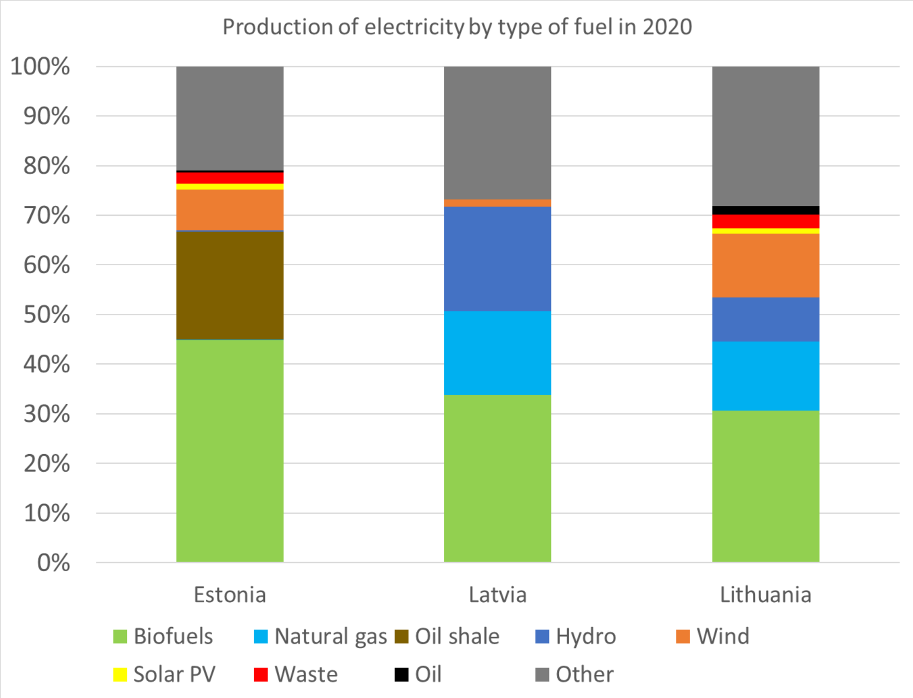


Figure 4.2. Electricity generation by fuel type in 2019 (based on [61])

Latvia is one of the leading countries in terms of the achieved share of RES in the power generation mix due to a significant share of hydropower. However, Latvia has a limited installed capacity of RES variable energy from solar and wind energy, but this is likely to grow as the market develops and natural gas prices rise. Even if the general energy policy continues to prioritise the use of biomass and improving energy production and transmission efficiency, more widespread electrification is possible. The heating network is anticipated to become more open and accessible to various heat sources, increasing the diversity of DH systems. Since the first large-scale solar thermal field has been successfully launched, it is predicted that the share of solar heat in DH may increase in the coming years. It is also expected that large-scale solar plants will get a larger share in DH, and energy accumulation technologies will develop.

In early 2021, the new Estonian government introduced plans to achieve carbon neutrality by 2050 and drastically reduce the use of oil shale. Estonia has met its mandatory 2020 emission reduction and renewable energy targets. In 2030, for the first time, Estonia will have to reduce emissions and not just limit their growth. Because of the incentives granted by the Electricity Market Act, which apply to the generation of electricity using renewable sources, the share of renewable energy has climbed to 30% and will continue to grow.

Lithuania reached its 2020 renewable energy target (23%) back in 2014. More than one third of all local electricity production in Lithuania comes from wind power plants. The share of solar PV is the highest in Lithuania among the Baltic countries due to energy policy that is favourable for investment subsidies and energy prosumers, as well as renewable energy communities. The installed capacity of energy prosumers increased from 30 MW in 2019 to 138 MW in 2021. The amount of electricity supplied by energy prosumers increased by about 4 times (from 9

MWh in 2019 to 35 MWh in 2021). For 5GDHC, the electricity mix and the particularly low electricity price is a major factor in the low maintenance costs of such a system.

4.1.7. Strategic DH Goals

In terms of RES use, the Baltic States' strategic DH goals are ambitious. According to the National Development Plan of the Energy Sector until 2030, 11 TWh of the total heat demand will be met by biomass in 2030, and 80% of DH in Estonia will be provided using renewable sources [74]. In 2020, RES already accounted for 71.5% of the total energy production in the DH networks in Lithuania. Furthermore, Lithuania has set a goal to increase this percentage to 90% by 2030 and bring it to 100% by 2050, which is the most ambitious goal among the Baltic states. According to the Latvian NECP 2021-2030, the share of RES in DH will increase by around 0.8-1.0 percentage points each year from 2020 to 2030, reaching 57.6% in 2030 [75].

5GDHC is not mentioned in any of the Baltic countries' strategic documents. In the DH sector, development is focused on renewable energy, primarily biomass. However, 5GDHC may have important infrastructure that can integrate different types of renewable energy technologies, especially in areas with new high-energy-efficiency buildings.

4.2. Identified Barriers and Drivers in the Baltic States

The main drivers behind the implementation of 5GDHC and barriers that limit its development in Europe are summarised in Table 4.1. Based on the literature review, the main aspect that distinguishes 5GDHC from 4GDH is the dependence on the electricity system. Therefore, a significant increase in electricity prices could limit not only the implementation but also the economically viable operation of 5GDHC. A new piping system for the ultra-low temperature DH system, as well as a dedicated new infrastructure capable of handling simultaneous heating and cooling, renewable energy sources, necessitate significant initial costs and limit the initial stage of selecting 5GDHC over other heating/cooling alternatives. For example, a lack of financial resources for newly constructed and energy-efficient buildings, which could be a potential area for 5GDHC, as well as a shortage of qualified personnel, limit its development. The lack of public acceptance of 5GDHC makes managing the interests and risks of many stakeholders difficult. However, the main barrier in all three Baltic States concerns the well-developed and widespread high-temperature 3rd generation DH systems that feature centralised energy generation, limiting the potential market for ultra-low temperature 5GDHC. Existing biomass boilers and CHPs are relatively new in the Baltic States and will be in operation for several decades, limiting other options. Regulatory and policy barriers to selling excess low-temperature waste heat or sharing energy between buildings also limit 5GDHC development. As a result, 5GDHC can mainly be implemented in newly built areas, as alongside the existing DH network.

Table 4.1. 5GDHC barriers and drivers

BARRIERS	DRIVERS
Dependence on the electricity system	Climate change targets (low GHG emissions): e.g. stop using natural gas
High initial costs	Geopolitical implications of using imported

	natural gas
Specific new infrastructure is required	Ambitious energy transition targets of the country
Increase in the price of electricity	Reduced price volatility
Financial sources (lack of adequate funding and financing products)	Positive effect on health
Awareness (lack of skilled personnel)	Strengthening energy security
Institutional and administrative barriers	Creating local economic value and jobs
Market barriers	Increased access to affordable, reliable, and sustainable energy for heating and cooling
Lack of public acceptance	Ability to reuse waste heat
Regulatory and policy barriers	
Separate pipes are needed to provide both heating and cooling	
Centralised energy production, limiting network expansion area	
Dwelling spatial impact and dwelling noise	
High resident risk	
Existing biomass based district heating systems	

The country's ambitious energy and climate change targets may be the primary drivers for the development of 5GDHC. Other drivers include the possibility of recycling low-temperature waste heat not only from industries but also from other local sources (supermarkets, electrical transformers, data centres, etc.), as well as the development of local economic value and the creation of jobs. Because of the sharp increase in imported natural gas prices, the geopolitical situation has become a favourable driver for the implementation of 5GDHC, which helps to reduce future heating/cooling price volatility and has a positive effect on health when compared to other air pollution alternatives. The war in Ukraine has accelerated the achievement of ambitious energy transition targets and the development of RES in many European countries in order to reduce dependence on imported natural gas for heating and electricity generation. By improving energy security and increasing access to affordable, reliable, and sustainable energy for both heating and cooling, 5GDHC could be one of the alternatives for integrating not only RES but also other low temperature waste heat sources.

4.3. Multi-Criteria Analysis

4.3.1. Criteria for Potential Implementation of 5GDHC in the Baltic States

A multi-criteria analysis was used to assess the feasibility of introducing 5GDHC in the Baltic countries. A qualitative comparison was made by discussing the barriers and drivers that each country faces, and a quantitative comparison was made by assigning numerical values to each criterion. The quantitative analysis was performed using a multi-criteria decision method to compare various aspects of potential 5GDHC implementation. The quantitative analysis ranked each country according to each criterion.

The obtained values were evaluated using the method of multi-criteria analysis called the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) and the Analytic

Hierarchy Process (AHP) method to determine the weight of each criterion. The TOPSIS method of multi-criteria analysis is widely used to compare different environmental strategies for sustainable development [76, 77], taking into account different points of view. The main purpose of TOPSIS is to allow users to compare and choose between multiple alternatives.

The evaluation criteria are shown in Table 4.2. The authors used 15 different criteria to quantify and compare barriers and drivers for 5GDHC implementation in the Baltic countries.

Table 4.2. Overview of criteria used

Criterion	Unit	Source
1 Average final price of electricity	EUR/MWh	Eurostat [61]
2 Share of RES energy	%	Eurostat [61]
3 Share of heat supplied via HPs	unit per 1,000 households	
4 CO_2 emission factor for electricity	t CO_2/MWh	
5 Future CO_2 emission factor for electricity	t CO_2/MWh	
6 Maximum heat tariff	EUR/MWh	
7 Minimum heat tariff	EUR/MWh	
8 DH tax rates	%	
9 Available support measures for possible 5GDHC implementation	Evaluation scale	
10 Possibility to implement innovative business models	Evaluation scale	
11 Specific building heat consumption	kWh/m^2	Odysee-Muree [78]
12 Share of new buildings	%	Odysee-Muree[79]
13 Excess heat source potential from shopping centres	MWh	
14 Excess heat source potential from transformers	MWh	
15 Excess heat source potential from data centres	MWh	

The assessment includes criteria related to the existing power system, since the operation of 5GDHC is highly dependent on the implementation of power-driven HPs. The authors compared the average final electricity price across countries, anticipating that lower electricity prices will encourage HP adoption. Furthermore, because electricity for 5GDHC must be produced in an environmentally friendly manner, the share of electricity supplied by RES was included. Finally, the authors included two criteria related to electricity CO_2 emission factors: the current CO_2 emission factor and the projected CO_2 emission factor for each country's future energy balance based on [80, 81]. Criteria related to the current status of HP units in the country have also been included as they indicate whether the HP market is mature. This is important from the perspective of stakeholders such as HP resellers and users.

Since 5GDHC can be considered a competitor to traditional DH systems, the authors included several criteria that characterise the main parameters of the existing centralised heat supply system: the maximum and minimum heat tariffs and tax rates. The analysis suggested that the implementation of 5GDHC is preferable if the existing DH systems' heat tariffs and taxes are high. Two qualitative criteria have been introduced to describe the available support measures and the possibility of introducing innovative business models in each country. These criteria were evaluated using a three-point scale. The three points of available support measures apply if subsidies or other support policies for DH and individual heating solutions have been implemented in recent years with the possibility of introducing innovative technology solutions. The most points are awarded for innovative business models if the legal framework allows for the establishment of different tariffs and discounts for thermal energy for consumers, as well as the affordable entry of various heat producers into the heat supply market.

The heat supply of energy-efficient buildings with low heating demand is addressed by 5GDHC solutions. Therefore, two criteria were introduced that describe the existing consumer situation: the average specific heat consumption for space heating and the proportion of new buildings. Both criteria were taken from the ODYSSEE-MURE database, describing the situation in the residential sector. The average heat consumption for space heating is expressed in kWh per m^2 of heating area and is normalised based on climatic conditions. The proportion of new buildings represents the total area of new buildings built over the past 10 years.

In addition, three criteria were created to assess the accessible potential of low-temperature heat sources in each country, characterising the available heat from agents (shopping centres, electrical transformers, and data centres). As mentioned above, it is crucial to identify 5GDHC agents. The identification of agents will allow for the evaluation of their potential use in 5GDHC. The first section of the paper described the potential evaluation. This potential is one of the most important criteria for evaluating the concept's implementation. The preliminary potential of the following agents has been determined: shopping centres, electrical transformers, and data centres.

The obtained criteria values were further normalised and weighted. The decision-making matrix and normalisation of the obtained criteria values were performed using the TOPSIS method described by Loken [82]. Multi-criteria analysis' TOPSIS is often used to evaluate environmental strategies for sustainable development [83]. The main purpose of TOPSIS is to allow for comparison and choice between several alternatives or, in this case, a comparison of barriers and drivers for the implementation of 5GDHC systems.

The ability to prioritise the analysed criteria is one of the most important aspects of using multi-criteria analysis. In this study, the AHP method was used to rank the identified criteria. In order to evaluate the problem using the AHP method, it is necessary to determine the priority criteria using pairwise comparison. The selected pairs of criteria were compared in terms of their importance on a scale from 1 (equally important) to 9 (absolutely more important). Following the comparison of the criteria, the obtained results must be checked for consistency. The consistency check looks for inconsistencies in the evaluation of the criteria. If there are inconsistencies, it is necessary to check whether the problem and the criteria are clearly defined, and to revise and re-evaluate the pairs of criteria. The criteria ranking results are shown in Figure 4.3.

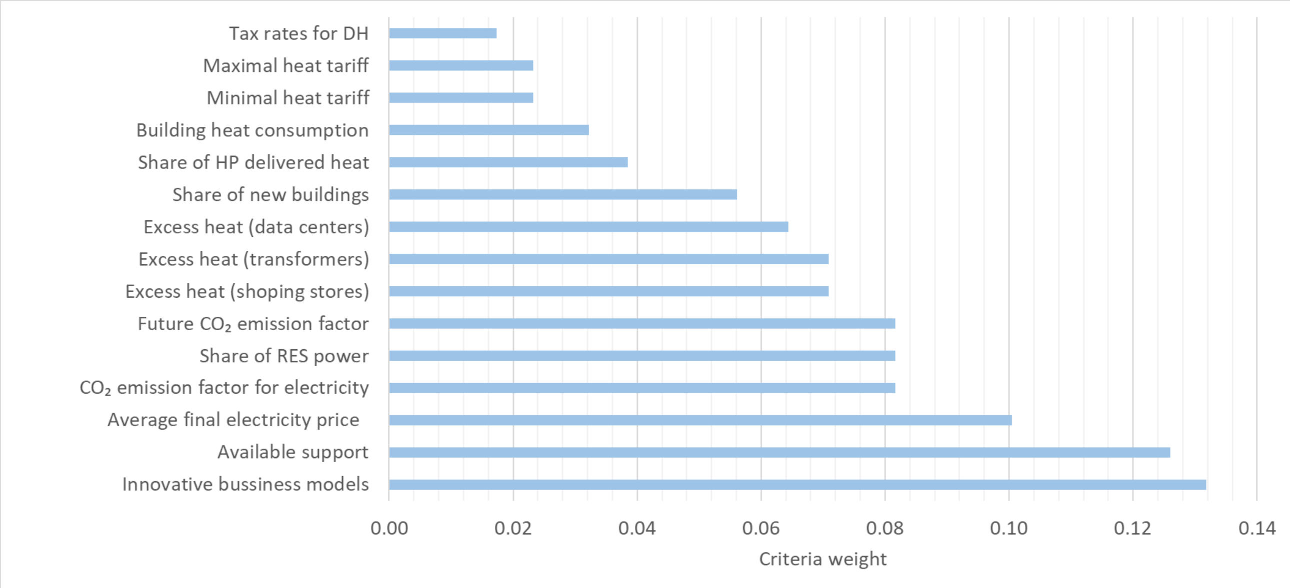


Figure 4.3. Overview of the specific weight of each criterion

The authors believe that the ability to introduce an innovative business model and the availability of technology implementation support in accordance with the criteria that describe the current situation in each country's energy sector are critical factors for the implementation of 5GHDC. The criterion is re-evaluated with equal weights for all options to determine the impact of the criteria weights set by the AHP on the evaluation of the criterion.
The final comparison between the Baltic countries was performed by multiplying the weight of the criterion by the corresponding normalised criterion value. An ideal positive decision and an ideal negative decision are calculated when constructing a normalised weighted decision matrix. The distance to the ideal solution and the distance to the non-ideal solution are calculated first [84]. The next step after determining the distance to the ideal and non-ideal solutions is to determine the ideal positive and ideal negative solutions. The relative proximity of the alternative to the ideal solution is calculated by determining which country has the greatest potential to implement 5GDHC systems.

4.3.2. 5GDHC Multi-Criteria Assessment Results for the Baltic States

The section presents the results of a quantitative assessment of several identified barriers and drivers for the implementation of the 5GDHC system in the Baltic countries. A summary of the obtained criteria values is provided in Table 4.3. The lowest final electricity price is in Estonia (0.12 EUR/kWh), but the prices in Lithuania and Latvia are nearly identical. The highest share of renewable electricity is in Latvia due to its high share of hydropower. Lithuania relies heavily on imported electricity. Therefore, its share of RES is low at 18.79%. However, the share of RES in Estonia is not much higher, at 22%.

The share of RES is directly related to the CO_2 emission factors for electricity from the grid. Due to the high penetration of imported energy, the CO_2 emission factor and local renewable energy generation for Lithuania is 0.02 t_{CO2}/MWh, which is relatively low compared to the values for Latvia (0.12 t_{CO2}/MWh) and Estonia (0.6 t_{CO2}/MWh). The authors also included projected CO_2 emission factors based on [85, 86] as the implementation of 5GDHC systems is likely to be delayed and may not begin until the next decade. It is predicted that CO_2 emissions may decrease in Latvia and even more so in Estonia. CO_2 emissions from electricity generation in Lithuania, on the other hand, may increase.

Table 4.3. Summary of criteria values for the Baltic States

Description	**Latvia**	**Lithuania**	**Estonia**
Average final electricity price, EUR/kWh	0.14	0.14	0.12
Share of RES energy, %	53.42	18.79	22.00
Number of individual HPs, unit/1000 households	1.00	9.00	29.30
CO_2 emission factor for electricity, t_{CO2}/MWh	0.12	0.02	0.6
Future CO_2 emission factor for electricity, t_{CO2}/MWh	0.08	0.06	0.22
Maximum heat tariff, EUR/MWh	69.98	79.63	86.96
Minimum heat tariff, EUR/MWh	35.45	32.57	35.33
DH tax rates, %	21	9	20
Available support measures for possible 5GDHC implementation	2.00	2.00	1.00
Possibility to implement innovative business models	1.00	2.00	1.00
Specific building heat consumption, kWh/m^2	159.7	131.3	142.8
Share of new buildings, %	5	6	2
Excess heat source potential from shopping centres, %	10%	13%	16%
Excess heat source potential from transformers, %	3%	1%	1%
Excess heat source potential from data centres, %	1%	0%	2%

The criteria analyses show that Estonia has a higher cumulative knowledge of HP use, a technology closely related to 5GDHC. According to the European Heat Pump Association, there are 29.3 HP units/1000 households in Estonia and 9 units/1000 households in Lithuania [87]. Because the number of HP units in Latvia is rather low, at just 1% [88], an estimate of one unit per 1000 households was chosen.

According to the criteria used to evaluate existing DH systems, Estonia had the highest maximum heat tariff in 2019, whereas Latvia had the highest minimum heat tariff. Latvia and Estonia have identical tax rates, whereas Lithuania has a lower rate. As previously stated, when heat tariffs in existing DH systems are high, the 5GDHC system is presumed to be a better option.

Based on previously implemented support programs for local and district heating systems, the qualitative assessment criteria indicate probable support for 5GDHC systems in Lithuania and Latvia. Furthermore, due to the open heating market conditions in Lithuania, innovative business models that are crucial for 5GDHC systems are more likely to be implemented there. However, different heating tariffs are not permitted under current market rules in Latvia and Estonia. As a result, the criteria score is lower.

In terms of building stock, Lithuania has the best conditions due to lower specific heat consumption (131.3 kWh/m^2) and a higher proportion of new buildings (6%). Latvia has the most inefficient buildings (159.7 kWh/m^2), while Estonia has the lowest proportion of new buildings (2%).

Finally, the selected low-temperature heat source agents described in the previous section have been identified and allocated to the national total heat supply. The results show that Lithuania has the largest share of excess heat obtained from shopping centres (16% of total heat consumption), but Latvia has the highest share of excess heat obtained from electrical transformers (3%). The identified share of excess heat from data centres is relatively low in all three countries, peaking at 2% in Estonia.

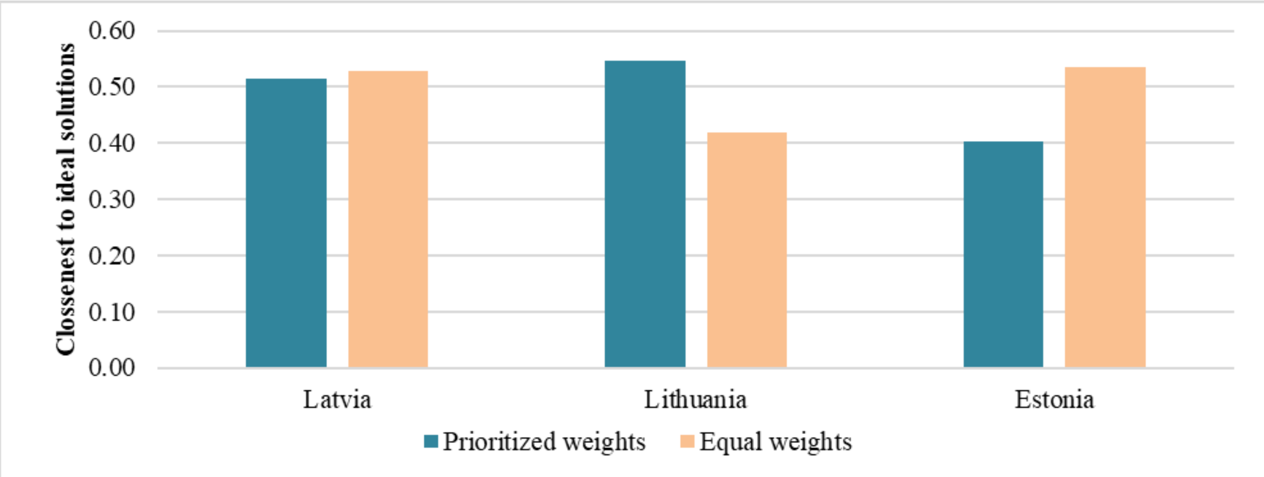


Figure 4.4. Results of multi-criteria assessment with prioritised criteria weights and equal criteria weights

In accordance with the methodology described above, the values of the identified criteria from Table 4.3 were normalised and weighted to determine the proximity to the ideal solution for each country. The results in Figure 4.4 show different values for similar and prioritised criteria values. When the identified criteria are prioritised by assigning higher weight values for the possibility of introducing an innovative business model and available support for technology implementation, followed by criteria describing the existing situation in each country's energy sector, Lithuania has the highest score due to support availability and open heating market conditions. However, when equal criteria weights are assigned, the highest evaluation rank belongs to Estonia due to its widespread use of HPs and greater excess heat potential.

The multi-criteria analysis method was used to quantify the main identified barriers and drivers behind the implementation of 5GDHC systems. The authors examined the three Baltic countries from a variety of angles, including possible competition with existing DH systems, power market sustainability, excess heat potential from different sources, and potential support policies. Although Latvia, Lithuania, and Estonia have similar conditions, there are some differences. For example, different fuel mixes are used for power generation; stricter heating market regulations exist in Latvia and Estonia; and Estonia has more experience with HP use, whereas Latvia has almost no HPs. The highest score in the multi-criteria assessment was achieved by Lithuania due to support availability and open heating market conditions. When all applied criteria are weighted equally, Estonia has the most favourable conditions for 5GDHC systems due to the widespread use of HPs and greater excess heat potential.

This study may aid in understanding how different agents can be integrated into 5GDHC and what waste heating or cooling potential they can contribute to the 5GDHC network. The findings of this study provide a solid foundation for future 5GDHC modelling and feasibility studies. The identified barriers and drivers also indicate directions for future efforts to implement the 5GHDC network.

The present geopolitical situation has significant impact on the imported energy prices, and this will further affect the electricity and natural gas prices in different countries. Countries that rely heavily on imported electricity, such as Lithuania, may be more sensitive to the geopolitical implications of 5GDHC development. However, with greater integration of renewable energy sources into the energy mix (in accordance with each country's climate goals), the impact of the geopolitical situation is expected to diminish in the long run. This study's findings will still be relevant in the long term.

4.4. Interviews with Stakeholders

Following the identification of potential 5GDHC agents, it was decided to arrange interviews with stakeholders associated with these agents.

The following stakeholder groups were selected: real estate developers, DH and power operators, shopping centres, and data centres (as both stakeholders and agents at the same time).

Table 4.4 contains information about the stakeholders and their interviews.

Table 4.4. Information on stakeholder interviews

Stakeholder	Related agents	Number	Country
Private real estate developer	Residential buildings	4	Estonia, Lithuania, Sweden
DH operators	Heat sources, low-temperature heat sources, waste heat, thermal energy storage	3	Estonia, Lithuania, Latvia
Power operators	Heat pumps, electrical transformers	1	Lithuania
Shopping centres	Shopping centres	1	Lithuania
Data centres	Data centres	1	Sweden
Public sector	Non-residential (public) buildings	1	Lithuania
		1	Latvia

The interviews were conducted in the format of a workshop because in some cases respondents needed additional clarifications, regarding the topic of discussion.

The interview consisted of:

- Presentation of the project idea;
- Description of the 5GDHC concept;

- Questions (prepared ahead of time) and answers;
- Discussion.

The results of the interviews were outlined in a report/brief summary.

4.4.1. Interviews with Real Estate Developers

Ülemiste City (Estonia)

Ülemiste City is a smart business campus located close to Tallinn Airport and the future Rail Baltic passenger terminal. It covers 36 hectares and has a development potential of 550,000 km^2. There are over 500 smart companies there, and most of them are in the IT industry. In addition to IT and technology companies, there are many other types of businesses and services, including health centres, supermarkets, entertainment venues, gyms, and office spaces.

The campus requires both heating and cooling. The total heating demand for the campus is around 30 MW. While there are many buildings that have been built within the last ten years that have intelligent ventilation and heating systems, there are also many old buildings with very poor energy efficiency. Campus management hopes to reduce heating and cooling demand using AI solutions. Last year (2021), the campus invested more than 11 million euros in collaboration with the local district heating company, Utilitas, to connect the campus to the Tallinn district heating network and create a district cooling network. Investments have been made to reduce the campus' ecological footprint and CO_2 emissions and to move away from using natural gas for heating. The majority of campus buildings are now connected to district heating, while the Ülemiste Centre shopping mall and Tallinn Airport use local heating and cooling solutions.

There are no 5GDHC agents near the campus, because the ground beneath the campus is mostly limestone, which is not a good source of ground heat. There are several industrial waste heat sources, including the Kuehne+Nagel data centre, the Elcogen fuel cell plant with multiple boilers with considerable excess heat potential, and the Dvigatel-Energeetika electrical substations and transformers. Shopping centres, schools, kindergartens, office buildings, airports, hotels, gyms, and industrial structures are among potential prosumers and consumers. The were also plans to install PV panels and medium voltage inverters.

Campus management regards the 5GDHC concept as a future possibility since it significantly reduces the need for primary energy sources and production. Although the economic impact has yet to be determined. Campus management notes that there are institutional barriers to implementing 5GDHC due to district heating regulation, since the city assigns only one heat provider per area. On the other hand, the 5GDHC solution does not require additional piping or separating the area from the central system. They believe that if the 5GDHC system is widely implemented, the necessary adjustments can be made to the administrative regulations. Campus management feels that while a green future will surely be the starting point for implementing 5GDHC solutions, the economic impact is also important. From an economic standpoint, tariffs for electricity and heating can be considered during calculations. When the campus invests more in greener energy solutions, property owners can also increase rent as many international companies place more emphasis on a greener environment, which benefits the campus.

According to campus management, 5GDHC is better implemented as a brand-new district rather than replacing an existing one. They feel that if replacing existing systems and components in Ülemiste City is relatively easy and cost-effective, they will consider becoming a heat prosumer.

Old City Harbour, Tallinn (Estonia)

The development of the Old City Harbour is aimed at creating a fully integrated multifunctional district within the active harbour area, while taking into account the specific requirements of the seaport. In the future, the Old City Harbour plans to become Estonia's biggest and most attractive tourism gateway and an integral part of the modern cityscape. Tallinn's Old City Harbour has 16,2 ha of land that could be used for luxury real estate development. At the moment, the total built-up gross area is 400,000 m^2. It is also possible to increase the area by 160,000 m^2 through reclamation. There are plans to reconstruct passenger terminals, install a movable pedestrian bridge, and install automatic mooring equipment. In addition to the refurbished passenger terminals, a new cruise terminal is also planned to service cruise tourists and host numerous events throughout the year.

Currently, Tallinn's Old City Harbour has both heating and cooling needs, with a heating demand of 20 MW. The cooling demand is 4 MW at the moment, but there is a potential demand of 8 MW.

Tallinn's Old City Harbour believes that 5GDHC has potential and such solutions can be implemented in the harbour. Seawater, for example, can be used as a 5GDHC agent, while sewage and the nearby electrical substation are other sources of waste heat in the area. There are no data centres planned in the area. The most important issue is one of investment and costs. It is critical that the investments yield a profit. Legal issues, such as heat pump ownership, are also important. Furthermore, the solution must be cost-effective for consumers. It is also important for consumers that the pricing is consistent. The issue of a backup heat source also arises in the case where it is impossible to use heat from seawater or other sources. If the backup heat source is district heating, would district heating companies be interested in providing their services? The need for a backup heat source can lead to higher prices.

At a microscopic level, 5GDHC has already been implemented at the cruise terminal via seawater heat exchangers. Heat exchangers inject heat into the heating medium, which is then used to generate heat and energy for cooling. This project demonstrated that there is an issue with freezing. The project has not been tested in summer conditions and has thus far demonstrated the necessity of a backup energy source. This project is similar to the heating system of Tallinn's Seaplane Harbour, which also uses seawater as a heat source, although there are several differences.

The harbour believes that adopting 5GDHC solutions would be more appealing if the implementation was simple and resulted in significant energy savings. At this point, it is clear that compared to other alternatives, 5GDHC solutions can be rather expensive. Another barrier, in their opinion, is a lack of skills and assurance that the solutions will work in practise as well as in theory. If something happens at the 1 km water intake, how will this affect the port's heavy maritime traffic?

If the DEMO project were more appealing, the harbour management feels it would motivate them more to become a prosumer. The project could be made more profitable with the help of EU funding.

SBA Urban, Kaunas, Lithuania (private developer)

SBA Urban is a subsidiary of SBA Group, which has a total revenue of 342.5 million euros. SBA Urban has been in the real estate industry since 2007. SBA Urban is an investor developing new urban areas. SBA Urban collaborates with world-renowned architects to create unique buildings that are changing the face of cities. SBA Urban's vision for the cities of the future involves intelligent architecture, green building philosophy, sustainability, and collaboration with local communities.

SBA Urban has successfully implemented several business centre projects in Vilnius (Green Hall Valley: Green Hall 1, Green Hall 2, and Green Hall 3) and Kaunas (BLC, BLC 2, and Kauno Dokas). SBA Urban develops energy-efficient buildings that use renewable energy sources.

Green Hall Valley and Kaunas Dokas buildings have heat pumps installed. All buildings are connected to district heating networks. The use of heat pumps is highly dependent on the outside air temperature. For example, during the past winter, which was rather warm, geothermal heating was sufficient for two Green Hall buildings. There was no need to buy heat from the district heating network. Heat pump use is also greatly affected by energy prices. When electricity prices are really high, heat pumps are not cost-effective. SBA Urban buildings have a design network temperature of 50-70ºC and 30-35ºC during the transition period. Temperature, humidity, and other aspects of indoor thermal comfort are essential. In the summer, the heat is used to dehumidify the air. In the winter, the heat is used to warm up the air through the radiator system and underfloor heating.

Chillers are the primary sources of cooling in all buildings. SBA Urban was the first developer to use river water to cool the entire Kauno Dokas business centre. River water cooling was found to be three times less expensive than using a cooler and resulted in significant energy savings. The river depth at the water intake in Kaunas Dokas is only 1.5 m, so when the summer was extremely dry last year and the river level dropped dramatically, the water intake was higher than the water level, making it difficult to use river water for cooling.

At Kaunas Dock, the heat from the waste water (from the toilets) is recovered through a heat exchanger and reused, resulting in energy savings. The average heating consumption of the Kaunas Dokas building is 12 kWh/m^2.

SBA Urban has plans to develop smart commercial and residential buildings in the near future, so it is important to assess the feasibility of incorporating new innovative technology from the start.

5th generation district heating has good prospects, but such a technical solution can only be implemented in new buildings with high energy efficiency. A 5GDHC system can be implemented in new real estate properties because it requires a separate infrastructure that must be considered at the design stage.

Many sources of heat and storage units should be available in low-temperature networks. The feasibility of supplying low-temperature heat to the district heating network must be investigated.

A 5GDHC system appears to be easier to implement with underfloor heating than with radiator heating. With radiator heating, it will be necessary to increase the area of radiators, which is not always possible due to the architecture of the building.

Because the building's geographic location (north/south) is crucial for providing suitable heating and cooling conditions, it should also be considered when designing a 5GDHC system.

There may be administrative and regulatory barriers to collecting waste heat from other buildings since waste heat sources may not be available to SBA Urban. The technical feasibility of wastewater heat recovery in new residential buildings is being investigated by SBA Urban.

Incentives are crucial for business and can impact decision-making, but it's all about opportunity in the end. SBA Urban is a socially responsible company that is exploring all opportunities for sustainable development. SBA Urban has a green electricity agreement in place with an electricity provider. All business centres have access to green electricity.

The BLC building was the first business centre in the Baltics to be awarded a 3-star Fitwel certification. Green Hall Valley is on track to become BREEAM certified.

Anonymous (Sweden)

The residential agent, on the other hand, is mostly in need of heating during the winter. A few days throughout the summer require cooling, but it is not critical. Very interesting conclusions were obtained when discussing their views on 5th generation district heating. They are concerned about the actual implementation of 5th generation DH, as they believe that heat recovery and collection of low-temperature waste heat won't be easy. Gray water pipes (domestic water and shower water) could theoretically provide waste heat, but collecting waste heat from them is a very challenging process given the cost and limited amount of waste heat inside. If we want to collect more waste heat, we'll have to increase the diameter of the collector pipe, which will increase the network's cost. They also compared residential use of waste heat with industrial use of waste heat. The cost of collecting heat from industrial sources is low since the temperature of the heat is high (high-grade waste heat). However, gathering heat from residential areas or distributed sources can be expensive (low-grade waste heat).

4.4.2. Interviews with District Heating Operators

District heating operators are another group of stakeholders. Three district heating operators were interviewed.

Vilnius District Heating Company (AB Vilniaus šilumos tinklai), Vilnius, Lithuania

Vilnius District Heating Company is the largest heat and hot water provider in the Lithuanian capital (population over 594,000 people). AB Vilniaus silumos tinklai is owned by the Vilnius City Municipality and provides heat to more than 210,000 households and businesses via a 748 km heating network. AB Vilniaus silumos tinklai has a long-term strategy (2021-2040) that envisions a gradual transition to a newer generation low-temperature network, investments in intelligent control systems, installation of smart meters in consumer substations, integration of waste heat from businesses, district cooling, and other renewable energy-related innovations.

The Vilnius District Heating Company has set the goal of switching to 4th generation DH. In the summer of 2021, the first low-temperature DH project was implemented in Lithuania. The temperature was reduced to 63-65°C. The National Energy Regulatory Council assisted in the implementation of this project. Low-temperature DH has piqued the curiosity of a number of private investors. New districts will be connected to the low-temperature grid via mixing units.

The Vilnius District Heating Company is currently discussing 5GDHC with a private investor. However, there are far too many concerns with 5GDHC right now. There is a shopping mall with heat recovery potential in the area of new residential buildings, but the question is how much heat can be taken in winter, when demand for it is highest. There is also an issue of how to persuade the shopping mall to provide waste heat. The most acceptable solution at this time is air/water heat pumps, but there will be a noise concern for residents. It's also up for discussion whether hot water will be prepared at the building level or at the apartment level.

Regulatory issues are one of the most significant barriers to the future implementation of 5GDHC. The Vilnius District Heating Company is responsible for the DH network but cannot make any changes to consumer substations as they are part of the building, according to national regulations. As a result, either investors or consumers must invest in consumer substations. Moreover, it’s best if private investors design the building’s internal systems. Another major obstacle in Lithuania is the lack of waste heat collection regulations. Lithuania has introduced a competition-based DH model, which means that waste heat must participate in the Lithuanian Baltpool market's auction process.

There are potential 5GDHC agents in Vilnius. A feasibility study on collecting waste heat from the wastewater treatment process has already been conducted, with an estimated potential of 14 MW. There are several data centres and multiple shopping malls in Vilnius. The lack of a forecast of how much heat can be provided could be the biggest barrier.

Utilitas Tallinn (Tallinn district heating company), Tallinn (Estonia)

AS Utilitas Tallinn supplies heat to 2/3 of Tallinn’s residents as well as the town of Maardu. The company operates a 479 km district heating network. Heat is generated by the company's own biomass CHP plant, three large natural gas boiler houses, and two biomass CHP plants. In addition, one waste incineration unit produces heat throughout the year. Utilitas Tallinn provides heat to 4,200 buildings. Over the last few decades, the company has worked hard to develop its network. Over 40% of pipes were renovated/replaced with pre-insulated pipes. Utilitas has also begun developing the district cooling sector. The network operator believes that integrating 5GDHC into the existing network is not feasible. Local small ultra-low temperature district heating networks, where low-temperature heat sources generate heat, could be a viable solution for 5GDHC. A possible business model for a DH operator was also discussed. The operator, who has a lot of experience with heat supply, can take up the task of providing heat to the substation. One option would be to install a small heat pump that provides heat to 2–5 buildings. Residential buildings as heat prosumers are not of interest to the DH operator, since the amount of heat that can be provided is very small. The DH company's main responsibilities will include network operation, maintenance, and repair, as well as the utilisation of current infrastructure with remote metering, dispatchers, and invoice processing. When discussing potential technical issues, the representative of the DH company stressed the importance of striking a balance between heat generation and consumption. In addition, having backup energy, such as a container-type boiler and/or an electric generator, is necessary in emergency situations. In this case capital/operating costs should be allocated per the number consumers (10-15 apartments or neighbourhood).

Salaspils Siltums DH operator (Salaspils, Latvia)

Salaspils Siltums Ltd. is a modern heat supply company that provides district heating in the town of Salaspils. The company's efforts are geared toward long-term, environmentally responsible development, with the goal of providing clients with reliable heat for the lowest possible price. The total heat production is about 60 GWh per year with a maximum heat load of 27 MW. The heating plant consists of two wood chip boilers (7 MW + 1.68 MW flue gas condenser and 3MW + 0.5 MW flue gas condenser) and 3 gas boilers (10, 10, and 3MW) to cover peak loads. Salaspils Siltums has the first district heating system with a large-scale solar field in the Baltics. The solar collector field's active area is 21,672 m^2, and the thermal energy storage tank's total volume is 8,000 m^3.

A representative of the DH system visited a 5GDH system in Belgium, which uses low-temperature mine water and borehole technology for heating and cooling. However, she concluded that the DH systems in Latvia are not yet sufficiently developed to achieve this level of innovation. The first step is to switch to the 4th generation system since some buildings still have low-efficiency substations. Salaspils Siltums has set a goal of replacing current substations with automatic ones by 2023, but the introduction of 5GDH systems requires a more advanced level of consumer substation development.

According to the representative, 5GDH could be an excellent alternative for new development areas when used in conjunction with existing DH networks. However, the first step would be to launch a pilot project that could show how prosumer involvement could work in Latvia. There are still many unresolved issues, e.g. how to ensure the requisite quality of the heat carrier.

When asked about the possibility of transitioning from a heat producer in existing systems to a heating network operator in a 5GDH system in the future, the Salaspils Siltums representative said the company is ready to operate such a system if new development areas with suitable conditions become available. DH operators need to be flexible and diversified in their energy sources. The DH operator has already begun negotiations with local companies about recovering heat and feeding it into the district heating network, but the companies are currently reusing all recovered heat internally, and the DH system lacks integrated sources.

The representative also stressed that due to the recent increase in natural gas and electricity prices, an increasing number of commercial buildings want to switch from individual heating to district heating. Businesses are interested in DH generating a wide range of energy, particularly from renewable energy sources. However, the representative does not believe that district cooling has any potential because there is little demand for cold in Latvia's small towns.

4.4.3. Interview with a Power Grid Operator

Transmission System Operator (AB Energijos Skirstymo Operatorius, ESO)

ESO is managed by Ignitis Group, a state-owned energy company that is one of the largest in the Baltic States. ESO's main activities include electricity and natural gas distribution and supply, connection to electricity and gas networks, as well as maintenance and development of electricity and gas distribution networks, and ensuring security and reliability of energy distribution. ESO serves 1.6 million clients across Lithuania. The company's service area is 65,300 km^2.

Electrical transformers are among the 5GDHC agents. The normal operating temperature of ESO electrical transformers is 35-40°C. In the winter, the temperature is about 10ºC. The Vilnius District Heating Company is interested in waste heat from electrical transformers, but the temperature of 35ºC is not suitable for the existing DH network temperature of 70ºC.

The main issue is that while transformer cooling is required in the summer, it is not needed in the winter. As a result, waste heat is generated in the summer, but the greatest demand for heat is in the winter.

A project for heat recovery from electrical transformers was already in place in Alytus, Lithuania, over 20 years ago. Waste heat from a 330 kW electrical transformer was used for substation space heating. The main issue is that 330 kW electrical transformers are located far from urban areas (cities and towns), limiting the usage of recovered heat to the ESO's own needs.

The primary barrier to 5GDHC implementation is that it will impair critical infrastructure reliability. It would be necessary to develop a new transformer technology that already has the capability of recovering excess heat. Another barrier is the fact that ESO is unable to sell heat due to regulatory restrictions. Under current regulations, 5GDHC's only option is to utilise waste heat from electrical transformers for its own needs.

ECO establishes technical requirements for transformers, which define the minimum and maximum heat loss. The table below shows the heat loss of a distribution transformer under various operating conditions.

Table 4.5. Transformer heat loss based on load factor [2].

Transformer power	**Heat loss, no load**	**Heat loss, maximum load**	**Approximate heat loss, 30% load**
25 MVA	≤ 12 kW	≤ 113 kW	~40 kW
40 MVA	≤ 19 kW	≤ 160 kW	~55 kW
63 MVA	≤ 30 kW	≤ 210 kW	~80 KW

Source: https://www.eso.lt/lt/eso-partneriams/elektros-partneriams/sutarciu-valdymas_1954/techniniai-reikalavimai/projektu-techniniai-reikalavimai.html#!cat11/topic38

Based on the transformer specifications and assuming a transformer load factor of 30% under normal operating conditions, distribution transformer heat loss ranges between 40 and 80 kW.

A transformer's normal operating temperature is between 35°C and 40°C. Fan cooling is activated when the temperature of the transformer's radiator hits 50°C, ensuring safe and reliable operation. The temperature of the transformer is highly dependent on the load factor and the ambient temperature. The operating temperature of the transformer can drop to 10°C in the winter if the load factor and ambient temperature are both low.

The transformer’s critical operating temperature is 70°C. This temperature must not be exceeded since it jeopardises the distribution network's reliability. Temperature sensors and cooling fans are used to prevent the transformer from exceeding the critical temperature. Under normal operating conditions, the load factor of a transformer can range from 20% to 50%.

The primary motivation for repurposing excess transformer heat is to save energy and protect the environment. However, using the transformer’s residual heat will not yield financial benefits. Because the heat loss from distribution network transformers are generally negligible, the question of whether utilising their excess heat has a financial benefit arises. The fact that a transformer is part of a critical grid infrastructure means that any changes to its operation must first be approved by the transformer manufacturer. Because ESO is a supplier of electricity and natural gas, there may be regulatory and legal issues with heat provision. The transformer's excess heat can only be used for the electrical substation's own needs.

4.4.4. Interview with a Shopping Centre

Molas shopping centre, Kaunas, Lithuania

Molas (K. Baršausko street 66a, Kaunas) is a shopping centre that opened in 2003. It is currently managed by the international property management company Newsec and is part of the Dutch private equity group Westerwijk Properties. Molas was renovated in 2016-2017, with a total investment of 3 million euros. It has a commercial area of 22,000 m^2. Today, there are more than 15 different businesses, 5 cafes and restaurants, and more than 50 different stores selling clothing, footwear, home decor, accessories, and other items.

Molas is heated via district heating networks (AB Kauno Energija). In the summer, the premises are cooled by local equipment. There are seven cold generators. The Molas representative claims that the 5th generation DHC is a cutting-edge technology with a bright future in the country, but he is unable to say whether there is a possibility of redesigning Molas facilities to remove disposable energy, such as heat in the summer from cold generators. The representative assumed that redesigning the network would be too expensive and economically unviable for the owner unless investors were interested in participating. The representative was unable to comment on the use of low-temperature heat from agents located in the vicinity of Molas and the management's other projects, as he did not yet have information about it. He speculated that the introduction of 5th generation DHC may be associated with many barriers, but was unable to explain it further. To get Molas and its management to adopt the technology and become a prosumer, a sister project should be involved in terms of payback, profitability, etc. In other cases, it can only be implemented if it is based on legal regulation.

4.4.5. Public Sector Interview

Kaunas University of Technology, Faculty of Electrical and Electronics Engineering, Department of Electrical Power Systems

The total area of the Faculty of Electrical and Electronics Engineering (KTU) building is 15,000 m^2, and it is connected to the district heating network. The building's annual heating expenses were around 80,000 euros, while its annual electricity expenses were around 50,000 euros. This situation changed drastically when, in 2019, solar power plants with an area of 5,500 m^2 were installed on the roof of the Faculty of Electrical and Electronic Engineering. The installed capacity of the solar power plant is 380 kW. The heating system was renovated by integrating a 180 kW water/water heat pump and 500 m^3 underground thermal energy storage facility.
Solar PV panels generate electricity which is needed to cool the KTU server room, producing excess heat during the cooling process. This heat is stored in an underground energy storage facility. The energy storage system was constructed to store geothermal energy generated during the summer. If there is still energy left over from the cooling process, the PV modules supply this energy to the heat pump. This is an example of a hybrid system, where the cold generated by the geothermal boiler is used to cool the servers; the heat generated by the servers is used to heat the buildings; excess heat is stored in an underground storage facility; and PV solar power generation is incorporated.

Solar power plants are expected to provide up to 20% of electricity and more than 50% of thermal energy, enough to heat 14,000 m^2 (two buildings) and cut CO_2 emissions by more than

6,000 tonnes over the course of 20 years. The system has been in use for two years. Heating costs have been reduced by 52% in the last year. Monitoring and measurements are currently underway, so it will be possible to assess the benefits of this system for KTU in the coming years. The payback period was estimated to be within 8 years when the project was being developed, but due to the large increase in energy prices following the COVID-19 outbreak, it may be shorter.

Because the installed innovative system is incapable of meeting the heat demand, the building is still connected to the district heating network. The district heating network also ensures system reliability.

Since energy is becoming more expensive, it is vital to consider how to meet the need for energy from other sources in order to remain competitive and efficient. This would be a solution for both large shopping malls and industries that waste heat instead of storing it and utilising it when it is needed throughout the year. The project's developers are confident that a similar approach can be used for many Lithuanian companies, but each project's solution is personalised and unique. There is no way to implement technology in a typical fashion. In the future, heating systems will feature many sources for waste heat utilisation and heavy integration of renewable energy sources.

The implemented project is an excellent example of the widespread use of renewable energy sources as well as the collaborative efforts of the scientific and business communities. The biggest issue throughout the project's implementation was determining the amount of waste heat generated by the server room and its mode of operation, which was difficult due to a lack of measurement data. The measurement data available will allow us to optimise the energy storage unit's operation. Data collection and monitoring are necessary to improve the system’s performance and provide information for new projects.Based on past experience, we can see that a 5GDHC system can only be implemented in new or renovated buildings with high energy efficiency.5GDHC systems are rather complex, incorporating a variety of technological options. For example, PV must be combined with heat pumps, and if energy storage is not possible, waste energy must be fed into the district heating network.This project piques the public's interest in novel energy-saving technologies and their application. The accumulated experience and knowledge will increase the competitiveness of Lithuanian enterprises. This innovative project, implemented at Kaunas University of Technology, received the Energy Globe Award in 2020.

Riga Municipality

In 2020, the total area of the Riga housing stock reached 20.1 million m2 or 33 m2 per capita. The volume has increased by 14% since 2012. The Riga housing stock makes up 26% of the country's total housing stock. The number of new apartments taken into operation has increased every year since 2010. In 2020, a total of 1,358 new apartments were taken into operation area of 133.6 thousand. m2 or 0.7% of the total area of the housing stock of that year.

The district heating of the city of Riga provides ~ 56% of the total heat demand in Riga, where 70% of consumers are housing and 30% are other users. The total amount of heat transferred to consumers in 2020 was 2756 GWh. In the city of Riga, district heating is provided by JSC “Rīgas siltums”, which in 2020 produced 32% of the total heat energy demand in the company's 39 automated boiler houses and 5 heating plants but purchased the remaining amount of heat energy from other companies.

The representative from Riga Municipality highlighted that the implementation of the 5th generation district heating solution should be beneficial in the areas where there is no well-developed existing district heating network. The Representative identified several newly built areas in the Riga suburbs where there are large shopping malls which would be suitable for ultra-low district heating. However, the economically justified connection of such areas to the existing higher temperature district heating system would be preferable to maintaining the existing infrastructure. It is crucial to analyse different possible alternatives for the areas and there could be districts where 5GDHC. The representative also stated that in the case of innovative heating solutions the consumers would be more motivated to follow the heat consumption and reduce it.

When answering the question about the municipality's role in future innovative heat supply the representative believes that the municipality should follow all the changes in the urban areas for individual and district heating solutions. In Riga city, there is the Energy Agency which approves requests for changes in heat supply. It recommends the most sustainable alternatives for heat sources in particular zones in the city and can advise also considering such innovative systems as 5GDHC. In future, the municipality could also try to advise the real estate companies to consider the utilisation of low-temperature sources.

As for now, the integration of waste heat into the existing district heating of Riga is not successful due to a lack of stability of such sources and the resistance of DH operators. Recently, there have been ideas about potential pilot projects for waste recovery in newly built areas but until now there are no successful innovative hat supply stores in Riga.

In conclusion, the representative highlights the necessity to analyse the case study and its suitability for the 5GDHC solution not to compete with the already well-developed infrastructure.

4.4.6. Interview with a Data Centre

Anonymous (Sweden)

A major concern for the data centre is the amount of waste heat that can be recovered. It may not be enough to meet the heating needs of a large number of residential buildings. In this case, using waste heat from the data centre next door instead of transferring it to the distribution network for other uses is the best solution. Due to the small amount of heat that can be recovered, the scalability of the 5GDHC may be low. They believe that it may only be suitable for smaller areas. Since cities are dense areas, that may be a possibility. However, most data centres are located outside of cities. Waste heat sources are frequently located outside of the city centre, and the amount of waste heat produced is insufficient to make it economically viable.

Swedish agents have also provided feedback on the barriers and the balance between identifying waste heat sources and collecting waste heat. Finding high-temperature waste heat is challenging, but collecting it is simple. While it is easy to find low-temperature waste heat, it is difficult to collect it. As a result, questions about how feasible, scalable, and cost-effective a 5GDHC system is arise. What is the best way to locate sources? How to collect the low-T waste heat in a cost-effective way? As a result, optimisation is required to establish the temperature level at which it is feasible. Another issue is that each agent uses heat pumps. The use of the network is questioned by a number of agents. Why not use heat sources with a temperature near to the ground temperature from the surrounding environment if the network's supply temperature is close to the ground temperature? The agents also mentioned that the application area is not clear, especially considering the different temperature needs. A single heat pump in a 5GDHC may not be able to meet different temperature needs (space heating and hot water). This isn't an issue for 4GDHC because the supply temperature can be used directly for space heating. It is not as clear in the case of 5GDHC. The economic benefits are also vague. How should the economic models account for the difference between large apartment buildings and villas? Should they be subject to different fees, heating and electricity costs? They have different needs and different levels of dependence on the network and system as a whole.

Regarding the motivation for the introduction of 5GDHC, both agents emphasised that there is no waste heat and no waste energy. This can save resources and increase profitability. Especially in the case of data centres, since they use money to buy electricity and produce waste heat. If waste heat can be used and profited from, this will greatly reduce operating costs.

Conclussions

The project goal was to evaluate technical and economic performance of the 5GDHC technology and explore the feasible applications of the 5GDHC in the Baltic and Nordic regions. The project has strengthen Baltic-Nordic knowledge in the areas of energy-efficient buildings and energy systems.

Firstly, the definition of 5GDHC was clarified and the differences between 4GDH and 5GDHC were brought out. The main difference is that the 5GDHC technology is geared towards consumers and there is only one thermal grid instead of separate heating and cooling netowrks. Heat pumps and waste heat sources are very important in 5GDHC concept. It is also important to state, that 5GDHC concept can be introduced only to new, energy-efficient building areas that are not yet connected to large thermal grids and it is not supposed, that 5GDHC will replace 4GDH or existing large-scale district heating systems.

Identification and mapping of possible available 5GDHC agents was the key activity to estimate technical potential of 5GDHC in the Baltic States, like operating temperature range, appropriate technologies and installed capacity.

Following 5GDHC agents have been evaluated: electric transformers, retail stores and data centres. Excess heat temperature level was in the range of 20-40°C. For all agents, the heat flow is available all year round continuosly, which makes it easy to use.

All information about available agents was gathered in a database and added to a GIS map. As a conclusion can be said about that retail stores are the most available agents as they are normally located near heat and cooling consumers, while data centres and electric substations are more often located further away from populated districts. According to calculations made within the project, the amount of usable excess heat was determined, resulting approximately 0.56 MWh/m^2 for Estonia, 0.55 MWh/m^2 for Latvia and 0.47 MWh/m^2 for Lithuania. In Estonia, total excess heat potential within DH networks is 1 184 GWh, in Latvia the potential is 1 051 GWh and in Lithuania 1 303 GWh. In most cases, the barriers for using the excess heat are non-technical and more related to business models and regulations.

The main drivers behind the implementation of 5GDHC and barriers that limit its development in Europe were summarized after the literature analysis and the possibility for 5GDHC introduction in the Baltic states was assessed using a multi-criteria analysis in order to quantify the main identified barriers and drivers behind the implementation of 5GDHC systems. The authors examined the three Baltic countries from a variety of angles, including possible competition with existing DH systems, power market sustainability, excess heat potential from different sources, and potential support policies. The criteria analyses showed that Estonia has a higher cumulative knowledge of HP usage, which is a closely related technology to 5GDHC. Due to the open heating market conditions in Lithuania, innovative business models that are crucial for 5GDHC systems are more likely to be implemented. Lithuania has the largest share of excess heat obtained from shopping malls (16% of total heat consumption), but Latvia has the highest share of excess heat obtained from electrical transformers (3%). The identified share of excess heat from data centres is relatively low in all three countries, peaking at 2% in Estonia. The highest score in the multi-criteria assessment was achieved by Lithuania due to support availability and open heating market conditions. When all applied criteria are weighted equally, Estonia has the most favourable conditions for 5GDHC systems due to widespread use of HPs and greater excess heat potential. The identified barriers and drivers can indicate directions for future efforts to implement the 5GHDC network and findings of the multi-criteria analysis can provide a solid foundation for the future 5GDHC modelling and feasibility studies.

The main barrier to the 5GDHC development in the Baltic States are well maintained and widespread high-temperature DH in all three countries. Based on that, it is assumed that the existing DH is the main competitor for implementing 5GDHC, another being individual heating and cooling solutions for every building. Compared to the existing DH, the new system could have lower operating costs and more possibilities for optimisation, which would significantly contribute to paying off the investments in countries with high salaries and expensive human resources workforce. However, both approaches interact with the same customers that 5GDHC implementers are trying to reach and the same suppliers since many technological needs will overlap.

Therefore, innovative business models are crucial in the districts where implementing the 5GDHC system would be beneficial. While the general technical principles are not changing in various business scenarios, the price for the customers can be significantly affected by them changing the cost balance. It is crucial to find the optimal model that would be interesting enough for the investors but at the same time would allow pressuring energy questions to be solved where it is needed the most – at the consumer level, especially where increased prices are contributing to the energy poverty.

The research identified three different business models for 5GDHC system implementation and highlights the role of each involved stakeholder. In each scenario, the system owner is the one who gets the funds and a large part of the income and carries the highest risks. While socially, it is the most beneficial for society to lower the price for the customers, lack of professional management is the weak point of the scenario that anticipates energy communities.

Scenario 1 implements that the operator owns the system. If that is an independent business, in case of forfeiture, it may quit the project without extra losses. Scenario 2 and Scenario 3 are organised by the players directly linked to the particular location, so they have fewer possibilities to quit, thus being more motivated to make changes to work. The main driver for the operator is financial gain, so it is interested in making prices as high as possible. The risk for the rural areas is that independent operators might choose any location for investments, meaning that there might be places where no investor is interested even if they have a good heat recovery and accumulating potential.

The performed cost and gain assessment shows that with all players considered, Scenario 2 is with lower costs, however, only if the prosumer is ready to administrate the system. Also, the energy community option would work in favour of everyone. Still, the previously mentioned administrative risks must be considered. The starting point of the decision tree and the consequence paths to the choice of the scenario depends on who was the initiator of the switch toward the 5GDHC. All possible loans and investments should be considered, preferably with the involvement of governmental and legislative techniques. Despite all efforts, the initiator could always be open to cancelling the project at any stage to avoid larger losses further on and effort justification bias.

Currently, it is difficult to predict how exactly the participation of prosumers in the market will go into account that in many countries, the existing market regulations forbid different heating tariffs. Prosumers might push for equal prices for heat and cooling, making heating more expensive than it could be.

Within the study, it is assumed that there will be no competition among various providers, such as various companies wanting to invest in the same location. However, the approach may become more favoured in the future. The implementation of the 5GDHC is likely to pay off if the heat tariffs and taxes of existing systems are high, meaning that those economic parameters are critical for balancing out the likelihood of the change of existing DH systems. Governmental subsidies and other kinds of support can significantly change the equilibrium.

Further research should analyse the application of proposed business models in real case studies to identify other benefits and barriers to 5GDHC system implementation.

In additiona a techno-economic analysis of a 5GDHC system has been conducted using a detailed thermo-hydraulic model of a small district in Tallinn. Analysis has shown, that the competitive advantage of 5GDHC increases if the electricity for HP operation can be obtained at a low cost and with the least amount of CO_2 emissions. Because of the grid's strong focus on renewable energy, electricity costs and emissions are expected to decrease significantly, which could benefit low-temperature heating networks.

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