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District Cooling Network Planning. A Case Study of Tallinn

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ABSTRACT

The planning procedure for district cooling as an urban system was described and implemented using the example of the city centre of Tallinn. The following steps were described in detail: determining cooling demand, planning cold supply and analysing cold water distribution. Based on the three proposed methods (average specific cooling load, satellite imagery analysis of a specific building, dry cooler fan counting, and the combination method), the cooling capacity of the evaluated district was estimated at 63.2 MW. In terms of cold supply, the analysis showed that free cooling with seawater can cover up to 55% of the annual cooling demand. Electric chillers and absorption chillers that use excess heat can cover the rest of the district's cooling demand. The district cooling network was designed for three scenarios: single generating unit, two generating units and a looped network. Despite the fact that the looped network is the most expensive option, it is deemed feasible as it simplifies the connection of new consumers.

Keywords

Energy planning;
District heating;
District cooling;
Free cooling.

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1. Introduction

To achieve the European Union's (EU) goal of reducing greenhouse gas emissions, the energy system must undergo significant changes and overcome major challenges. In the EU, heating and cooling needs account for about 50% of final energy consumption [1]. Mathiesen et al. [2] emphasised that increasing the share of district heating (DH) and district cooling (DC) would help achieve the EU climate objectives at minimal cost. According to the International Energy Agency's (IEA) 2018 Global Energy and CO_2 Status Report, cooling needs have increased due to changing weather conditions and hotter summers [3]. The number of hot days in Europe will increase by 4%, according to [4] Furthermore, cooling needs are often unmeasured and the information available is limited [5]. Various studies highlight that DC systems are a very efficient way to provide cooling [6].

The district cooling network is considered as an integral part of the smart energy system [7], as well as the 4th generation district heating system [8].

Every year, the field of district cooling becomes more and more important. Buildings are usually cooled with local cooling units, but district cooling can provide more sustainable solutions. Compared to local cooling solutions, district cooling can use a variety of cold resources, including natural free cooling resources. District cooling may benefit from economies of scale and provide consumers with more cost-effective solutions, as opposed to local cooling solutions. In the Nordic countries (Sweden and Denmark), district cooling is very popular and well-established [9,10]. In Estonia, the district cooling system is still under development. Tartu and Pärnu have established district cooling networks, whereas Tallinn is presently developing the technology. Two consumers

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have already been connected to the network, and new pipelines and generating facilities are being designed and engineered.

In the case of district cooling, the refrigerant cooled by the central cooling system is distributed to consumers (typically office buildings, hotels and other buildings) via the district cooling network.

The district cooling system consists of three key components: the district cooling production plant, the cooling network, and the consumers connected to the cooling system. The cooling medium can be cooled centrally via the following methods:

- absorption chillers that use excess heat to produce cold (e.g. excess heat from district heating cogeneration plants);
- electric compressor chillers;
- natural sources or free cooling.

District cooling can be a cost-effective solution under the right circumstances, namely in large cities with a lot of buildings that require cooling. Furthermore, because different types of buildings have different cooling needs, district cooling becomes even more cost-effective, making the centralised supply of cold generation of central cooling energy even more efficient. The advantages of district cooling, such as improved cooling quality, space saving, and the absence of sound pollution, should also be mentioned [11].

Free cooling from local natural cold resources can be used for district cooling. Examples of natural cold resources sources include rivers, lakes, and seas. Seawater district cooling is also referred to as seawater air conditioning (SWAC) [12]. There are two types of SWAC: deep, where the seawater temperature is consistently below 5°C, and shallow SWAC, where the seawater temperature is dependent on the outside temperature. In the case of deep SWAC, free cooling can be utilised without any backup measures, but in the case of shallow SWAC, free cooling via seawater can only cover a portion of the district cooling load, necessitating the use of additional sources such as compressor chillers [12,13]. Examples of DC systems integrated with natural cold resources include the DC system in Stockholm (Sweden), which uses cold water from the Baltic Sea; the DC system in Paris (France), which uses water from the Seine River for 100% free cooling at water temperatures of 8°C or lower [14]; the DC system in Tartu (Estonia) that uses water from Emajõgi river [15]; the DC system in Toronto (Canada) that uses deep lake water from 83 m below the surface [16]; the DC system in Goteborg (Sweden), which uses cold water from free cooling from Göta Älv [17]. In the Netherlands, natural sources such as underground aquifers and lakes can be used as potential cooling sources [18].

A district cooling network is similar to a district heating network in that it has one supply pipe and one return pipe, but instead of hot water, the system circulates cold water. The supply temperature is typically 4-7°C [19,20], but a 0°C mixture of water and ice is occasionally used [21]. The supply temperature depends on the needs of the consumers and is limited by the performance of the district cooling plant and the network parameters of the district cooling system. The cost-effectiveness of district cooling largely depends on the difference in supply and return temperatures. The cold water supply for consumers is heated by cooling the air in the ventilation system of buildings or during some kind of industrial process. The temperature in the return pipe is usually between 12 and 17°C [20,22]. The return water is pumped back to the district cooling plant, where it is cooled again.

District cooling systems never cover the entire city. Because the temperature difference between the supply and return flows is insignificant, transferring cooling energy is expensive, since the flow of refrigerant transferred for the required cooling capacity is large and requires pipes of a much larger diameter than in a district heating network of the same capacity. Thus, the district cooling network is usually used only in urban areas with high cooling density, such as city centres and business districts. Heat pumps, absorption chillers, and thermal energy storage can all be integrated into district heating and cooling systems [23].

There are two viable options for connecting district heating and cooling systems. A heat pump evaporator can be used for cooling in a district cooling system while simultaneously producing heat in the district heating system [24]. Another option is to use summer excess heat from combined heat and power (CHP) plants to produce cold via absorption chillers [25–27]. This is a good solution, as the CHP plants would otherwise have to be shut down due to the lack of summer heat load.

The Nordic countries (Sweden, Denmark and Finland) provide the most notable examples of successful district cooling implementation [28]. This is due to an increase in cooling demand in recent decades as a result of climate change, as well as a large and well-developed district heating infrastructure, which makes consumers more reliant on district energy supply.

In Finland, the development of district cooling began in 1998, when the first district cooling network was launched in Helsinki [29], followed by other cities. The annual sales of cold via the district cooling network and the associated capacity have only increased since the first network was introduced. The temperature of the water in the district cooling supply pipelines in Finland varies depending on the network and the time of year, but it is normally in the range of 6-8°C, and the temperature difference between the supply and return pipes is about 8-10°C [29].

Around 30 years ago, Sweden began its attempts to develop district cooling [9,30]. In 1992, the first Swedish district cooling system was launched in Västerås, inspired by the US district cooling experience. Larger district cooling systems are located in Stockholm, Gothenburg, Linköping, Solna-Sundbyberg, Lund and Uppsala. The 2014 national district cooling statistics covered systems in 40 urban areas with a total of 3.6 PJ of cooling supply, indicating that the cold supply for district cooling and the cooling demand are much lower than for district heating. Since 2000, the average annual growth rate has been 8% [31].

Future district heating and cooling (DHC) networks will be quite complex, including both free cooling and excess heat conversion capabilities. However, despite all these features, district cooling poses many challenges.

The transition of existing urban district heating and cooling systems from fossil fuels to renewable energy sources for municipalities in Southern Europe was studied in Ref. [32]. In Ref. [33], the performance of the new district's cooling system was evaluated during the planning phase of a new Hong Kong development area. Based on this assessment, district cooling has been found to be more efficient than individual cooling systems. Various studies have discussed that proper planning of district cooling systems is essential [6,34–36].

District cooling is a relatively new concept in Estonia. There are examples of district cooling based, in part, on free cooling from natural sources, e.g. rivers (Pärnu and Tartu), as well as district cooling based on compressor chillers (Tallinn) [25]. Despite the fact that Tallinn, the country's most populous city, is located by the sea, there are no examples of seawater-based district cooling in Estonia. The main goal of this paper is to show, how planning the implementation of district cooling in urban areas without existing district cooling systems can be realised, based on the availability of free natural cold resources. It is vital to consider several variables connected to cold production, district cooling demand, and distribution when establishing a fully new district cooling network, especially if it is planned in a city with an established infrastructure. The purpose of this paper is to describe the planning process for a district cooling network, with a step by step focus on each element of the network, based on the experience of implementing the cooling network in Tallinn. The description of the process can be further applied to the development of district cooling networks in other cities. The second part of the article presents simplified methods for identifying potential consumers, producers, and network layout. To use these methods, only a small amount of publicly available initial data is needed. The third section presents the results of the application of these methods to the case study of the city of Tallinn. The fourth section contains a discussion, which includes a review of Tallinn-specific details. Conclusions are presented at the end of the article.

2. Methodology for Urban District Cooling Planning

Energy conversion (from fuel to electricity, electricity to cold, fuel to heat, heat to cold, and so on), energy distribution, and energy demand (cooling demand, heating demand and power demand) are all factors in the planning of each energy system. Typically, power and district heating networks must be partially planned when connecting new consumers or installing a new generating unit. However, in the case of district cooling, particularly in countries with cold climates, where there was previously no district cooling infrastructure, the system must be built from the ground up. In this case, planning for a district cooling system consists of determining the cooling demand, planning the cold supply, and analysing the cooling network. In addition, the energy efficiency of the system must be assessed. The Method section presents the planning steps that can be carried out based on the DC implementation experience in a Northern European city.

2.1. District cooling demand estimation

District cooling demand estimation should start with identifying potential areas with high cooling demand. Non-residential buildings might be considered district cooling consumers in countries with cold climates due to present conditions. Regions with a low proportion of non-residential buildings and a high proportion of office buildings, malls and public buildings have a high potential for introducing district cooling. Therefore, a cooling density map cannot be used to determine the district cooling potential in Tallinn. Non-residential heat density can indirectly aid in the identification of locations with a higher concentration of non-residential buildings. In addition, district heating consumer data stored by district heating operators can help identify areas with higher potential for district cooling connection, as these data include information on building type, area, and heat demand profile.

Figure 1 shows the cooling density map (see Figure 1a) and the heating density map (see Figure 1b) for the non-residential sector.

A detailed analysis showed that the yellow area on the right (Figure 1a) contains a dense concentration of residential apartment buildings, as well as non-residential buildings with low cooling demand (warehouses, workshops, and production facilities). According to the detailed analysis, there are three potential district cooling areas in Tallinn (Figure 1c).

It is critical to determine the cooling demand for each region after identifying the most promising regions based on cooling density, indirect heating density, and a detailed analysis of potential locations. The main tasks of cooling in a building are to keep the room temperature low enough for people to feel comfortable and to keep the relative humidity low enough to avoid chilled

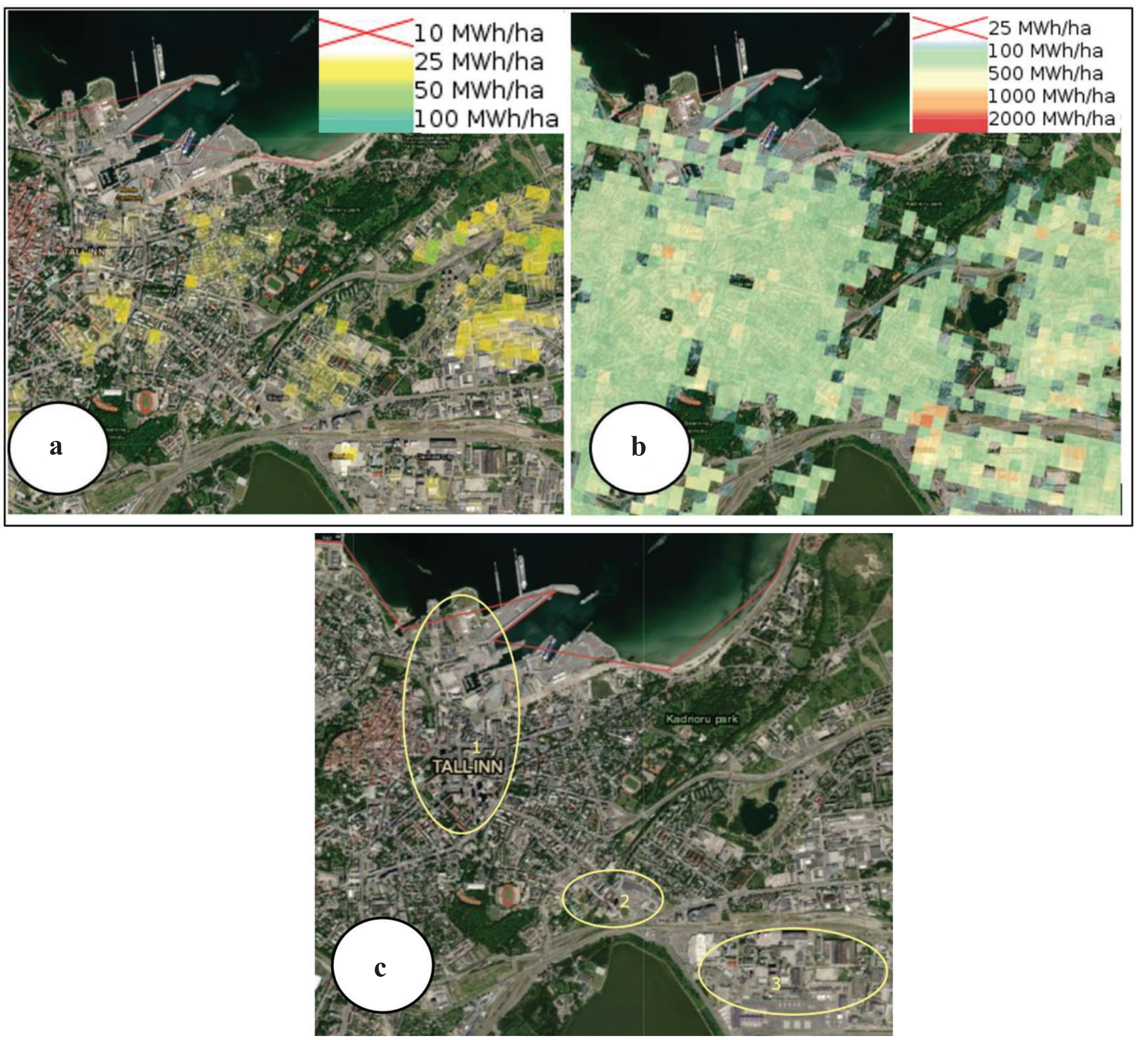

Figure 1: Identification of potential district cooling areas
a) Cooling density b) heating density of the non-residential sector c) identified areas

beam condensation. If the outside temperature exceeds the balance point temperature, the building starts to heat up. The term "balance point temperature" refers to the temperature below which a building requires heating and above which a building requires cooling. The lower the balance point temperature, the greater the DC demand in the building. In modern energy-efficient buildings, the balance point temperature is 7-15°C [37]. The balance temperature in residential buildings is relatively stable and is based primarily on the outdoor temperature and area, whereas the balance temperature in office buildings is based on a variety of factors, including the number of people, type of electrical equipment, area per person, working hours, and the nature of activity. The excess heat from these sources means that the cooling of an average office building in a cold region like Estonia will start when the outside temperature is around 13-14°C .

District cooling demand can be calculated using a variety of methods.

The balance point temperature and cooling degree days can be used to calculate district cooling demand. Due to the fact that degree days do not cover the DC demand for ventilation dehumidification, cooling degree days only indicate a portion of the DC demand. To calculate the DC demand for ventilation, cooling and drying, information about the building's cooling and automation systems is needed, namely critical humidity to avoid condensation, actual air flow, and whether the ventilation is partially turned off at night to save energy. Using this information, the DC demand can be calculated. This information is too detailed and will not be available during the district cooling planning stage. Therefore, a simplified method can be used. One of the key indicators for methods is the public availability of data, which tends to limit the granularity of the data. Research based on publicly available open data, for example, has been shown to have a positive impact and can serve as a starting point for the continual evolution of the energy system [38,39].

The following simplified methods are suggested:

Method 1: The idea behind this method is that the cooling demand of the region under consideration can be usually determined based on the likely availability of housing area, house type (with an emphasis on offices and stores), and energy efficiency. According to this method, the estimate is based on several examples of buildings from Tallinn and Stockholm. A typical office building has 700 full load hours (FLH), and the number of FLH increases as the cooling demand grows. Potential cooling capacity and demand can be predicted using the specific cooling capacity of 45 W/m2 (useful area) recommended by the cooling system designers and the above information on buildings located in the cooling area from the Estonian Register of Buildings [40] . The main disadvantage of this approach is the lack of data on each building.

Method 2: This method considers the potential cooling demand for existing buildings that will switch from individual to district cooling. The number of fans in dry coolers is counted using this method, which is based on the analysis of satellite imagery (Google maps) of a certain building. Small coolers have 30 fans, medium coolers have 45 fans, and large coolers have 58 fans, according to the preliminary evaluation based on building samples. The issues associated with this approach include buildings without visible dry coolers, buildings with dry coolers located on neighbouring facilities, and the fact that dry coolers of the same size have a broad capacity range and their installed capacity differs from their actual capacity.

Method 3: Method 1 and Method 2 were combined to determine the average cooling demand for consumers in some cases when both rooftop and building register information was available and calculation results were different for each method.

Figure 2 shows an example of data sampling from a satellite image and the Building Register.

At this point, it is recommended to identify the key DC consumers. Key consumers should be identified based on a cooling demand greater than 1 MW and a convenient location when the piping system is built around this demand and the type of buildings.

The criteria for key consumers are as follows:

- modern or renovated offices, hotels, and social facilities that use local cooling and have stable cooling demand;
- new large buildings in accordance with the city's master plan;
- neither old nor new residential buildings were considered as key cooling consumers.

Key consumers are needed to create the backbone of the network. Without them, it is impossible to build a large efficient network. You can limit yourself to local networks, which, however, can be combined into a large network in the future, but additional investments will be required to create connecting pipelines of a larger diameter. As a result, it is important to pinpoint the location of the key consumer concentration as soon as possible and install pipelines for the future.

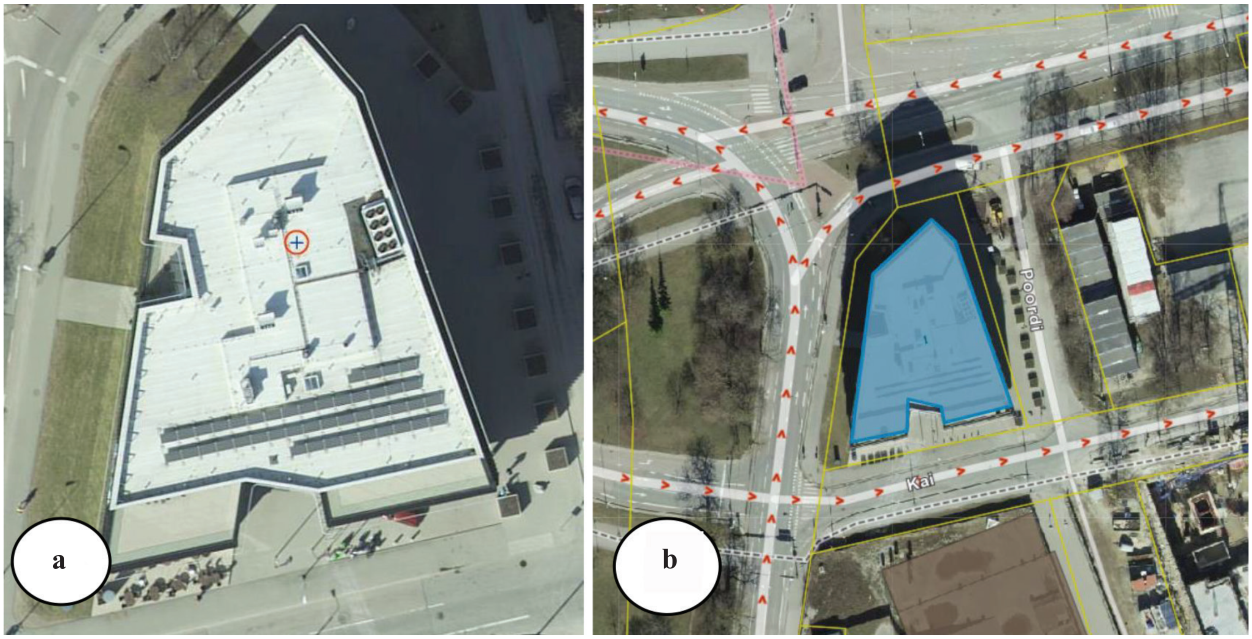

Figure 2: Cooling demand determination via a) fan counting b) based on specific cooling load from the Building Register

2.2. Cold supply planning for district cooling

When planning cold supply for district cooling, all options should be taken into account to build the most efficient DC plant. As previously stated, seawater-based free cooling is the ideal alternative, although it necessitates the use of additional technologies. When seawater-based free cooling provides more than 50% of the annual cold supply, the rest of the cold supply can be covered by electric chillers. Seawater can also be used to cool the condensers of electric chillers.

It is critical for free cooling planning that the district cooling plant (DCP) is located near the free cooling supply, which in this case is the sea. The capacity of the free cooling unit depends on the water intake points. To calculate the amount of cold supply, options with different points of intake should be compared. On the one hand, the farther the intake point, the lower the water temperature and the deeper it is. On the other hand, further water intake leads to higher network construction costs, as well as to an increase in operating costs, including pumping costs.

In the case of Tallinn, the second priority option after free cooling will be the cold supply using the heat rejected by biomass CHPs in the summer. Cold supply via absorption chillers using rejected heat from a CHP that was transferred through the district heating network was analysed in detail in a previous study [25].

Cold supply capacity is only limited by the installed capacity of the absorption chillers. Tallinn has three biomass CHP plants with a combined heat output of 125 MW, thus excess heat is ample in the summer. The heat load on the DH network in the summer is 75 MW. The excess heat is about 50 MW and can be used to cool the DC. With an absorption chiller's COP of 0.7, it's possible to generate around 35 MW of cold without burning any additional fuel at the CHP.

Unlike absorption chillers, electric chillers start quickly and easily, making them perfect for peak loads. The electric compressor can be started immediately and attain full cooling capacity in a matter of minutes. There are various types of compressors, including scroll, piston, screw, and centrifugal, and their cooling capacity varies from a few kW to 20 MW. The energy efficiency ratio (EER) of electric chillers in Tallinn is about 5. EER can be as high as 7 when centrifugal compressors are used. Centrifugal compressors are the largest of compressors, and their cooling capacity typically starts at 2 MW. They are difficult to employ in a medium-sized office building because of this, but they are perfect for a DCP.

In the summer, when seawater temperatures are around 20-25°C, chillers will run as close to their maximum EER as possible. The EER cannot be higher because the minimum condenser inlet water temperature is often about 20°C. At part load, EER for chillers with screw compressors can be 5-6, and for chillers with centrifugal compressors, EER can be 7-8 or even more than 10 [41]. Chillers with centrifugal compressors are a great choice for DC plant peak loads.

2.3. District Cooling Distribution Planning

The district cooling network can be planned once the district cooling consumers and generating units have been identified.

In order to plan the city's district cooling network, it is necessary to identify the key consumers. As previously stated, satellite imagery of buildings with dry coolers on the roof can be used to accomplish this.

NetSim, a digital tool from Vitec AB [42], was used to plan the piping system of the cooling network. It is a simulation software that calculates the dynamics of district heating and cooling, taking into account the difference in pressure, flow rates and water temperatures. NetSim was used for district heating modelling of the Tallinn district heating network [43,44]. Examples of using NetSim for district cooling planning can be found in Ref. [45–47].

The following aspects should be taken into account when designing a piping system for a district cooling network:

The NetSim model uses the following input parameters: specific pressure drop of 50 Pa/m-75 Pa/m, so that the maximum pressure difference in the network does not exceed 10 bar, and a water temperature difference of 10 degrees (temperature schedule is 6/16 degrees).

Three district cooling network scenarios were analysed during the development:

1 1 DCP: a scenario with a single district cooling plant
2 2 DCP: a scenario with two district cooling plants
3. Looping: A looped network of pipelines with two district cooling plants. This scenario is a more versatile option, allowing large loads to be transferred in different directions from the loop, both inward and outward.

2.4. Compatibility with Efficient District Cooling Requirements

The Estonian Power and Heat Association (EPHA), in cooperation with Tallinn University of Technology (TalTech), has developed a methodological approach for calculating and awarding the Efficient District Cooling label that certifies and recognises the efficiency of a DC system or certifies that renewable energy and cogenerated heat are mainly used by the DC system. This label informs consumers about the efficiency of the DC system and promotes DC as an efficient, environmentally friendly, reasonably-priced, and convenient way to supply cold [48].

A DC network is considered efficient when the requirements of Directive 2012/27/EU of the European Parliament and of the Council (Energy Efficiency Directive) are met [49]. A DC network is efficient if it uses at least 50% renewable energy, or at least 50% excess heat, or at least 75% co-generated heat, or 50% combination of such energy and heat.

If absorption chillers are used to generate cold from DH heat, the proportion of renewable energy, co-generated energy, and excess energy in the heat produced in this DH system must be known. These values change from year to year.

For the Tallinn DH system, the available data for 2020 shows, that 53% of heat was produced from renewable fuels (wood chips) and 17% from industrial excess heat. Remaining DH heat (30% from total heat productions) was generated based on fossil fuels (mainly natural gas and peat). Share of co-generated heat was 54%.

The following potential scenarios should be evaluated:

- 1st case: seawater is used to produce cold for district cooling while, centralised electric chillers cover the rest;
- 2nd case: absorption chillers produce cold from DH heat, assuming that all available excess heat from DH CHPs is used (55 MW), and the rest is covered by electric chillers;
- 3rd case: seawater produces 55% of cold for district cooling, 12% is generated by the absorption chiller from district heating heat as shown in the previous study [19], and the rest is covered by the electric chiller.

The annual cold supply data are shown in Table 1.

3. Results

3.1. District cooling demand

Based on the algorithm described above, the potential demand for district cooling was determined first. As shown in Figure 1c, three potential districts have been identified.

An example of District 1 layout is presented below. Figure 3 shows how the planned district was divided into district cooling zones, with each zone analysed separately.

Different methods were used for different zones in the area, depending on the availability and quality of data. Method 1 was used for Zone 3 and Zone 4 because no

Table 1: Cold supply scenarios for district cooling

District cooling plant	Case					
	1		2		3	
from DH	0	0%	39 MW	59%	8.2 MW	12%
compressor (EER = 7) (fossil)	30	45%	27 MW	41%	21.8 MW	33%
seawater (renewable)	36	55%	0 MW	0%	36 MW	55%
total	66	100%	66 MW	100%	66 MW	100%

dry coolers are visible on the satellite image. Method 2 was used for Zones 1 and 2. Method 3 was used for Zone 5 because the difference between the results obtained using Methods 1 and 2 was more than 400%.

Based on a combination of these methods, the planned installed district cooling capacity was determined to be 63.2 MW. 12 key district cooling consumers with 41.8 MW capacity have been identified.

3.2. Cold supply for district cooling

The potential for free cooling as a district cooling source was determined using near real-time seawater temperature data from the Copernicus product. The product consists of NEMO-Nordic 2.0 general circulation model data for 2019-2021 [41]. The thickness of the vertical layer of the model is 1 m at the surface and 10 m at a depth of 75 m, allowing it to accurately represent the seasonal thermocline that forms at a depth of 10-15 m in the Baltic Sea. The data are available in daily temporal resolution and 1 square nautical mile (nmi²) horizontal resolution. The bottom layer temperature at the model grid point closest to the study area was selected for the analysis.

Figure 4 shows how the temperature has changed over the past three years.

It is worth noting that seawater temperatures are below 6°C for approximately 45% of the year, and below 16°C for approximately 95% of the year. Free cooling can be used for the first stage (pre-cooling) from the end of May to December.

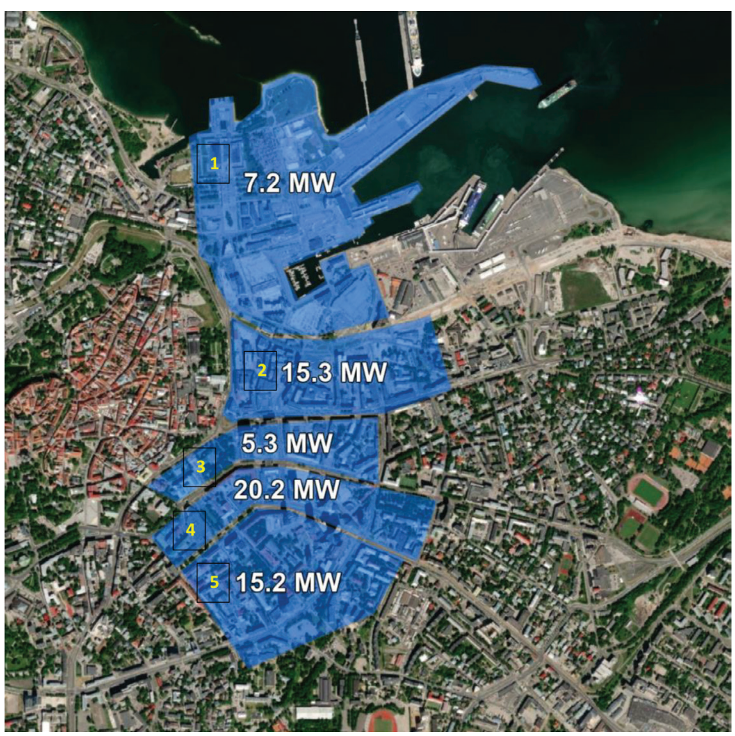

Figure 3: Layout of District 1 (5 zones)

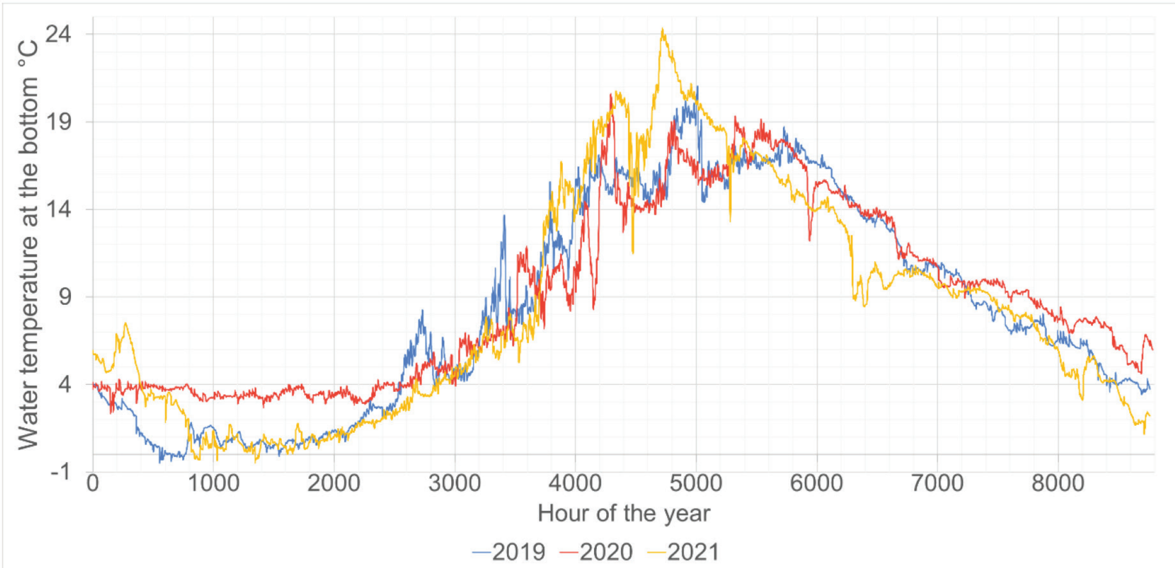

Figure 4: Water temperature at the bottom of the sea (20 m depth, location near Tallinn coastline)

Measurements of the average monthly temperature were taken based on the distance from the shore and depth. As you can see, a greater distance from the water intake point will allow obtaining the cooling medium at lower temperatures, see Figure 5. For further calculations, average temperatures at a depth of 20 m were used (514 m out in the sea).

Region 1, which is adjacent to the sea, has a cooling need of 63.5 MW, according to prior calculations. A simplified cooling profile was built based on the outdoor temperatures. For the operation strategy, a more detailed analysis will be required; however, for preliminary studies analysing the feasibility of the DC concept, this approach was adopted. (See Figure 6.)

Figure 6 shows the cooling demand and cold supply mix. For the calculation, the following input assumptions were used: the seawater DC plant capacity is 40 MW, the maximum outdoor temperature is 28°C, the

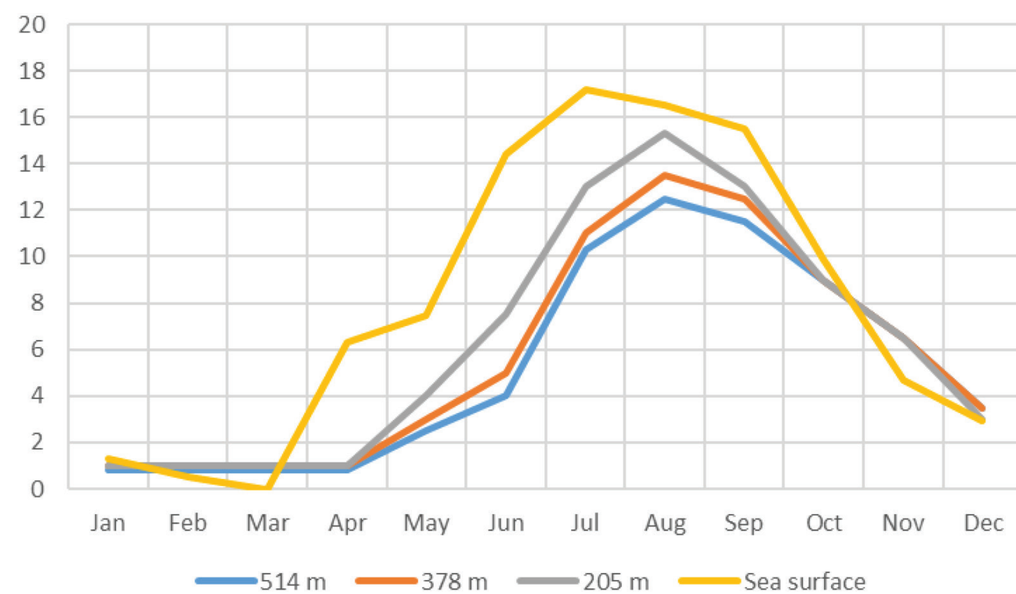

Figure 5: Water temperature in the Baltic Sea for points at different distances from the coast and surface water temperature in the Baltic Sea in Tallinn [50].

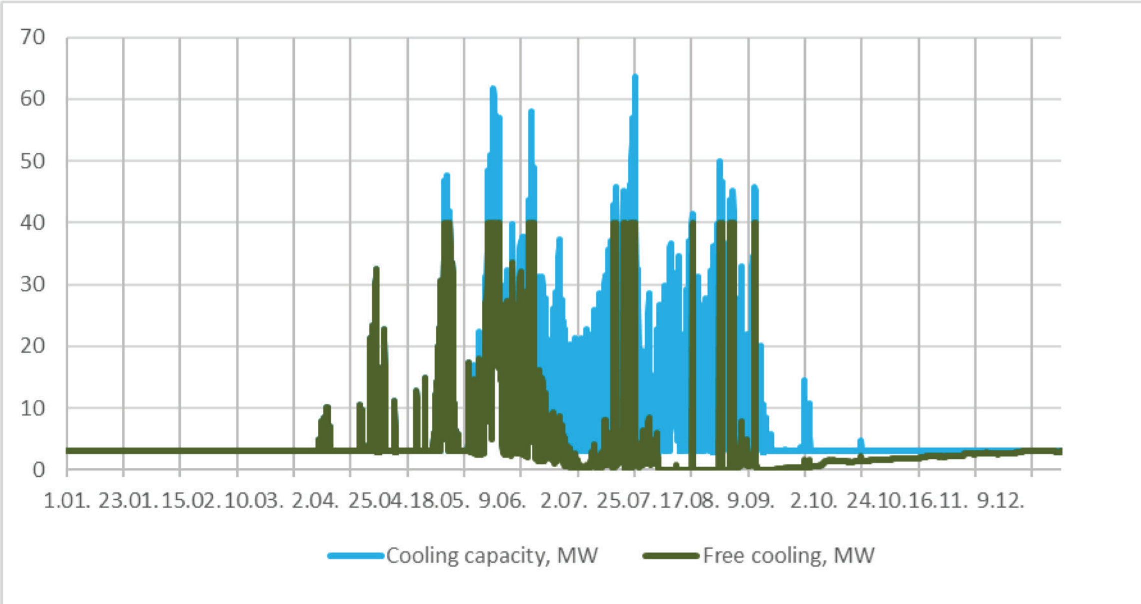

Figure 6: Cold supply for district cooling

balance temperature is 13°C, and the minimum base load is 3 MW.

It was determined that the total annual cold supply is 66 GWh, of which free cooling is 36 GWh (55%); the summer cold supply is 39 GWh, of which free cooling is 14.5 GWh (37%).

3.3. District Cooling Transfer

Based on 1 DCP, a network with a single seawater cooling source is planned (Figure 7A, point A). Under 2 DCP, the network will have one seawater-based cooling source (Figure 7B, point A) and one electric compressor-based source (Figure 7B, point B). The first cooling consumers may appear before the seawater district cooling plant is built (Figure 7C, point A), and the initial cold water will be fed into the network from the compressor district cooling plant. A compressor station will operate in the early years of network development, transferring cold to the first consumers via the DN450-DN500 pipeline (up to 15-20 MW of load can be transmitted with an increase in specific pressure losses of up to 100 Pa/m). Further development will take place as the key consumers are connected and a seawater district cooling plant is built. Many key consumers already have their own cooling systems and connection to the district network is theoretically possible if the existing equipment fails, as well as if it is economically feasible to connect to the network.

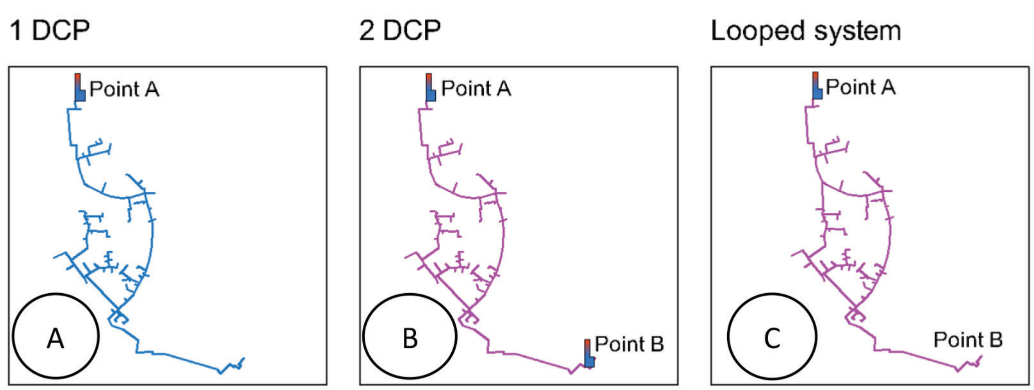

Figure 7: NetSim district cooling pipeline simulation

Pipe comparison is shown in Table 2.

Table 2 shows that for all analysed systems, all pipes DN200 and smaller are about the same length. Since the amount of coolant per cubic meter is relatively small, DN200 and smaller pipes are usually used to connect to consumers, so they are the same in all three scenarios. The difference is in the main pipes. As already mentioned, in the first scenario, there is only a district cooling plant located by the sea. This is the main reason why the pipe DN is larger in the 1 DCP scenario. In the 2 DCP scenario, there are two cooling plants located on the opposite sides of the network. This scenario allows us to split the network in two and make pipes of slightly smaller dimensions from the connections of DC plants.

The idea behind the looped solution is to make at least one large loop so that it's possible to provide cooling to consumers in different ways [51].

The looped network covers four of the five southern parts into which the city centre is divided. The total investment required to build a looped network is slightly higher than for the other options. Since the main district cooling plant with free cooling will be located close to the sea, the piping has been resized for the looped system. As you can see, the maximum DN is even higher than in the 1 DCP and 2 DCP scenarios, but this allows most of the cooling demand to be covered by free cooling from the sea.

It is also very important to provide consumers with secure DC supply, which can be done with the looped solution. In the case of the looped system, there is a great opportunity to connect more consumers without any major reconstruction of the network, which will be built in the first stages.

It can be concluded that constructing the entire massive looped network with a seawater cooling plant would be impractical, since it would require too much investment and the requisite number of users would not be available. It is best to develop the network gradually, the most suitable plan is to place compressor refrigeration units at point B in addition to the existing chillers that supply cooling to the local network of the business district located next to the source, and go along the main to the city centre and the first consumers.

In terms of cost, the looped network can be considered the most expensive, since installation costs are 15,238 thousand EUR, which is about 8% higher than for 1 DCP or 2 DCP. But, as mentioned above, this type of scenario will allow new DCNs to be connected at a lower cost in the future.

Table 2: Pipe comparison

	1 DCP	**2 DCP**	**Looped system**
DN type		**Length (m)**	
DN80	525	525	525
DN100	1731	1731	1654
DN125	2347	2347	2347
DN150	1235	1235	1235
DN200	1949	1949	1665
DN250	1014	1014	1014
DN300	3912	3912	3771
DN350	637	637	163
DN400	632	632	175
DN500	3219	3359	3219
DN600	848	848	4256
DN700	621	5275	2010
DN800	4655	0	0
DN900	0	0	1804
TOTAL	**23325**	**23464**	**23838**
		Average diameter (mm)	
	397.1	377.9	407.9

Table 3: Estimation results of DC energy efficiency

Case	1	2	3
Cogenerated, %	0%	32%	7%
Renewables, %	55%	31%	61%
Excess heat, %	0%	10%	2%
Total, %	**55%**	**73%**	**70%**
Energy-efficient DC	YES	YES	YES

3.4. Energy efficiency calculations

Based on the energy efficiency methodology described in Section 2.4., the results of estimating the compatibility of the proposed solution with efficient district cooling requirements are presented in Table 3.

According to a preliminary assessment, all solutions are classified as efficient DC. As for case 1, if the proportion of seawater-based free cooling decreases or the cooling demand increases, the DC system will not be considered energy-efficient.

4. Discussion: Obstacles to District Cooling

Specific details and conditions were discovered during the planning of the system in Tallinn that were not included in some of the broad aspects of the methodology and results. In countries like Estonia, district cooling is primarily used for office buildings and shopping centres (residential buildings usually do not have a centralised district cooling system). These consumers (office buildings and shopping centres) are usually located in the city centre, in which case we face the following problems associated with district cooling:

- There is usually no space in the city centre for new underground networks. In the case of a district cooling network, space must be allocated for two pipelines. For example, the diameter of the main distribution pipeline of the Tallinn district cooling network is 1000 mm (due to the small delta T in district cooling networks), therefore, considering the insulation of the supply pipeline and the distance between the networks, approximately 3000 mm of free space is required. And it's not easy to find in the city centre. Additional engineering, such as vertical installation of district cooling piping with one pipe on top of the other, is required to make room for networks. If maintenance is required, this sort of installation is deemed impractical; nonetheless, this type of installation is only used in extremely limited spaces. For this installation, the return line of DCN goes to the bottom; with this pipeline the need of maintenance is the least.
- In addition, if we work with consumers located in the city centre, then the refrigeration units have to be installed in the city centre, which is quite difficult, since the price of land in the city centre is quite high, and installing a generator set (which requires space, electrical connection, and makes noise) can also be problematic.

We also have to take into account the fact that usually the cooling devices of existing buildings (which can be converted to district cooling) are located on the roof, so it is not enough to simply connect the building to the district cooling network underground, there should also be a technical solution for bringing the cooling pipelines to the roof (by finding a place inside the building, for example, using elevator shafts; or by installing district cooling pipelines in the façade of the building; hydraulic aspects should also be evaluated to determine whether there is enough pressure in the network to get the pipelines to the roof or additional pumping facilities must be installed). Reconnecting existing consumers to the district cooling network is also a challenge. Typically, the service life of local cooling devices is about 15-20 years, so during this period, it is usually impractical for the building owner to reconnect to the district cooling network, and it is better to wait until the service life of the local cooling device is over, and then decide whether to invest into and upgrade the local cooling device or connect to district cooling.

Because the potential for the use of district cooling has not yet been realised, and many cities are still in the early stages of development, future district cooling demand will not decrease but will increase due to factors such as increased urbanisation and more potential consumers, the consumers whose local cooling system will become obsolete, changes in climate, and a gradual increase in district cooling demand. All this will lead to an increase in the total and peak cooling loads.

5. Conclusions

District cooling planning is essential for successful urban development. Since modern district cooling networks are complex systems that include the coupling of district heating and cooling and the integration of free cooling and renewable energy sources, system planning is rather challenging. The planning process for district cooling has been described step-by-step for the Tallinn case study. The procedure and implementation of the following steps were described: cooling demand determination, cold supply planning, and district cooling distribution analysis. The density of potential consumers with cooling demand is higher in the city centre, and their calculated cooling capacity is 63.2 MW. Using seawater for free cooling can cover up to 55% of the annual cooling consumption. The rest of the cold can be produced using absorption chillers + excess heat and electric chillers. By combining these three cold supply methods, an efficient DC system can be successfully developed in Tallinn. Tallinn is located by the sea, which provides an excellent opportunity for the development of the DC network. The loop geometry of the district cooling network was chosen as the most feasible option because it allows the network to be developed gradually. Despite the fact that the looped network is 8% more expensive than the other scenarios, this type of solution will allow connecting new DCNs at a lower cost in the future.

Nomenclature

Abbreviation	
EU	European Union
IEA	International Energy Agency
SWAC	Seawater air conditioning
DH	District heating
DC	District cooling
DHC	District heating and cooling
CHP	Combined heat and power plant
DCP	District cooling plant
FLH	Full load hours
EER	Energy efficiency ratio
DCN	District cooling network
DN	Nominal diameter

References

[1] European Commission. An EU Strategy on Heating and Cooling 2016. https://doi.org/10.1017/CBO9781107415324.004.

[2] Mathiesen BV, Bertelsen N, Schneider NCA, Garcia LS, Paardekooper S, Thellufsen JZ, et al. Towards a decarbonised heating and cooling sector in Europe: Unlocking the potential of energy efficiency and district energy. Aalborg University, Department of Planning, 2019.

[3] International Energy Agency (IEA). Global Energy and CO2 Status Report. 2018.

[4] van Ruijven BJ, De Cian E, Sue Wing I. Amplification of future energy demand growth due to climate change. Nat Commun 2019;10:2762. https://doi.org/10.1038/s41467-019-10399-3.

[5] Werner S. European space cooling demands. Energy 2016;110:148–56. https://doi.org/https://doi.org/10.1016/j.energy.2015.11.028.

[6] Gang W, Wang S, Xiao F, Gao DC. District cooling systems: Technology integration, system optimization, challenges and opportunities for applications. Renew Sustain Energy Rev 2016;53:253–64. https://doi.org/10.1016/j.rser.2015.08.051.

[7] Nielsen TB, Lund H, Østergaard PA, Duic N, Mathiesen BV. Perspectives on energy efficiency and smart energy systems from the 5th SESAAU2019 conference. Energy 2021;216:119260. https://doi.org/10.1016/j.energy.2020.119260.

[8] Lund H, Werner S, Wiltshire R, Svendsen S, Thorsen JE, Hvelplund F, et al. 4th Generation District Heating (4GDH). Integrating smart thermal grids into future sustainable energy systems. Energy 2014;68:1–11. https://doi.org/10.1016/j.energy.2014.02.089.

[9] Werner S. District heating and cooling in Sweden. Energy 2017;126:419–29. https://doi.org/10.1016/j.energy.2017.03.052.

[10] Arabkoohsar A, Sadi M. A solar PTC powered absorption chiller design for Co-supply of district heating and cooling systems in Denmark. Energy 2020;193:116789. https://doi.org/10.1016/j.energy.2019.116789.

[11] Chua KJ, Chou SK, Yang WM, Yan J. Achieving better energy-efficient air conditioning – A review of technologies and strategies. Appl Energy 2013;104:87–104. https://doi.org/10.1016/j.apenergy.2012.10.037.

[12] Jangsten M. Gothenburg District Cooling System - An evaluation of the system performance based on operational data Gothenburg District Cooling System 2020;0.

[13] Hunt JD, Byers E, Sánchez AS. Technical potential and cost estimates for seawater air conditioning. Energy 2019;166:979–88. https://doi.org/10.1016/j.energy.2018.10.146.

[14] Damien Casetta, Cynthia Nerbollier, Guillaume Brecq, Pascal Stabat, Dominique Marchio. Dynamic modelling of a district cooling network with modelica- proceedings of 14th International Conference of IBPSA - Building Simulation 2015, BS 2015, Conference Proceedings, Paris, 2015.

[15] Külaots M. District cooling , Tartu experience. 39th Euroheat Power Congr Nantes, 2019 2019.

[16] M. Calderoni et al. Sustainable District Cooling Guidelines. IEA DHC/CHP Annex XII Report, No. 5. 2019.

[17] Jangsten M, Filipsson P, Lindholm T, Dalenbäck JO. High Temperature District Cooling: Challenges and Possibilities Based on an Existing District Cooling System and its Connected Buildings. Energy 2020;199. https://doi.org/10.1016/j.energy.2020.117407.

[18] van Leeuwen R, de Wit JB, Smit GJM. Energy scheduling model to optimize transition routes towards 100% renewable urban districts. Int J Sustain Energy Plan Manag 2017;13:19–46. https://doi.org/10.5278/ijsepm.2017.13.3.

[19] Olama AA. District Cooling Theory and Practice. 2017.

[20] Frederiksen S, Werner S. District heating and cooling. Studentlitteratur AB; 2013.

[21] CHAN A, CHOW T, FONG S, LIN J. Performance evaluation of district cooling plant with ice storage. Energy 2006;31:2750–62. https://doi.org/10.1016/j.energy.2005.11.022.

[22] Jangsten M, Lindholm T, Dalenbäck J-O. Analysis of operational data from a district cooling system and its connected buildings. Energy 2020;203:117844. https://doi.org/10.1016/j.energy.2020.117844.

[23] Lazzeroni P, Olivero S, Repetto M, Stirano F, Verda V. Design of a polygeneration system with optimal management for a district heating and cooling network. Int J Sustain Energy Plan Manag 2019;22:81–94. https://doi.org/10.5278/ijsepm.2450.

[24] Pellegrini M, Bianchini A. The Innovative Concept of Cold District Heating Networks: A Literature Review. Energies 2018;11:236. https://doi.org/10.3390/en11010236.

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

[26] Matak N, Tomić T, Schneider DR, Krajačić G. Integration of WtE and district cooling in existing Gas-CHP based district heating system – Central European city perspective. Smart Energy 2021;4:100043. https://doi.org/10.1016/j.segy.2021.100043.

[27] Büchele R, Müller A, Hummel M, Kranzl L, Hartner M, Deng Y, et al. Comprehensive assessment of the potential for efficient district heating and cooling and for high-efficient cogeneration in Austria. Int J Sustain Energy Plan Manag 2016;10:3–19. https://doi.org/10.5278/ijsepm.2016.10.2.

[28] Jakubcionis M, Carlsson J. Estimation of European Union residential sector space cooling potential. Energy Policy 2017;101:225–35. https://doi.org/10.1016/j.enpol.2016.11.047.

[29] Inayat A, Raza M. District cooling system via renewable energy sources: A review. Renew Sustain Energy Rev 2019;107:360–73. https://doi.org/10.1016/j.rser.2019.03.023.

[30] Eveloy V, Ayou D. Sustainable District Cooling Systems: Status, Challenges, and Future Opportunities, with Emphasis on Cooling-Dominated Regions. Energies 2019;12:235. https://doi.org/10.3390/en12020235.

[31] Pieper H, Ommen T, Elmegaard B, Volkova A, Brix Markussen W. Optimal Design and Dispatch of Electrically Driven Heat Pumps and Chillers for a New Development Area. Environ Clim Technol 2020;24:470–82. https://doi.org/https://doi.org/10.2478/rtuect-2020-0117.

[32] Popovski E, Fleiter T, Santos H, Leal V, Fernandes EO. Technical and economic feasibility of sustainable heating and cooling supply options in southern European municipalities-A case study for Matosinhos, Portugal. Energy 2018;153:311–23. https://doi.org/10.1016/j.energy.2018.04.036.

[33] Gang W, Wang S, Gao D, Xiao F. Performance assessment of district cooling systems for a new development district at planning stage. Appl Energy 2015;140:33–43. https://doi.org/10.1016/j.apenergy.2014.11.014.

[34] Khir R, Haouari M. Optimization models for a single-plant District Cooling System. Eur J Oper Res 2015;247:648–58. https://doi.org/10.1016/j.ejor.2015.05.083.

[35] Al-Noaimi F, Khir R, Haouari M. Optimal design of a district cooling grid: structure, technology integration, and operation. Eng Optim 2019;51:160–83. https://doi.org/10.1080/0305215X.2018.1446085.

[36] Pol O, Schmidt R-R. Development of district heating and cooling in the urban planning context. Adv. Dist. Heat. Cool. Syst., Elsevier; 2016, p. 319–37. https://doi.org/10.1016/B978-1-78242-374-4.00015-X.

[37] Kredex. Energy efficiency - Tools for measuring energy efficiency (in estonian) 2021.

[38] Miguel-Herrero FJ, Serna-González VI, Hernández-Moral G. Supporting tool for multi-scale energy planning through procedures of data enrichment. Int J Sustain Energy Plan Manag 2019;24:125–34. https://doi.org/10.5278/ijsepm.3345.

[39] Volkova A, Latõšov E, Lepiksaar K, Siirde A. Planning of district heating regions in Estonia. Int J Sustain Energy Plan Manag 2020;27:5–16. https://doi.org/10.5278/ijsepm.3490.

[40] Ministry of Economic Affairs and Communications. Estonian Register of Buildings 2021.

[41] York ®. Data sheets for centrifugal and screw compressors. 2021.

[42] Vitec Software Group. NetSim, Grid simulation software, http://www.gssnetsim.com/ 2021.

[43] Latõšov E, Volkova A, Hlebnikov A, Siirde A. Technical improvement potential of large district heating network: Application to the Case of Tallinn, Estonia. Energy Procedia, 2018. https://doi.org/10.1016/j.egypro.2018.08.197.

[44] Volkova A, Mašatin V, Siirde A. Methodology for evaluating the transition process dynamics towards 4th generation district heating networks. Energy 2018;150:253–61. https://doi.org/10.1016/j.energy.2018.02.123.

[45] Gunasekara SN, Bilek Z, Edén T, Martin V. Distributed cold storage in district cooling—Grid dynamics and optimal

integration for a Swedish case study. Energy Reports 2021;7:419–29. https://doi.org/10.1016/j.egyr.2021.08.086.

[46] Helal AA, Abdalla AY. Electricity Power Demand Comparative Analysis of District Cooling and Conventional Cooling Systems - Case Study in Diyar Al Muharraq (DAM) Development Project). 2020 Int. Conf. Decis. Aid Sci. Appl., IEEE; 2020, p. 832–8. https://doi.org/10.1109/DASA51403.2020.9317010.

[47] Simonsson J, Atta KT, Schweiger G, Birk W. Experiences from City-Scale Simulation of Thermal Grids. Resources 2021;10:10. https://doi.org/10.3390/resources10020010.

[48] Estonian Power and Heat association (EPHA) n.d. www.epha.ee.

[49] European Parliament. Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency. Off J Eur Union Dir 2012:1–56. https://doi.org/10.3000/19770677.L_2012.315.eng.

[50] Saaremäe I. Water temperature in Tallinn gulf (Merevee temperatuur Tallinna lahes). Est Weather Serv 2014.

[51] Delmastro C, Lavagno E, Schranz L. Energy and underground. Tunn Undergr Sp Technol 2016;55:96–102. https://doi.org/10.1016/j.tust.2015.10.021.