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# Planning of district heating regions in Estonia

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**ABSTRACT**

It is quite evident that district heating (DH) networks will continue to be developed in order to complete their transition towards the 4th generation district heating by decreasing heat losses, increasing the share of renewable and waste heat sources, and integrating energy storage units and smart operating solutions. The significance of district heating in Estonia is very high, and developing this sector is very important for achieving climate and energy targets set by Estonia. Consumers play important role in the transition process, and for the purpose of informing and educating consumers, a district heating promo app has been implemented at the national level. One of the app's modules shows consumers the energy mix that will be required to supply heat via district heating in the future, with all of the planned changes and different district heating regions taken into account. Measures and goals proposed in the Estonian National Development Plan of the Energy Sector until 2030, as well as all available heating strategies from various district heating regions have also been considered. The algorithm of the methodology takes into account possible changes in heating demand caused by increased energy efficiency of the building sector, heat loss reduction due to renovation of existing DH networks and possible reduction of DH temperature, as well as increase in the share of renewable energy sources and its impact on primary energy consumption and $CO_2$ emissions in DH area. Scenarios show which fuel/primary energy mix is expected to be used for heat generation in the future (the data is given for each district heating region), as well as the amount of $CO_2$ emissions. Several typical case studies are also provided.

***Keywords:***

4GDH;
Energy planning;
Consumers;
Wood chips;
Heat loss;

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## 1. Introduction

The importance of district heating (DH) for the future decarbonisation of the energy sector is undeniable and has been widely discussed in various studies (e.g. [1,2]). This is due to various DH advantages, such as high energy efficiency of heat generation, ability to utilise renewable energy sources, and stable heat supply among others. In order to assess the level of decarbonisation of the energy sector that can be achieved through the implementation of DH, it is necessary to plan district heating systems (DHSs) both at the national and local levels. It should be noted that DH planning is required not only for new but also for existing DH networks.

One of the most detailed studies on DH planning is *Heat Roadmap Europe* [3], which discussed the possible future of DH in Europe. National heat roadmap scenarios have been developed for 14 countries. The results of these studies show that there is a potential for DH development both for countries with a higher share and a lower share of DH in terms of heating supply. The analysis determined that only in two of these countries (Sweden and Finland) the share of DH has reached recommended level required for the decarbonisation of the heating sector through the use of renewables, large heat pumps, excess heat, and cogeneration. But in countries such as Belgium, Italy, the UK, Germany, and the Netherlands, the potential

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for implementation of new DH networks is very high due to its rare use of DH in the past [4]. DH planning is very important for countries and regions where this sector is not developed because it provides the potential for the implementation of modern infrastructure and transition from individual heating to DH.

There is a variety of methods used in DH planning. Spatial modelling was used to analyse DH development potential, and various parameters have been determined, such as heat demand and density, transmission pipeline costs, and potential of renewable energy sources use, etc. [4]. GIS-based, deterministic mixed-integer linear programming superstructure model for the design of an entirely new DHS was presented and tested using the case of Northern Japan [5]. Another example of a spatial DH planning tool was used for the UK regions. This tool is based on the multi-criteria analysis, and it provides calculations of the three parameter groups: technical feasibility and economic viability, management, and potential for achieving social and environmental value [6]. The GIS-based method together with a simple scenario-based formulation created in accordance with heat investment decisions can also be used to plan certain segments of the DHS [7]. DH planning for urban areas can be done by analysing heat demand data using fuzzy logic and spatial mapping [8]. DH development planning aided by the implementation of support mechanisms (e.g., taxes, fees for each kWh of heat consumed) for end users who decided to be connected to a DH networks, as well as a guarantee fund for DH utilities in the Lombardy region (Italy) has been covered in [9]. The following parameters for 20 fossil and biomass-based DH networks (existing and potential) in this region have been calculated: primary energy savings and prevented emissions over the course of 20 years. Life Cycle Assessment methodology can be used to conduct a more detailed analysis on the environmental impact of renewing/modernising scenarios [10]. According to the results of the case study on DH created for a municipality in Latvia, there is a significant improvement in the environmental performance of DH due to the modernisation of the boiler house and subsequent temperature reduction.

DH supplies heat to more than 50% of residents in the following EU Member States: Denmark, Estonia, Finland, Latvia, Lithuania, Poland, and Sweden [11]. On the one hand, it means that the infrastructure and market is already there, and consumers have their DHSs installed and connected to the DH network. On the other hand, it sometimes means that the heating installations in the houses are quite old or designed for operation with existing parameter of DH networks which are in opposition with 4th generation DH network. In this case those consumers are not ready to have their homes connected to a modern DH network and it leads to various obstacles for the transition of the existing DHS into the modern DH network. It is important to understand how the DH network can be changed at the regional and national levels. There are various studies on DH planning for countries/regions where DH is already widely used.

Spatial modelling of the marginal extension of an existing DH network is covered in [12]. A mixed integer linear programming approach was used to simulate and optimise future energy centre operation by selecting the best combination of technologies to get maximum cost savings and minimum greenhouse gas emissions [12]. Another study was focused on demonstrating the possibilities of expanding DHSs using GIS software modelling for an in-depth analysis of a city's heat demand [13]. In effective heat supply radius study, the maximum effective heat supply radius at minimum cost price on production and distribution heat in DHS is determined, taking into account requirements to reliability heat supply to consumers. This approach helps to plan and evaluate connection of new consumers to the DHS [14]. Pakere et al., proposed the following steps for the DH planning process: 1. evaluate the overall DH system of the region/city; 2. identify the best transformation path; 3. select the appropriate district/area for the pilot case study which should be analysed in great detail [15]. Stennikov and Iakimets developed a methodology for DH planning, which consists of two stages, and validated this method using a case study of the DH system in Irkutsk (Russia). The first stage includes territorial zoning by heat supply type with designation of district and individual heating zones. And the second stage involves an assessment of the system's centralisation degree and validation of the existing heat source zones [16]. As part of the study on DH flexibility in Nordic countries, four types of DH plants were analysed (combined heat and power (CHP), electric boiler, wood chip boiler, oil boiler, and their combinations for sustainable DH development in these countries). Various scenarios and the impact of taxes, subsidies, and electricity and distribution (T&D) grid tariffs on DH development were simulated by applying hourly-based operation optimisation over a 20-year period using the EnergyPRO modelling software for DH systems in Finland, Sweden, Norway, and Denmark [2]. The goal of another research project was to examine how the existing system in Helsinki responds to the introduction of renewable heat sources (solar heating and heat pumps). The simulations covered 4 milestone years, i.e., 2014, 2018, 2024, and 2030, and helped the DH operator in their future planning [17].

Consumer awareness is crucial for DH development, which has been extensively discussed in previous study [18]. The key parameters that matter for consumers are the price of heat and heat production/transition impact on the environment. The dynamics of these parameters during the development process should be additionally evaluated. The following processes occur during the development and transition towards the 4$^{th}$ generation of DH systems: decrease in heat consumption, heat loss, and heat transition temperature. These processes lead to changes in heat generation.

The following modifications are possible:

- Reducing heat production and reducing or eliminating heat production using peak fossil fuel boilers (if fossil fuels based peak boilers were used before);
- Increasing the share of heat produced by base load heating plants. Base load heating plants often include biomass boilers, biomass CHP or waste incineration plants(if renewable fuels related base load boilers were used before);
- Introducing low-temperature heat sources.

Additional positive changes in heat generation efficiency are also possible, due to replacement of existing equipment by more efficient or installation of new additional energy efficient equipment such as flue gas condensers. The introduction of CHP and thermal energy storages will make heat production even more efficient [19,20]. Another way to alter heat generation is partial or full fossil fuel replacement with renewable energy sources, such as solar heat [21], heat pumps [22,23], and waste heat [24].

To estimate the share of energy sources and the amount of $CO_2$ emissions for DH heat production in the future, current DHS parameters and all of the abovementioned transition processes should be taken into account.

The main goal of this study was to develop an algorithm for the evaluation of parameters, such as the energy consumed by heat generation, consumption of fuels and the share of the fuels required for heat generation, and $CO_2$ emissions due to heat generation after possible transition to sustainable DH. These parameters should be calculated per consumed heat amount. The algorithm description is available in Section 3. This algorithm was used in planning the development possibilities of 146 Estonian DH regions covering about 85% of the total DHSs in Estonia. Examples and results of the algorithm application can be found in Section 4.

## 2. Background

DH is very common in Estonia. In 2018, DH took up around 60%. One of the reasons of its continuous growth is the support from the Estonian government. According to the 2016 amendments to the Estonian District Heating Act, local authorities are able to create 'district heating regions' (DHR) within their respective administrative territories [31]. DHRs are areas where consumers receive heat through DH. When a DHR is established, all buildings within the DHR must ask for connection to the DH network as a primary heat supply source (with the exception of the ones that did not have DH prior to and during the time the DHR was being established), so the consumers cannot choose an alternative heating source (if connection to DH network is technically feasible and accepted by DH company). This is a form of government support extended to DH. The amendments were aimed at providing heat producers with guarantees and additional motivation to expand the use of renewable sources, while reducing the use of fossil fuels (shale oil or natural gas). In addition, according to this Act, DH operators must strive to produce heat in the most efficient and cost-effective way to offer consumers a competitive final price.

It should be noted that Estonia is not the only country with this type of support measure. For instance, France has a DH zoning rule ("Procédure de classement des réseaux"). This rule, updated in 2012, allows local authorities to make connecting to the DH network mandatory for consumers under certain conditions and in a particular area, for any new or existing buildings undergoing major renovations and with a capacity of more than 30kW (heating, cooling, or domestic hot water), satisfying three conditions: the DH or DC grids get over 50% of their supply from renewable energy sources; appropriate energy metering devices are installed for each consumer; balanced business-model of the heating network [25].

According to Estonian District Heating Act and the Competition Act, the DH market in Estonia is regulated, and Estonian Competition Authority approves the maximum prices that can be charged in various regions [26]. The Environmental Investment Centre allocates funds provided by the European Regional Development Fund to finance the DH development plan for various regions [27]. There are 239 specific regions, but not all of them have DH, as some of the only plan to be connected to DH. Most of region authorities together with the experts in the field have already prepared heat supply development plans for their respective regions. Usually, this type of plan includes a detailed analysis of the current situation regarding consumers, the DH network, and heat generation units. Development scenarios were provided as part of the heat management development plan. Scenario modelling methods are often unclear and/or based on local authority/expert opinion, and there is no general method used for all plans, so the results of these analyses cannot be compared among each other.

The main development trends related to energy efficiency in Estonia include the renovation of the building sector, pipe renovation, replacement of fuel boilers with biomass boilers, and installing CHP where possible. This can be explained by both financial and political factors. The Environmental Investment Centre of Estonia supports the following actions related to DH: renovation of DH boilers and fuel replacement (74 projects); renovation of depreciated and inefficient piping (142 projects); preparation of the heat management development plans (120 projects). The amount of support received both from the European Regional Development Fund and the EU Cohesion Fund in 2007–2018 is more than 90 million euros, but the combined total with company contributions/self-financing, the investments into the abovementioned actions exceeds 200 million euros during the 2007–2018 period [27].

It was important for the authors to collect and analyse data on the DHR and evaluate both current and future state if DH is admitted as sustainable in particular region and if the development of this region continues. This data was used as input data for the mobile app promoting DH at the national level. The authors have developed a user-friendly mobile app to inform, educate, and provide DH consumers with approximate calculated parameters based on the real DHS input data. In accordance with the revised Renewable Energy Directive of the European Union, DH operators must inform their consumers about the energy sources used to produce heat, as well as the efficiency of the system. The mobile app was created as an easy to use solution for the new rule. As was widely discussed in the previous research paper, the main idea of this app is to demonstrate to the apartment/building owner that their apartment/building is a part of the DHS, let them know how much fuel is used to produce heat for that particular apartment, compare their current heating solution with the other heating supply solutions available, as well as educate them on the possible changes the DHS sustainable development will bring, including future changes to primary energy and $CO_2$ emissions. The method used for calculating the parameters reflecting the current situation in DHRs was extensively covered in previous study [18], and the calculation of the future development parameters was briefly presented. However, the analysis was performed for the three DH regions, and the analysis of future development was conducted for each individual region based on the opinions of experts and DH operators. This approach can be used to analyse small amount of regions, but a more general approach is required for the analysis of a larger group. The purpose of this research project was to develop a general approach that can be used to analyse future developments and changes in the structure of primary energy, changes in quantities, as well as reduction in $CO_2$ emissions in various DHRs.

The analysis began with data collection. The data was collected from heat management development plans, as well as directly from the DH operators. As a result, 146 DHRs were analysed. These regions cover about 85% by heat generation of all existing DH networks in Estonia. The main characteristics of the analysed DHRs are given in Table 1.

**Table 1: Characteristics of analysed DHRs**

| Characteristics | | Number of regions |
|---|---|---|
| Length | <1,000m | 40 |
| | 1,000m–10,000m | 85 |
| | >10,000m | 21 |
| Pre-insulated pipes | <20% | 36 |
| | 20%–50% | 27 |
| | 50%–80% | 35 |
| | >80% | 48 |
| Share of renewable sources | 0% | 31 |
| | <80% | 8 |
| | 80%–95% | 16 |
| | 95%–99% | 32 |
| | 100% | 59 |

## 3. Decision algorithm

There are various options for DH system development, and for each system, many scenarios of future development can be simulated. It is intended that the mobile app will provide parameters for only one scenario. This scenario should reflect the best-practice option, taking into account the conditions that are specific to Estonia. The following parameters will illustrate the current and future state of the DHR: fuels/primary energy used for heat production and transmission, heat consumption by a particular apartment/building by type of energy and $CO_2$ emissions generated during current heat production. For these purposes, relative parameters must be determined, which means that fuel/energy is used per 1 MWh of heat consumed. Analysis includes changes' evaluation in heat consumption, transition and generation sector and starts with consumer side.

### 3.1. Changes in heat consumption

The share of fuels used for heat generation may change. This is valid for conditions where DH production units will stay the same. Lowered heat consumption will reduce the needs for peak load boilers (mainly use gas or fuel oil) and in some cases will allow avoiding use of peak boilers and vice versa.

There are two main factors that can affect heat consumption in DHRs: a reduction in heat consumption through energy efficiency measures in the buildings, and an increase in heat consumption due to the addition of new consumers to the DH network.

The amount of heat consumed by a building can be significantly reduced through energy efficiency measures [28]. The Estonian government has announced the minimum energy efficiency requirements for buildings, and all new buildings must comply with these requirements. The type of building determines how much primary energy it can consume per year per 1m$^2$ of heated area. There are also regulations concerning renovated houses, meaning that renovated houses must also meet energy efficiency requirements [29] Due to the renovation of older buildings in some DHRs (where construction of new buildings is negligible) the demand for heat has decreased, as did heat demand density. This leads to the possibility that some DHNs may stop being profitable due to low heat demand, unless new consumers are added to the network [30]. Despite the fact that more energy-efficient houses that use low-temperature heating help reduce primary energy use and grid losses, it is still necessary to reach 55˚C in domestic hot water to prevent Legionella growth and spread [31].

According to the assessment of the age of the building stock and current state of DH in Estonia, and according to the Estonian Energy Development Plan, upgrading the building stock and increasing the efficiency of heat consumption can lead to a 30% reduction in DH sales by 2030, compared to 2010, as building heat consumption will decrease by 30% [26]. This is possible due to two trends: renovation of existing buildings to increase their energy efficiency and replacement of existing buildings with new energy-efficient ones.

But, on the other hand, heat demand can be increased by adding new consumers to the network. First of all, new consumers are getting connected due to the District Heating Act, if their house is located in the DH. Another factor is the renewal of the housing stock, which is estimated from 1% to 2% per year. It should be noted that the main investments in this sector are made in largest cities, as an example in Tallinn and Tartu. On the other hand, the share of historic buildings is significant in these cities, and in many cases the possibilities of implementing energy efficiency measures in historic buildings are limited because external wall insulation is not possible due to historic preservation or other restrictions [32,33]. The tempo of renovation is significantly depends on renovation grants. For the last years the budget to support renovation is significantly reduced and previously mentioned heat reduction tempos may not be achieved. To evaluate the reduction in heat consumption, both actual and potential heat consumers were taken into account. We conservatively assume that this parameter varies for different DH regions and on average is about 20%.

### 3.2. Changes in heat distribution

For the analysis of the current heat transmission system, the following data were collected for each DH region: annual relative heat losses, length and average diameter of the networks, the share of pre-insulated pipes, supply and return temperatures, and annual outside temperature duration curve for the region.

As part of the heat distribution improvement, there are two measures that can reduce heat loss: piping renovation and decrease in DH network temperature level. These changes will lead to alterations to the amounts of fuels used, heat generated and structure of fuel mix in the heat generation process. For example, in a Helsinki case study, it was determined that after reducing heat supply and return temperature, the share of renewable sources increases [17].

The first action is pipe renovation/replacement. As mentioned earlier, it is possible to apply for 50% co-financing by the Environmental Investment Centre. Many DH operators have already renovated their piping (see Table 1), and many pipes will be renovated or replaced with pre-insulated pipes in the near future.

For further calculations, it is important to determine relative heat loss in DH network in the future. A study by Mašatin et al. examined how various factors affect heat losses in DH network [34]. According to this analysis, relative heat losses can be calculated by Eq. (1):

$$Q_{hl} = K \cdot \pi \cdot D_a \cdot 2L \cdot G \tag{1}$$

where

$K$ is effective average heat transfer coefficient of the network, W/m$^2$K

$D_a$ is average diameter of pipes, m

$L$ is pipes length, m

$G$ is the difference between heat supply and heat return and is calculated by Eq. (2), ˚C

$$G = \left(\frac{1}{2}\left(t_s + t_r\right) - t_{amb}\right) \cdot 8760 \tag{2}$$

where

$t_s$ is supply temperature, ˚C

$t_r$ is return temperature, ˚C

$t_{amb}$ is ambient temperature, ˚C

Based on the Eq. (1), it can be seen that heat loss is affected by both the overall network heat transmission and the temperatures in the network, i.e. a decrease in temperature will lead to heat loss reduction due to the lower temperature gradient between the heat supply carrier and the environment where DH network is located. Coefficients received in the previous research will be used for further calculations [34]. The high-quality technical reference conditions are defined as pre-insulated pipes class 2, buried in soil at 0.5 m depth using the calculation methodology according to European standart EN13941. The low-quality technical reference conditions are defined as old channel layout pipes with 50 mm mineral wool insulation. Based on calculation following coefficient has been determined for pipes before the renovation/replacement (see Eq. (3)).

$$K_{low} = 0.7676 \cdot D_a^{-0.341} \tag{3}$$

where $K_{low}$ is effective average heat transfer coefficient of the low quality DH network, W/m$^2$K

and for pipes after renovation, the coefficient is calculated as Eq. (4)

$$K_{high} = 0.1088 \cdot D_a^{-0.619} \tag{4}$$

where $K_{high}$ is effective average heat transfer coefficient of the higher quality DH network, W/m$^2$K.

Heat losses for high-quality pre-insulated pipes can be calculated by Eq. (5).

$$Q_{hl_{high}} = \frac{K_{high}}{K_{low}} Q_{hl_{low}} = 0.1417 \cdot D_a^{-0.278} \cdot Q_{hl_{low}} \tag{5}$$

Heat losses in the network, when share of pre-insulated pipes is $s_{pre}$ can be calculated by Eq. (6).

$$\begin{aligned} Q_{hl_{current}} &= s_{pre} \cdot Q_{hl_{high}} + \left(1 - s_{pre}\right) \cdot Q_{hl_{low}} \\ &= Q_{hl_{low}}\left(s_{pre} \cdot 0.1417 \cdot D_a^{-0.278} + 1 - s_{pre}\right) \end{aligned} \tag{6}$$

where

$s_{pre}$ is share of pre-insulated pipes in the network, (0…1)

After all pipes are renovated heat losses can be calculated by Eq. (7)

$$Q_{hl_{future}} = 1 \cdot Q_{hl_{high}} = 0.1417 \cdot D_a^{-0.278} \cdot Q_{hl_{low}} \tag{7}$$

If not all pipes have already been replaced with pre-insulated pipes, heat losses after replacing all pipes is calculated as

$$Q_{hl_{future}} = \frac{0.1417 \cdot D_a^{-0.278} Q_{hl,current}}{s_{pre} \cdot 0.1417 \cdot D_a^{-0.278} + 1 - s_{pre}} \tag{8}$$

A decrease of the network's supply and return temperatures will result in an additional heat loss reduction, which can be attributed to the entire system. An equation showing how heat losses will be reduced due to the complete pipe replacement and decrease in temperature is as follows Eq. (9):

$$Q_{renov\&low\,temp} = \frac{0.1417 \cdot D_a^{-0.278} Q_{hl,current}}{s_{pre} \cdot 0.1417 \cdot D_a^{-0.278} + 1 - s_{pre}} \frac{\left(t_{a\,low\,temp} - t_{amb}\right)}{\left(t_a - t_{amb}\right)} \tag{9}$$

where

$t_a$ is average temperature between supply temperature $t_s$ and return temperature $t_r$ before temperature lowering, ˚C

$t_{a,low\ temp}$ is average temperature between supply temperature $t_s$ and return temperature $t_r$ after temperature lowering, ˚C

As for the Estonian regions, the average heating period temperature can vary from 46.5˚C to 66.5˚C it is assumed that in the future the average temperature will be reduced by 7˚C.

When analysing the DH system in Estonia, it should be noted that there are various supply and return temperatures in DHRs. Temperature level depends on heat capacity, consumers, length of pipes. Usually in small DHN supply temperature of 70˚C and return temperature of 50–55 ˚C is applied. Medium DH networks that are longer than 1,000 m but do not exceed 10,000 m usually have temperature of 80/60˚C. And large networks exceeding 10,000 m have supply and return temperatures are 95/65 ˚C up to 115/65 ˚C.

To calculate heat loss reduction, two assumptions were made:

1. After the renovation, 100% of the pipes are replaced with high-quality pre-insulated pipes.
2. The average temperature will be reduced by 7˚C.

It should be mentioned, that these assumptions can lead to inaccurate results, since some of the existing pipes, which are not pre-insulated, already have a sufficiently high quality and low heat losses, while existing pre-insulated pipes can be quite old and have a higher heat transfer coefficient. In addition, due to optimisation of existing pipes the size of the new pipes may be corrected (in majority of cases reduced due to decrease in energy consumption in the regions), and the average diameter after renovation may differ in comparison to existing pipes which need renovation. Despite these shortcomings, this method can still provide an overall rough result, which can determine the ways the DHR can improve.

### 3.3. Changes in heat generation

As was mentioned above, changes in distribution and consumption will lead to changes in heat generation without any modification within energy production units. This will happen due to changes in consumption profile. To analyse those impacts a heat load duration curves were created for each DHR and for different options described below.

The degree-day approach was used to plot the heat duration curve. Six Estonian regions with varying degree days diverse enough to represent the whole country were identified based on the research conducted by Loigu and Kõiv [35].To determine the heat duration curve it was assumed that when the average daily outdoor temperature is above 10˚C, there is no need for space heating in the building. Primary energy consumption in DHR will be reduced by reducing the amount of heat that must be generated. Another factor that can lead to primary energy reduction is an increase in generation efficiency due to the replacement of the existing equipment with a more efficient ones or transition to more environmental friendly or/and cheap fuels/energies. As for the fuel type used to generate heat, usually a decrease in heat production leads to an increase in the share of renewable energy sources. Renewable fuels (biomass) are mainly used to

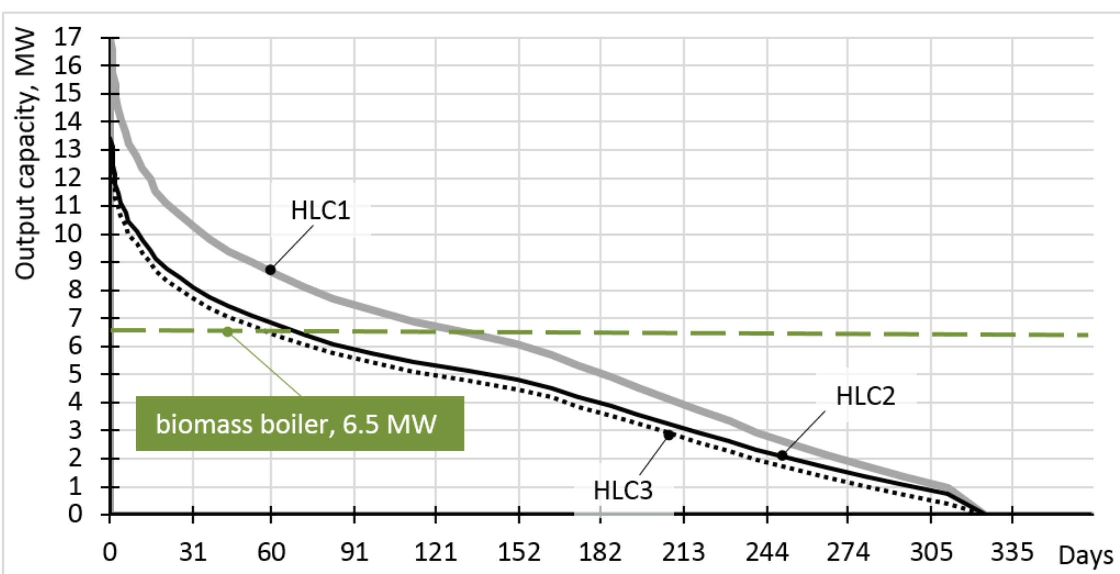


Figure 1: Heat production duration curve changes

cover base load and reduction in energy production will result an increase in the share of renewables. To illustrate that the following heat production duration curves (HLC) are constructed (Figure 1):

- HLC1 – Current situation. Biomass boiler (6.5 MW) produces 83% of the all energy.
- HLC2 – Heat consumption reduced by 20%.
- HLC3 – Heat consumption reduced by 20%, relative heat losses in DH network reduced from 17% to 11% and DH network temperature is reduced by 7˚C.

According to this analysis the share of renewable energy has increased from 83% till 91.7% after heat consumption reduction and till 92.4% after improvements in the networks.

Due to the fact that currently the main source of renewable energy used in heat production at the DH plants in Estonia is biomass (mainly wood chips) and biomass is proposed as a main fuel to replace natural gas and shale oil in heat management development plans, the decision was made to focus on one, the most viable for sustainable DH development in Estonia renewable energy source, i.e. wood chips.

After the final required amount of generated heat is determined, possibilities to expand the share of renewable energy sources are analysed. General decision-making principles regarding the replacement of existing fossil fuels based generation plants with new plants used in mobile app is shown in Table 2. It should be noted that the main peak/reserve fuel used in Estonia is shale oil [36]. Shale oil is extracted from local fossil fuel oil shale via the process of pyrolysis [37,38].

As can be seen in Table 2, after a decrease in heat generation, if the share of renewable fuel exceeds 95%, and the share of fossil fuel is 5% or less, it is expected that significant share of biofuel is already reached and additional investment is not feasible (this boiler will work for some days per year only).

It should also be mentioned that there are few exceptions from the main trend in biomass consumption for base load production.

First of all, there are regions where peat is the main fuel used in heat production. Peat is not considered renewable, but it is a local fuel, and it helps to keep some technical issues (positive impact of peat ash on lining of the boiler). As it is a local fuel, its price is more stable than that of imported fuel. In DHSs that use peat as fuel, the price of heat is usually lower than the Estonian average [26]. There are regions where DH operators are also involved in peat extraction and peat product manufacture, at the same time providing heat to nearby DH systems. In these regions, heat plants are modern and energy-efficient, and replacing peat boilers with wood chip boilers is simply not feasible. There are 7 regions that use peat in heat generation. In addition it should be noted, that there are in some places peat boilers suitable to work with biomass as well.

**Table 2: Fossil fuel replacement strategy**

| | | |
|---|---|---|
| Biomass boiler efficiency | <85% | Replace with a boiler with an 87% efficiency |
| | >85% | Are as efficient |
| Share of renewable energy sources | <95% | Non-renewable fuel is replaced with wood chips |
| | >95% | No modifications expected |

In other group of DHRs, industrial waste heat is utilized. Heat is generated as a by-product during production process [39]. Oil shale gases are generated during the shale oil production process, which are then transferred to the waste gas boiler. The heat from those boilers is used in efficient way and for DH. Another case has to do with two DHRs where biogas is the main fuel, and there are no plans to replace biogas boilers with wood chip boilers. In addition, there is one DHR where the source of heat is waste heat from a power plant [40].

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## 4. Results

There are five different type DHR examples are presented in Figure 2. The key parameter for all scenarios is fuel consumption per unit of heat consumed ($MWh_f/MWh_c$).

Five scenarios are shown:

a- current state;
b- decrease in consumption;
c- decrease in consumption and heat loss;
d- decrease in consumption, and heat loss, and increase in efficiency (if applicable);
e- decrease in consumption and heat loss, increase in efficiency (if applicable), and fuel replacement, (if needed).

1st example illustrates the DHR, where the share of renewable energy is high. It can be seen, that a decrease in heat consumption led to an increase in the share of wood chips. For scenario c, fuel consumption is reduced. If it is possible to increase the efficiency of heat generation, fuel consumption is reduced even more. According to Table 3, fossil fuel is not replaced with wood chips in this case. 2nd

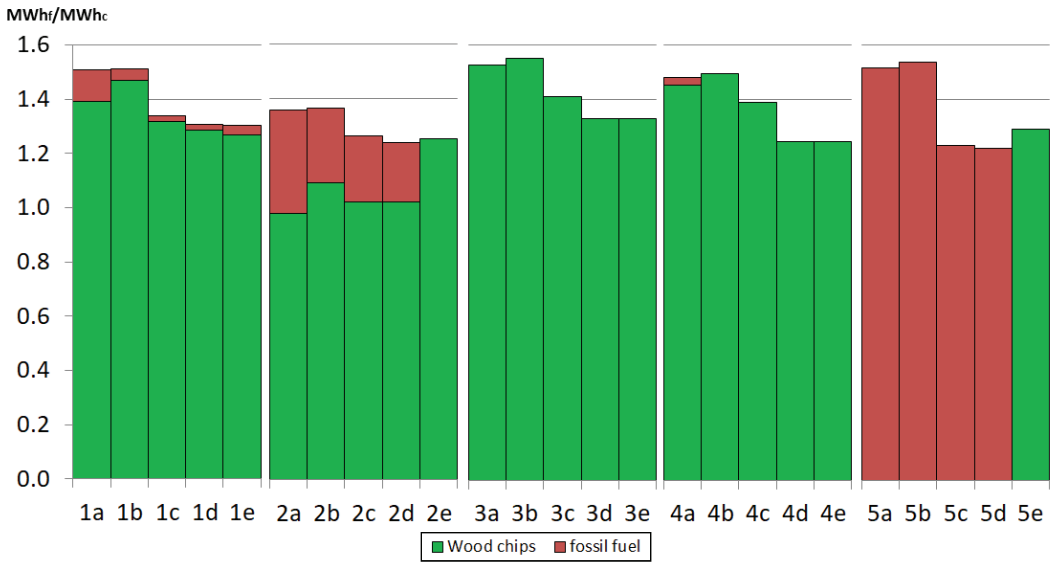


Figure 2: Scenarios for relative fuel consumption for heat generation in various DHRs

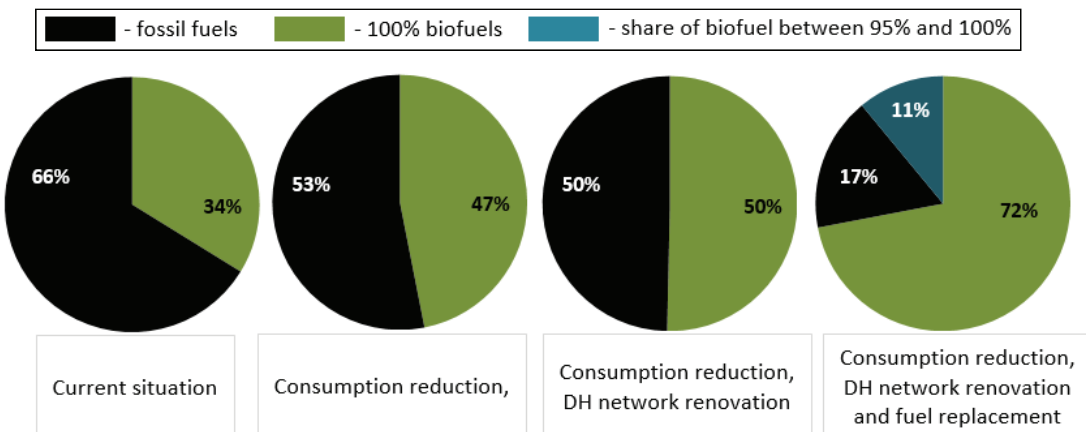


Figure 3: Share of carbon-neutral DHR

example demonstrates calculation results for a type of DHR that is similar to the 1st example (peak load is covered by fossil fuels); the difference is that it is reasonable to replace fossil fuel with wood chips. 3rd example illustrates calculation results for a different type of DHR. The amount of fuel is reduced due to DHR improvements. Because of the fact that this region is already RES-based, there is no change in fuel mix. 4th example demonstrates the situation, when, due to the improvements in the consumption sector, there is no need for peak fossil fuel boilers. In the case when heat is produced only using fossil fuel, as in 5th example, improving the system leads to a decrease in fuel consumption. Usually, these boilers are completely replaced with wood chip boilers.

District heating in Estonia is in the process of transitioning to the 4th generation district heating. Many heating plants have already been replaced with efficient biomass-based boilers and CHPs. Different types of DHS component modernisation and its impact on reducing $CO_2$ emissions were analysed. For a segment of Estonia's DHS, a significant reduction in $CO_2$ emissions is possible due to the decrease in heat loss achieved via pipe renovation. For another segment of the DHS, the most significant reduction in $CO_2$ emissions can be achieved by boiler modernisation and fuel replacement. In previous studies, the greatest positive effect was obtained through boiler modernisation [10,41], but it should be noted that these results largely depend on the current state of the boilers and networks of the analysed DHS.

The Figure 3 shows the case with Estonian DHRs.

As can be seen, at the moment, 34% of DHRs are already carbon-neutral. In case of planned consumption reduction the share will increase to 47%. A decrease in consumption along with loss reduction will result in half of the DHRs being carbon-neutral. If all of the above options are implemented, 72% of DHRs will be completely carbon-free. Moreover, 11% are the regions where the annual share of renewable energy sources will exceed 95%.

## 5. Conclusions

When designing a DHR, an integrated approach is needed that takes into account possible changes and improvements in consumption, distribution, and generation sectors.

This study was conducted to propose an algorithm to predict possible state of 146 Estonian DHRs of different size, length, capacity, and primary energy structure after more probable transitions to sustainable DH state and provide trial calculations. It was assumed that in general, according to planning documents and targets in energy efficiency of the buildings heat consumption would be reduced due to renovation and implementation of energy efficiency measures in the building sector: in some cases the growth in energy consumption may take place due to possible new consumers. The evaluation of heat loss reduction was based on the assumption that in the near future all old pipes will be replaced with high-quality pre-insulated pipes, and it will be possible to reduce supply and return temperature in average by 7 ˚C. In some cases, a decrease in heat consumption in both building and network sectors can make the DH region carbon-neutral without any change on heat production side. If, after all these improvements, the share of non-renewable energy in heat generation is still high enough, fossil fuels can be replaced with renewable energy sources. There are exceptions included in this analysis. First of all, when the share of fossil fuels is very low, it was decided that these peak/reserve fossil fuels based boilers will not be replaced, because in such cases installing new renewable fuel-based boilers with a low energy production is simply not feasible. Another exception is related to a current situation where waste heat from electricity production or shale oil production is utilized in DH. Another example specific to Estonia and which is still used in some places is usage of peat with biomass or purely peat consumption. In some cases the peat is used as additive to biomass to improve the lifetime of lining or due to lower price in comparison to biomass.

Wood firing was chosen as the priority option for sustainable DH in Estonia. Even before any improvements have been made, more than 1/3 of DHRs in Estonia are already carbon-neutral. After all measures have been implemented, this share may increase up to 72%.

Based on the data collected for the mobile app, and the existing state, a generalised approach was developed to calculate the parameters necessary for the future scenario module of the mobile app promoting DH.

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