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Research paper

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

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ABSTRACT

The 5th Generation District Heating and Cooling (5GDHC) network has great advantages in terms of integration of low-temperature resources, bi-directional operation, decentralised energy flows, and possible energy sharing. One way to develop the idea and concept of 5GDHC is to identify potential agents, including residential buildings, office buildings, shopping malls, data centres, electrical transformers, and so on, in 5GDHC in each target context. The prospects for 5GDHC have been assessed in light of the conditions in the Baltics. The multi-criteria analysis method was used to quantify the main identified barriers and drivers behind the implementation of 5GDHC systems. It should be noted that new urban areas in the Baltic states are being actively developed with low-energy buildings, so 5GDHS can be integrated to supply heat to these areas. The highest score in the multi-criteria assessment was achieved by Lithuania due to support availability and open heating market conditions. When all applied criteria are weighted equally, Estonia has the most favourable conditions for 5GDHC systems due to widespread use of heat pumps and greater excess heat potential.

1. Introduction

District heating and cooling (DHC) technology has been widely recognised as a promising solution to reduce both primary energy consumption and local emissions (Rezaie and Rosen, 2012; International Energy Agency, 2014). The 5th generation district heating and cooling (5GDHC) network is the latest district heating/cooling concept, which is characterised by low temperature supply (i.e. close to ground temperature), bi-directional operation (i.e. it can provide heating and cooling simultaneously), decentralised energy flows (i.e. it allows multiple heat sources and heat sinks in the network), and heat sharing (i.e. it can recover waste heat and share it with different users) (Buffa et al., 2019). Unlike the 4th generation district heating (4GDH) technology, the 5GDHC technology is geared towards the consumer/prosumer. It only needs one thermal grid, but it serves multiple purposes for both heating and cooling distribution, including heat and cold storage, and thus provides flexibility in adopting local renewable energy and waste heat resources. As pointed out in Revesz et al. (2020), by integrating the low-grade heat with photovoltaic arrays, batteries, and vehicle-to-grid applications, 5GDHC systems also support the electrification of both the building and transportation sectors towards the broader concept of 'fifth generation smart energy networks'.

The distinction between 5GDHC and 4GDH has been studied in the past. For instance, Lund et al. (2021) performed a systematic comparison of 5GDHC and 4GDH in terms of goals and capabilities. According to their findings, 5GDHC has five of the same core capabilities as 4GDH: (i) the ability to supply different types of buildings, (ii) the ability to distribute heat with small grid losses, (iii) the ability to recycle heat from low-grade sources, (iv) the ability to be integrated into large smart energy systems, and (v) the ability to ensure proper planning and cost-effective investment. The main differences in 5GDHC are the strong emphasis on combined heating and cooling, as well as the use of a collective network close to ground temperature as a common heat source or sink for heat pumps (HP). After reviewing various literature, they also concluded that 5GDHC can be viewed as a technology with its own merits. It does not have to replace other 4GDH technologies. Instead, it can coexist with other 4GDH technologies. Ref. Gudmundsson et al. (2021) compared the levelised costs of heat from both 4GDH and 5GDHC in Denmark and the UK. The results of this study showed that, under current cost scenarios, 4GDH is more cost-effective compared to 5GDHC in both of these countries. This is due to three key factors: (1) economy of scale of central

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Abbreviations

4GDH	4th Generation District Heating
5GDHC	5th Generation District Heating and Cooling
AHP	Analytic Hierarchy Process
DH	District Heating
DHC	District Heating and Cooling
HP	Heat pump
MILP	Mixed-integer linear program
MPC	Model predictive control
RES	Renewable energy sources
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution

HPs, (2) access to cheaper input energy, and (3) simpler building interface units. These factors can offset the additional cost of the insulated piping network and the associated distribution heat loss in 4GDH systems compared to 5GDHC. The key difference and barrier between 5GDHC and 4GDH is the HPs' reliance on the power supply system, as they must raise the temperature to fulfil the needs of the end users. Therefore, an increase in the electricity price will significantly increase the cost of 5GDHC.

Several studies have looked at 5GDHC technology from various perspectives. Grzegórska et al. (2021) reviewed the current status of district heating (DH) systems in terms of the application and solutions of novel approaches to smart asset management (i.e. maintenance approaches via control, prediction, optimisation, and selective refurbishment of assets with the aid of novel hardware and software solutions) for several countries of the Baltic region (Grzegórska et al., 2021). They compared the traditional maintenance system with smart asset management solutions for optimal design, operating conditions and management of the DH network. Their review concluded that integrating smart management tools into DH systems can solve issues in existing DH networks while also ensuring profitability for both heat providers and consumers. Buffa et al. (2019) conducted a comprehensive review of 40 thermal networks operating in Europe that can provide both heating and cooling to buildings. They conducted a drawback-benefit analysis to investigate the pros and cons of 5GDHC technology. They also explored the challenges associated with implementing 5GDHC technology, including the lack of guidelines for designers and planners, the lack of a local heat atlas, and the lack of new business models and tariff mechanisms. To improve the performance of energy transmission stations in a building, model predictive control (MPC) algorithms based on recurrent artificial neural networks were developed in Buffa et al. (2020). The results showed that MPC can effectively shift electricity consumption from energy transmission stations from peak to off-peak hours by up to 14%, and thus, the use of advanced control in 5GDHC can promote the coupling between the thermal and electric sectors. They also pointed out that the potential weaknesses of the 5GDHC technology mainly include complicated seasonal load balancing and increased complexity in both distribution network management and energy transmission stations at customer locations.

There are some studies related to the techno-economic analysis of the 5GDHC network. For example, Wirtz et al. (2021) developed a mixed-integer linear program (MILP) control method for short-term network temperature optimisation in 5GDHC systems that took into account the integration of both waste heat and free cooling. Their 5GDHC system includes a HP, a chiller and thermal storage in a central generation unit, as well as pumps, chillers, electric boilers and thermal storage in 17 agent buildings. The results showed that such temperature control can reduce the operating temperature of the network and cut operating costs by 10%–60%. Another study (Millar et al., 2021) provides an assessment framework for determining the economic, operational, and carbon benefits of HP-driven 5GDHC energy sharing networks for an urban centre. In particular, they created a load matrix to analyse which energy loads from various building types are suitable for energy sharing. Using the proposed assessment framework and load matrix, they conducted parametric studies of various scenarios for heat tariff, energy sharing, thermal storage, and carbon tax combinations. The results of the study showed that the financial benefits of 5GDHC are more dependent on factors such as the size of the thermal storage and time-of-use tariffs, while the carbon savings of 5GDHC are more dependent on system alternatives such as natural gas boilers. Energy sharing barely affects these metrics. A bibliographic analysis of the modelling and co-simulating of 5GDHC systems was published in Abugabbara et al. (2020). Their analysis concluded that the co-simulation between the district energy system and building energy models can help reduce oversized space heating and cooling systems, since proper advanced control strategies are still lacking for 5GDHC operation. They also stated that 5GDHC systems address two of the main challenges faced by the 4GDH, including (i) the need for separate pipes to provide both heating and cooling and (ii) centralised energy generation, which limits the expansion area of the network.

In the 5GDHC, different players can be considered as agents interacting with each other through pipes: consumers, suppliers, and prosumers. Consumers represent end users of heat and cold, such as residential buildings. Suppliers represent heat producers, such as the existing DH network, process excess heat, or solar thermal energy. Prosumers represent heat users that can sometimes produce heat, such as data centres and shopping malls. In 5GDHC, potential agents include office buildings, shopping malls, data centres, electrical transformers, etc., which can add low temperature heat to the network. The agents draw water at a temperature between 5-30 °C from the loop to cover their heating or cooling demand and re-inject the water back into the same loop. HPs can be utilised in a network to meet a variety of heating and cooling needs at various temperatures. HP can be powered with renewable energy from wind farms and photovoltaic (PV) farms. In this regard, the use of HPs by agents can also provide flexibility in balancing fluctuations in the power grid due to intermittent renewable energy sources (RES) (Fischer, 2014). Danfoss, as practitioners, emphasise that 5GDHC has a significant dwelling spatial impact, as well as medium dwelling noise levels due to the use of individual HP (Danfoss, 2021). There is a significant resident risk for the same reason that HP is used. Geothermal energy can also be integrated into 5GDHC as a potential agent (Boesten et al., 2019). The legal framework for shallow geothermal energy in 14 European countries is reviewed in detail in Tsagarakis et al. (2020). Their review showed that across European countries there are significant disparities in legal provisions, as well as in regulations, standards, and institutional support. These differences are barriers to the market's continued integration of geothermal energy into 5GDHC. 5GDHC is also subject to similar barriers, which prevent 5GDHC from being put into practice on a larger scale.

So far, there has not been a systematic study of potential agents that can be used in the 5GDHC, such as residential buildings, office buildings, shopping malls, data centres, electrical transformers, and so on. There is also no comprehensive review and analysis of the barriers and drivers for the implementation of 5GDHC. This may hinder the introduction of 5GDHC techniques on a large scale. Thus, this study provides a comprehensive review of potential agents that can be used as active heat sources or sinks in 5GDHC in the Baltic countries. This paper also explores the barriers and drivers for the implementation of 5GDHC in terms of economics, markets, technologies, policies, etc. Country-specific conditions such as heating tariffs, regulatory mechanisms, stakeholders, existing DH infrastructure, DH market and others are evaluated for the three Baltic states (Latvia, Estonia, and Lithuania). A preliminary evaluation is also conducted to explore possible implementation opportunities for the 5GDHC network in the Baltic states. This study can help to understand how different agents can be integrated into 5GDHC, and what waste heating or cooling potential they can bring to the 5GDHC network. This will provide a solid basis for the future 5GDHC modelling and techno-economic analyses. The identified barriers and drivers will pave the way for the implementation of the 5GHDC network in the future.

The structure of the paper is as follows. Section 2 reviews and analyses the barriers and drivers of 5GDHC. Section 3 presents the general research methodology. Section 4 presents waste heat potential results from a set of agents. The conclusions are provided in Section 5. A multi-criteria analysis is used to allow comparisons between countries.

2. Barriers and drivers of 5GDHC in the Baltic states

To identify the main barriers and drivers, it is necessary to assess the current situation. Due to the cold climate in the Baltic states, the heating sector plays a very important role. The majority of residents in the Baltic countries have their heat supplied via DH (62% in Estonia, 65% in Latvia, and 58% in Lithuania), which is well above the EU average of 26%. Despite the fact that the share of RES in the heating and cooling sector in the Baltic countries is rather high (52% in EE, 58% in LV, and 47% in LT (Eurostat, 2020a)), there is a potential to increase the share of renewable energy in this sector. The heat supply in these countries is mainly based on the combustion process, and the high share of renewable energy can be explained by the combustion of large amounts of wood chips in boiler houses and combined heat and power plants. It should be recognised that the share of energy from low-grade heat sources is minimal and can be significantly increased. The purpose of this section is to assess the possibilities for 5GDHC implementation in the Baltic states. The current situation was assessed and the main barriers to implementation were identified. Based on the 5GDHC definition, the following factors were analysed: stakeholders (DH operators and producers), regulatory mechanisms and DH tariffs, existing DH infrastructure, building stock, pilots, energy policy, and strategic DH energy goals.

2.1. Stakeholders

The main difference between DH stakeholders is ownership. In Estonia, DH operators are mostly private companies (Volkova et al., 2020), while in Latvia DH operators are mostly municipalities, but private companies also own some systems. There are both private and public DH operators in Lithuania.

Private DH companies are more experienced with specific DH operating issues and solutions, which is one of the key advantages when DH networks are operated or owned by private companies. Moreover, private entities as DH owners may be more interested in investing in improvements due to the profit orientation. In addition, private ownership of the DH network is less subservient because local municipalities do not need to buy services from private companies. The main disadvantages are that private companies are more profit-oriented and are not interested in less feasible DH networks (Egüez, 2021).

If the municipalities own DH, it is possible to implement complex heat supply renovation projects, including the improvement of heat supply and public buildings. For example, the municipality of Gulbene implemented the first small-scale low-temperature DH system in Latvia since it owned both the heat source and the buildings to which the heat was supplied. As a result, customer participation and agreements were not necessary. However, municipalities sometimes have limited access to adequate investment funds, modern management practices, and new technologies. In addition, municipal DH systems are subject to public and political control, which can slow down the adoption of innovative technological solutions.

Both private and municipal ownership are viable options for 5GDHC. Existing case studies show that private companies are more interested in developing the 5GDHC technology in parallel with 4GDH.

2.2. Regulatory mechanisms and district heating prices

The DH network in Estonia is regulated by the District Heating Act (Eesti Vabariigi Valitsus, 2017), while in Lithuania the DH sector is regulated by the Law on the Heat Sector. Only Latvia has no specific laws for the DH sector (The Cabinet of Ministers of the Republic of Latvia, 2008). However, the DH sector in Latvia is regulated by the Energy Law, which governs Latvia's energy sector, including heating as a sector of the economy that covers the extraction and use of energy resources. There is also a regulation on the Supply and Use of Thermal Energy, which establishes the procedure for the supply and use of thermal energy, as well as defines the obligations of the supplier and consumer of heat. In addition, the regulations on Energy Efficiency Requirements for Centralised Heating Supply Systems set out energy efficiency requirements for centralised heating systems, specifying the maximum heat loss in the DH network and the minimum requirements for the efficiency of heat production for various technologies.

All Baltic countries have DH price regulators. The main difference between the three countries is the market situation. In Estonia and Latvia, the DH monopoly exists, while heat production in Lithuania is based on heat producers competition (Volkova et al., 2020; Rušeljuk et al., 2020). In order to ensure competition between heat producers, NERC approves a set of conditions for the use of heat transmission networks, which are mandatory for all persons involved in energy activities in Lithuania's heating sector. Lithuania has a unique market mechanism for the DH sector. Each month, different DH suppliers compete in price level auctions. This competitive market model is the only one in European DH. Moreover, Lithuanian DH companies participate in the biomass market and the purchase of biomass is dependent on the market price. Independent heat producers have built about a third of biomass-based plants. Competition among heat producers is organised on the basis of monthly heat sale auctions. In Lithuania, there is a national biomass and heat energy exchange BALTPOOL, where all heat producers are obliged to buy biomass and sell heat in individual municipalities. The experience of the exchange is of interest to foreign politicians and officials. BALTPOOL is in the process of expanding its activities to other countries.

DH prices in the Baltic states are set in accordance with national legislation. The DH price limit in Estonia must be justified, cost-effective and enable the company to fulfil its legal obligations. Only justified sales volumes and profitability expenses may be taken into account when approving the heat energy price for the period of regulation. The validity of the costs included in the heat limit price and their cost-effectiveness are assessed. The maximum area price is set by the Competition Authority in accordance with technical indicators (Eesti Vabariigi

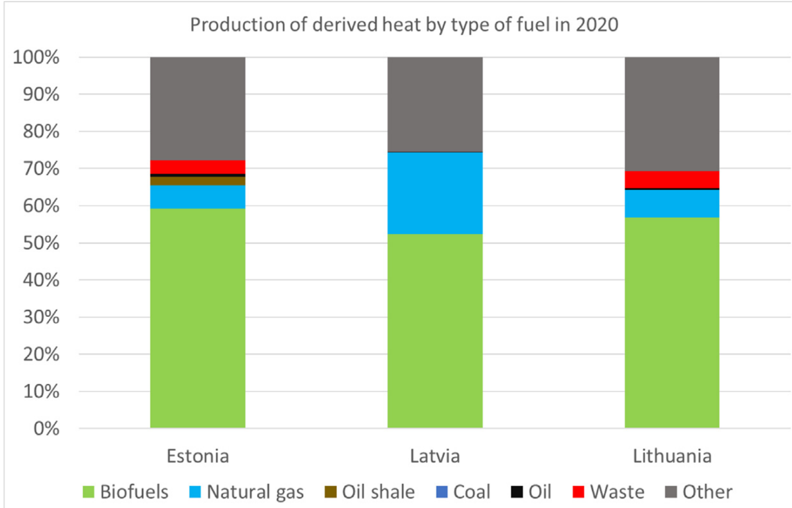

Fig. 1. Production of heat by fuel type in 2020 (based on Eurostat (2020b)).

Valitsus, 2017; Anon, 2020a). The Lithuanian National Energy Regulatory Council (NERC) sets the base price for heat. The municipal council determines the specific components of the heat price, submits documents to NERC for base price harmonisation, and provides feedback on the draft base price. The heat supplier, taking into account the established components of the price for heat, calculates the changed fuel prices and the changed prices for purchased heat, and publishes the final heat prices. Heating tariffs in Latvia depend on many factors, including the size of the system, the fuel used, the technical condition of the system, and even political considerations. Heat production, transmission and distribution are public services that are regulated by the Public Utilities Commission in Latvia. Small DH systems (up to 5000 MWh per annum) are not regulated (Latvian Public Utilities Commission, 2020).

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

2.3. Existing DH infrastructure

The DH infrastructure in the Baltic states is well-developed and widespread in many cities/towns. High-temperature DH is currently just in its third generation, but the heat generation sources are mostly renewable (Fig. 1).

Lithuania has a well-developed DH system. The share of DH in the overall heating sector has remained unchanged in recent years, on average, around 58% in the country and around 76% in cities. DH companies operate in all 60 municipalities of Lithuania. These entities are regulated by the NERC. Smaller heat supply companies are regulated by the municipalities. Municipalities own about 90% of DH companies and 10% have been leased to foreign and domestic investors. Private capital entered the Lithuanian DH market in 2000. Almost 70% of the heat is produced using RES (mainly biomass) and municipal waste in the Lithuanian DH sector (Eurostat, 2020a). The share of heat from natural gas in the fuel mix is less than 30%. Up until 2014, natural gas was the main fuel in the DH heat generation structure. The quick substitution of imported natural gas with local renewable biomass was beneficial to the local economy, created new jobs in the regions and expanded new industries. Penetration of biomass into the Lithuanian DH sector has been implemented by the use of EU support.

Historically, natural gas has been the dominant DH fuel in Latvia. Between 2014 and 2019, the share of heat produced using natural gas at cogeneration plants decreased from 75% to 53.5%, but in heat-only boiler houses, the share of natural gas-based heat decreased from 42.4% to 29.6%. This is mainly due to the support policy for switching to renewable fuels, particularly biomass fuels such as wood chips. Thus, biomass-based heat production increased from 19% in 2014 to 29% in 2019 at cogeneration plants and from 50% to 66% at heat-only boiler houses (Pakare et al., 2021).

The total length of heating networks in Latvia is about 2000 km, of which most of the heating pipelines are outdated and affected by large heat loss. However, there is a gradual renovation and optimisation of heating networks, and average heat loss has been on the decline since 2009, reaching 11% in 2020. The heat supply temperature in heating networks is around 80–90 °C during cold winter periods and around 70 °C during most of the season when the outdoor temperature is around 0 °C (Blumberga et al., 2020).

Oil shale is the main source of energy and the main fuel in Estonia's energy mix. On the one hand, the substantial use of oil shale as a domestic fuel guarantees energy security. Oil shale energy production, on the other hand, emits a substantial amount of greenhouse gases due to its high carbon intensity, which has a negative impact on the environment. As a result, the Estonian economy produces more than twice as much carbon dioxide (CO_2) as the EU average. The Estonian government is gradually decommissioning existing power plants and developing new technologies to drastically reduce CO_2 emissions and harmful environmental impact. Estonia exports electricity because its production slightly exceeds consumption. The total electricity output in Estonia in 2019 was 7.615 TWh, and while the total electricity demand was 8.257 TWh. Oil shale was used to generate more than half of all electricity (56%), followed by biomass (17%), wind power (9%), and renewable waste (1%) (Augutis et al., 2020).

There are over 200 DH networks in Estonia, with DH accounting for more than 60% of total heat production. Since 2014, with the EU's assistance, numerous small DH network boilers have been refurbished, and new biomass boilers have been deployed to replace ageing gas and oil-fired boilers. Oil and natural gas consumption in Estonia has been declining since 2010 (Statistics Estonia, 2020). In 2018, biomass accounted for 46.8% of the Estonian DH energy mix and natural gas for 25.6%. Oil shale (9.2%), municipal waste (6%), shale oil gas (6%), fuel oil (3%) and peat (2.8%) make up a small part of the DH energy mix in Estonia.

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

2.4. Building stock

According to Statistics Estonia, there are 23,600 apartment buildings in Estonia. Most of these apartment buildings were built during the period of industrial construction between 1960 and 1990. Apartment buildings in Estonia are mainly heated by DH and have a single-pipe heating system with hydronic radiators and no thermostats. The indoor temperature is regulated only at heating substations (Kuusk and Kurnitski, 2019). The annual energy consumption of residential buildings remains relatively stable at 10 to 12 TWh. Heating accounts for about 85% of consumption (∼9 TWh) and electricity accounts for ∼15% (∼2 TWh). The share of electricity consumption in residential building energy consumption has grown steadily over the years. The final energy consumption of non-residential buildings has also increased. In 2004, non-residential buildings consumed 4 TWh of energy. By 2017, their consumption has increased by 50%, reaching 6 TWh. Around 50% of non-residential building consumption is for heat (∼3 TWh) and the remaining 50% is for electricity (∼3 TWh). A reduction in final energy consumption of about 7 TWh/y would be possible if the buildings were fully renovated. It would be possible to reduce heat consumption by up to 70% (∼6.4 TWh/y) and electricity consumption by up to 20% (∼0.5 TWh/y). The slight reduction in electricity consumption is due to buildings that do not have an appropriate indoor climate, but this can be achieved by installing appropriate utility systems that use electricity (Ministry of Economic Affairs and Communications (Estonia), 2014).

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

Data provided by the State Land Service show that there were 39,000 apartment buildings in Latvia in 2019. The total housing stock is 91.08 million m^2, and the total area of non-residential buildings is 115.50 million m^2 (Ministry of Economics of the Republic of Latvia, 2020). The total consumption for space heating in 2019 was 10.24 TWh. Most existing buildings have a high heat consumption and significantly lower thermal properties than can be provided by currently available technologies. The average rate of depreciation for residential buildings is 38.9%. The average energy consumption for space heating among all types of buildings is 138–139 kWh/m^2 per year. In recent years, however, step-by-step measures have been taken to improve energy efficiency, resulting in a reduction in specific heat consumption. In apartment buildings, for example, the decrease between 2016 and 2019 is 13.8 kWh/m^2.

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

2.5. Pilots

DH operators mainly provide space heating and domestic hot water, while some also generate electricity in all three countries. The existing DH infrastructure is represented only by the 3rd generation (Volkova et al., 2018). The first steps to reduce the temperature are planned to be implemented in the Lithuanian capital Vilnius in 2022. A small low-temperature DH was also introduced in Latvia, in a parish of the Gulbene Municipality, which is more focused on the optimisation of the existing heating network in the village (Pakere et al., 2018). In Estonia, there are no implemented DH networks of the 4th generation. District cooling is implemented only in Estonia (Tallinn, Tartu and Pärnu) (Pieper et al., 2021; Volkova et al., 2022).

2.6. Energy policy

The electricity generation mix is diverse and unique in each of the Baltic countries. Estonia is the only country where more than 70% of oil shale is used to generate electricity. Latvia is the country where natural gas (50%) prevails over hydropower (33%). Since the shutdown of the Ignalina nuclear power plant in 2009, Lithuania has had a unique situation in the electricity market, with about 70% of electricity imported. The rest of Lithuania's electricity is generated primarily by wind (38%) and hydropower (24%), but hydropower generation in Lithuania is quite low compared to Latvia due to a substantial share of imported electricity. Electricity production can be seen in Fig. 2.

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

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

Lithuania reached its 2020 renewable energy target (23%) back in 2014. More than a third of all local electricity production in Lithuania comes from wind power plants. The share of solar PV is the highest in Lithuania among the Baltic countries due to energy policy that is favourable for investment subsidies and energy prosumers, as well as renewable energy communities. The installed capacity of energy prosumers increased from 30 MW in 2019 to 138 MW in 2021. The amount of electricity supplied by energy prosumers increased by about 4 times (from 9 MWh in 2019 to 35 MWh in 2021). For 5GDHC, the electricity mix and the particularly low electricity price is a major factor in the low maintenance costs of such a system.

2.7. Strategic DH goals

The strategic DH goals of the Baltic states are ambitious in terms of the use of RES. According to the National Development Plan of the Energy Sector until 2030, 11 TWh of the total heat

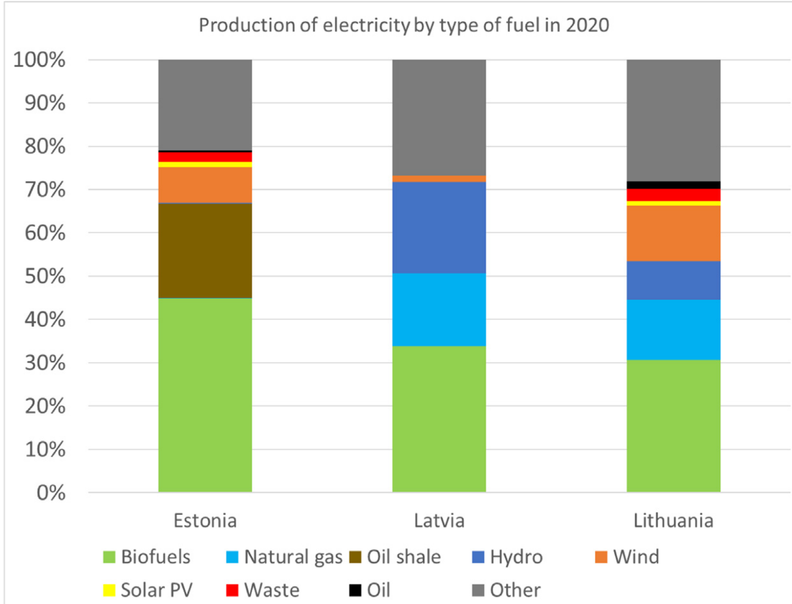

Fig. 2. Electricity generation by fuel type in 2019 (based on Eurostat (2020b)).

demand will be met by biomass in 2030, and 80% of DH in Estonia will be provided using renewable sources (Government of the Republic of Estonia, 2017). In 2020, RES already accounted for 71.5% of the total energy production in the DH networks in Lithuania. Furthermore, Lithuania has set a goal to increase this percentage to 90% by 2030 and bring it to 100% by 2050, which is the most ambitious goal among the Baltic states. According to the Latvian NECP 2021–2030, the share of RES in DH will increase by around 0.8–1.0 percentage points each year from 2020 to 2030, reaching 57.6% in 2030 (Ministry of Econonics of the Republic of Latvia, 2018).

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

The main drivers behind the implementation of 5GDHC and barriers that limit its development in Europe are summarised in Table 1. The main aspect that distinguishes 5GDHC from 4GDH is the dependence on the electricity system. A new pipe system for the ultra-low temperature DH system, as well as a dedicated new infrastructure that incorporates both heating and cooling and renewable energy sources, demand substantial initial expenses. The country's ambitious energy and climate change targets can be major drivers. Other drivers include the possibility of recycling low-temperature waste heat not only from industry but also from other local sources, as well as the development of local economic value and the creation of jobs.

3. Methodology

The possibility for 5GDHC introduction in the Baltic states was assessed using a multi-criteria analysis. A qualitative comparison was made by discussing the barriers and drivers that each country faces, and a quantitative comparison was made by assigning numerical values to each criterion. The quantitative analysis was performed using a multi-criteria decision method to compare various aspects of a potential 5GDHC implementation. The result of the quantitative analysis is the ranking of the country for each aspect.

The obtained criteria values were evaluated using the method of multi-criteria analysis called the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) and the Analytic Hierarchy Process (AHP) method to determine the weight of each criterion. The TOPSIS method of multi-criteria analysis is widely used to compare different environmental strategies for sustainable development (Balioti et al., 2018; Laktuka et al., 2021), taking into account different points of view. The main purpose of TOPSIS is to allow users to compare and choose between multiple alternatives.

The evaluation criteria are shown in Table 2. The authors used 15 different criteria to quantify and compare barriers and drivers for 5GDHC implementation in the Baltic countries.

The assessment includes criteria related to the existing power system, since the operation of 5GDHC is highly dependent on the implementation of power-driven HPs. The authors compared the average final electricity price between the countries, expecting that lower electricity prices will encourage HP adoption. In addition, the share of power supplied by RES is included because the power for 5GDHC must primarily be produced in a climate-neutral way. Finally, the authors included two criteria related to electricity CO_2 emission factors: the existing CO_2 emission factor and the projected CO_2 emission factor for each country's future energy balance based on Elering (2014), European Commission (2016). Criteria related to the current status of HP installations in the country have also been included as they indicate whether the HP market is in a mature stage. This is important from the point of view of stakeholders such as HP resellers and users.

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

Table 1
5GDHC barriers and drivers.

BARRIERS	DRIVERS
Dependence on the electricity system	Climate change targets (low GHG emissions): e.g. stop using natural gas
High initial costs	Geopolitical implications of using imported natural gas
Specific new infrastructure is required	Ambitious energy transition targets of the country
Increase in the price of electricity	Reduced price volatility
Financial sources (lack of adequate funding and financing products)	Positive effect on health
Awareness (lack of skilled personnel)	Strengthening energy security
Institutional and administrative barriers	Creating local economic value and jobs
Market barriers	Increased access to affordable, reliable, and sustainable energy for heating and cooling
Lack of public acceptance	Ability to reuse waste heat
Regulatory and policy barriers	
Separate pipes are needed to provide both heating and cooling	
Centralised energy production, limiting network expansion area	
Dwelling spatial impact and dwelling noise	
High resident risk	

Table 2
Overview of criteria used.

Criteria	Unit	Source
1 Average final price of electricity	EUR/MWh	Eurostat (Eurostat, 2020b)
2 Share of RES energy	%	Eurostat (Eurostat, 2020b)
3 Share of heat supplied via HPs	Unit per 1000 households	
4 CO_2 emission factor for electricity	t CO_2/MWh	
5 Future CO_2 emission factor for electricity	t CO_2/MWh	
6 Maximum heat tariff	EUR/MWh	
7 Minimum heat tariff	EUR/MWh	
8 DH tax rates	%	
9 Available support measures for possible 5GDHC implementation	Evaluation scale	
10 Possibility to implement innovative business models	Evaluation scale	
11 Specific building heat consumption	kWh/m^2	Odysee–Muree (Anon, 2020b)
12 Share of new buildings	%	Odysee–Muree (Anon, 2020b)
13 Excess heat source potential from shopping malls	MWh	
14 Excess heat source potential from transformers	MWh	
15 Excess heat source potential from data centres	MWh	

technological solutions. If the legal framework allows for the establishment of different tariffs and discounts for thermal energy for consumers, as well as the affordable entry of various heat producers into the heat supply market, the greatest number of points is granted for innovative business models.

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

In addition, three criteria were created to assess the accessible potential of low temperature heat sources in each country, characterising the available heat from agents (shopping malls, transformers, and data centres). As mentioned above, it is crucial to identify 5GDHC agents. The identification of agents will allow the potential of their use in 5GDHC to be assessed. This potential is one of the most important criteria for evaluating the concept's implementation. The preliminary potential of the following agents has been determined: shopping malls, electrical transformers, and data centres. According to Buffa et al. (2019), supermarkets and warehouses can play a significant role in the development of new 5GDHC projects. Retail stores as potential sources of low-grade heat were evaluated in Persson et al. (2020). It was decided to collect locally available information on retail stores in the Baltic states, including the total area and the exact location of each store.

The list of retail stores and shopping malls in Estonia was compiled using the websites of major retail chain stores and additional information obtained from companies. When most retail stores were added, the year of construction of each store and its total area were taken from the Estonian Register of Buildings (Ministry of Economic Affairs and Communications (Estonia), 2021). For Latvia, data on the total area were collected from large retail chain stores and supplemented with additional information from the data distribution portal of the State Land Service of the Republic of Latvia (Anon, 2021). For Lithuania, most of the information was obtained from large retail chain stores. The list of collected retail store data was added as a GIS map layer. The next step was to sort out the stores that are located within the DH regions and can be connected to the DH system. It was possible to merge the GIS map layer with retail stores and the layer with DH regions. The calculation results from the ReUseHeat report (Persson et al., 2020) were used to determine the estimated relative

Table 3
Excess heat potential of 5GDHC agents.

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

excess heat from retail stores in each country. Based on these results, the following average estimated excess heat amounts was determined: 0.555 MWh/m^2 for Estonia, 0.547 MWh/m^2 for Latvia and 0.469 MWh/m^2 for Lithuania. The results of possible excess heat amounts from retail stores in the DH region and beyond for the Baltic countries are presented in Table 3.

Electrical transformers can be considered as potential 5GDHC agents (Buffa et al., 2020). In Milan (Viale Gadio), there is a demo project consisting of a newly built low-temperature DH network that uses excess heat from an electrical transformer as a waste heat source. Excess heat from electrical transformers is available at 30 °C continuously throughout the year (Nathalie Fransson et al., 2021). To assess the excess heat potential of electrical transformers, a database of electrical substations has been created. Transformer location and voltage data were obtained from (Elektrilevi, 2021) for Estonia, (Sadales Tīkli, 2022) for Latvia, and (Regia:Regional Geoinformational Environmental service, 2021) for Lithuania. Locations of 330 kV and 110 kV substations were also obtained. Unfortunately, there was very limited information on transformers, so the substations were aggregated into two types: 110 kV and 330 kV. Based on previous studies on the potential of electrical transformers in Denmark (Petrović et al., 2019), it has been estimated that a 330 kV transformer can produce 18,400 MWh/y of excess heat and a 110 kV transformer can produce 560 MWh/y. Substations located in the DH regions were classified. Data centres are considered low-grade heat sources in the case of 4GDH and can be assessed as agents for 5GDHC systems. Public data on data centres were collected for each country. It was assumed that 65% of the total electricity consumption of the data centres can be considered as excess heat, as was done in Persson et al. (2020). All identified data centres are located in the DH regions.

The obtained criteria values were further normalised and weighted. The decision-making matrix and normalisation of the obtained criteria values were done using the TOPSIS method described by Loken (2007). Multi-criteria analysis' TOPSIS is often used to evaluate environmental strategies for sustainable development (Laktuka et al., 2021). The main purpose of TOPSIS is to allow for comparison and choice between several alternatives or, in this case, a comparison of barriers and drivers for the implementation of 5GDHC systems.

The ability to prioritise the analysed criteria is one of the most important aspects of using multi-criteria analysis. In this study, the AHP method was used to rank the identified criteria. In order to evaluate the problem using the AHP method, it is necessary to determine the priority criteria using pairwise comparison. The selected pairs of criteria were compared in terms of their importance on a scale from 1 (equally important) to 9 (absolutely more important). After comparing the criteria, it is necessary to check the obtained results by performing a consistency check. This check examines the evaluation of the criteria for inconsistencies. If there are inconsistencies, it is necessary to check whether the problem and the criteria are clearly defined, and to revise and re-evaluate the pairs of criteria. The criteria ranking results are shown in Fig. 3.

The authors believe that the ability to introduce an innovative business model and the availability of support for the implementation of the technology in accordance with criteria that describe the current situation in each country's energy sector are critical factors for the implementation of 5GHDC. The criterion is re-evaluated with equal weights to all options to identify the impact of the weights of the criteria set by the AHP on the evaluation of the criterion.

The final comparison between the Baltic countries was performed by multiplying the weight of the criterion by the corresponding normalised criterion value. An ideal positive decision and an ideal negative decision are calculated when constructing a normalised weighted decision matrix. The distance to the ideal solution and the distance to the non-ideal solution are calculated first (TOPSIS, 2013). The next step after determining the distance to the ideal and non-ideal solutions is to determine the ideal positive and ideal negative solutions. The relative proximity of the alternative to the ideal solution is calculated by determining which country has the most potential to introduce 5GDHC systems.

4. Results

The section presents the results of the quantitative assessment of several identified barriers and drivers for the implementation of the 5GDHC system in the Baltic countries. A summary of the obtained criteria values is provided in Table 4. The lowest final electricity price is in Estonia (0.12 EUR/kWh), but the prices in Lithuania and Latvia are almost the same. The highest share of renewable electricity is in Latvia due to the high share of hydropower. Lithuania relies heavily on imported energy. Therefore, its share of RES is low at 18.79%. However, the share of RES in Estonia is not much higher, at 22%.

The share of RES is directly related to the CO_2 emission factors for electricity from the grid. Due to the high penetration of imported energy, the CO_2 emission factor and local renewable energy generation for Lithuania is 0.02 t_{CO2}/MWh, which is relatively low compared to the values for Latvia (0.12 t_{CO2}/MWh) and Estonia (0.89 t_{CO2}/MWh). The authors also included projected CO_2 emission factors based on Elering (2014), European Commission (2016) as the implementation of 5GDHC systems is likely to be delayed and may start within the next decade. It is predicted that CO_2 emissions may decrease in Latvia and significantly so in Estonia. However, CO_2 emissions for electricity generation in Lithuania may increase.

The criteria analyses show that Estonia has a higher cumulative knowledge of HP usage, which is a closely related technology to 5GDHC. According to the report of the European Heat Pump Association, there are 29.3 HP units/1000 households in Estonia and 9 units/1000 households in Lithuania (European Heat Pump Association, 2018). Because the number of HP units utilised in Latvia is quite low, at just 1% (Ministry of Econonics of the Republic of Latvia, 2018), an estimate of one unit per 1000 households was chosen.

According to criteria used to evaluate existing DH systems, Estonia had the highest maximum heat tariff in 2019, whereas

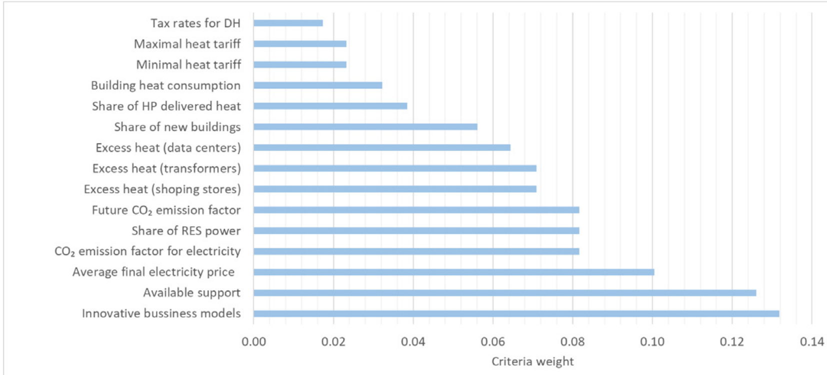

Fig. 3. Overview of the defined weight of each criterion.

Table 4
Summary of criteria results for the Baltic states.

Description	Latvia	Lithuania	Estonia
Average final electricity price, EUR/kWh	0.14	0.14	0.12
Share of RES energy, %	53.42	18.79	22.00
Number of individual HPs, unit/1000 households	1.00	9.00	29.30
CO_2 emission factor for electricity, t_{CO2}/MWh	0.12	0.02	0.89
Future CO_2 emission factor for electricity, t_{CO2}/MWh	0.08	0.06	0.22
Maximum heat tariff, EUR/MWh	69.98	79.63	86.96
Minimum heat tariff, EUR/MWh	35.45	32.57	35.33
DH tax rates, %	21	9	20
Available support measures for possible 5GDHC implementation	2.00	2.00	1.00
Possibility to implement innovative business models	1.00	2.00	1.00
Specific building heat consumption, kWh/m^2	159.7	131.3	142.8
Share of new buildings, %	5	6	2
Excess heat source potential from shopping malls, %	10%	13%	16%
Excess heat source potential from transformers, %	3%	1%	1%
Excess heat source potential from data centres, %	1%	0%	2%

Latvia had the highest minimum heat tariff. Latvia and Estonia have the same tax rates, whereas Lithuania has a lower rate. As previously stated, if the heat tariffs of existing DH systems are high, the 5GDHC system is presumed to be better.

Based on previously implemented support programmes for local and district heating systems, the qualitative assessment criteria indicate probable support for 5GDHC systems in Lithuania and Latvia. Furthermore, due to the open heating market conditions in Lithuania, innovative business models that are crucial for 5GDHC systems are more likely to be implemented. However, existing market regulations do not allow introducing different heating tariffs in Latvia and Estonia. Therefore, the criteria score is lower.

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

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

In accordance with the methodology described above, the values of the identified criteria from Table 4 were normalised and weighted to determine the proximity to the ideal solution for each country. The results in Fig. 4 show different values for similar and prioritised criteria values. When the identified criteria are prioritised by assigning higher weight values for the possibility of introducing an innovative business model and available support for technology implementation, followed by criteria describing the existing situation in each country's energy sector, Lithuania has the highest score due to support availability and open heating market conditions. However, when equal criteria weights are assigned, the highest evaluation rank belongs to Estonia due to the wider use of HPs and higher excess heat potential.

5. Conclusion

This study conducted a comprehensive review of potential agents that could be used as active heat sources or sinks in 5GDHC in the Baltic states. The barriers and drivers for the implementation of 5GDHC were also systematically investigated in terms of economics, markets, technology, policies, etc. Country-specific conditions such as heating tariffs, regulatory mechanisms, stakeholders, existing DH infrastructure, DH market and others were evaluated for the three Baltic states (Latvia, Estonia, and Lithuania). The main barrier to the development of 5GDHC in the Baltic countries is the well-maintained and widespread 3rd generation DH in all three countries. More than half of the population in each country is already connected to DH systems not only in major cities but also in smaller towns. Another major hurdle is the high initial costs of the new 5GDHC pipeline system for ultra-low heating and cooling temperatures and renewable energy sources. The main drivers for the development of 5GDHC in the Baltic countries are the countries' ambitious energy and climate change goals. Furthermore, the possibility of recycling low-temperature waste heat not only from industry but also from other local sources, as well as the development of local economic value and jobs are among the drivers.

The multi-criteria analysis method was used to quantify the main identified barriers and drivers behind the implementation of

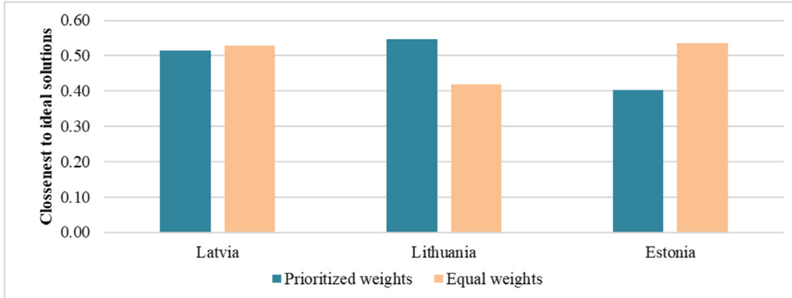

Fig. 4. Results of multi-criteria assessment with prioritised criteria weights and equal criteria weights.

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

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

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

The present geopolitical situation has significant impact on the imported energy prices, and this will further affect the electricity and natural gas prices in different countries. The countries with large electricity import (e.g., Lithuania) could be more sensitive to the geopolitical issues for the 5GDHC development. But in the long term, with more integration of renewable energy into the energy mix (corresponding to the climate targets in each country), the impact of geopolitical situation is expected to be decreased. The findings from this study are still valid in a long-term perspective.

CRediT authorship contribution statement

Anna Volkova: Conceptualization, Methodology. **Ieva Pakere:** Methodology, Software, Writing – original draft. **Lina Murauskaite:** Investigation, Writing – review & editing. **Pei Huang:** Methodology, Validation. **Kertu Lepiksaar:** Data curation, Visualization. **Xinxing Zhang:** Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Anna Volkova reports financial support was provided by Nordic Energy Research. Ieva Pakere reports financial support was provided by Nordic Energy Research. Lina Murauskaite reports financial support was provided by Nordic Energy Research. Pei Huang reports financial support was provided by Nordic Energy Research. Kertu Lepiksaar reports financial support was provided by Nordic Energy Research. Xingxing Zhang reports financial support was provided by Nordic Energy Research.

Data availability

Data will be made available on request.

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