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Faculty of Environmental Sciences
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Philosophiae Doctor (PhD)
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Nordic district heating and energy system flexibility – Challenges and opportunities

Nordisk fjernvarme og energisystem-fleksibilitet – muligheter og utfordringer

Eli Sandberg

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That I would reach this point has not been obvious all along. These years have had major ups and downs. Still, I count it all as part of the learning curve. I could never have managed this on my own, and I have many people to be thankful to.

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Sincerely,

Eli Sandberg

Summary

This thesis presents framework conditions for Nordic district heating and barriers and opportunities for flexibility in the district heating – electricity interface.

District heating has advantages and disadvantages. Security of supply, flexibility in the energy system and increasing the renewable energy share are arguments that have qualified for an investment support scheme for district heating in Norway. The district heating markets have several characteristics of market failure, such as natural monopoly, externalities and asymmetric information. The Nordic countries have different measures to correct for these market failures. In contrast to the homogeneous electricity market, the framework conditions for district heating vary greatly between the Nordic countries, and the tax systems are complicated and have many exceptions. The district heating sectors are also largely affected by framework conditions aimed at other targets. Among disputed areas of great relevance for the district heating sector are sustainable use of biomass and waste.

Norwegian district heating is limited compared to Danish, Finnish and Swedish district heating. The main reason is not the economic and political framework conditions, but rather of historical reasons. Electricity has gained a unique position in Norway, where electricity is relatively cheap; the infrastructure is built around hydro power and electricity has become a natural source of heating.

The district heating sector can contribute to decarbonizing the energy sector and can potentially be a significant provider of energy system flexibility. District heating can be produced by heat pumps or electric boilers when there is excess power supply in the system and use other fuels than electricity when there is a power shortage. When the power prices are high, combined heat and

power plants can produce electricity. Excess heat can be stored in tanks. In this way it might be profitable for the district heating producers to contribute to increasing the uptake of renewable power.

Results show that thermal storage is a no-regret investment. This is, however, mostly due to the fact that it enables increased utilization of the base load technology. Allowing thermal plants to run on partial load reduces the relative competitiveness of heat storages, suggesting that flexible thermal power plants are important providers of flexibility. The Balmorel model results show that investments in heat storage are largest in Denmark, where the need for flexibility is greater. Investments in electric boilers and heat storage correlate, suggesting an efficient interaction between these technologies. The results, however, further suggest that, under the current economic framework conditions and spot market prices, electric boilers are not competitive in the market for heat and that CHP plants are not profitable without a subsidy. Less flexible technologies, such as heat-only biomass boilers and heat pumps, are more competitive and are used as base load.

The flexibility potential of the district heating sector is thus largely unutilized. A fixed load demand component of the electricity grid tariff is one example of a barrier for energy system flexibility in the district heating – electricity interface, because it makes flexible electric boilers less competitive. A tax exemption for biomass-based fuels weakens the competitiveness of CHP in relation to biomass boilers.

List of papers

The thesis is based on the following papers, which are found in the appendix:

Paper I: Sandberg E, Sneum DM, Trømborg E. Framework conditions for Nordic district heating – Similarities and differences, and why Norway sticks out. Energy (2018); 149: 105-119. DOI: https://doi.org/10.1016/j.energy.2018.01.148

Paper II: Sneum DM, Sandberg E, Koduvere H, Olsen OJ, Blumberga D. Policy incentives for flexible district heating in the Baltic countries. Utilities Policy (2018); 51: 61-72. DOI: https://doi.org/10.1016/j.jup.2018.02.001

Paper III: Sneum DM, Sandberg E. Economic incentives for flexible district heating in the Nordic countries. International Journal of Sustainable Energy Planning and Management (2018); 16: 27-44. DOI: https://doi.org/10.5278/ijsepm.2018.16.3

Paper IV: Sandberg E, Kirkerud JG, Trømborg E, Bolkesjø TF. Energy system impacts of grid tariff structures for flexible power-to-district heat. Energy (2019); 168: 772-781. DOI: https://doi.org/10.1016/j.energy.2018.11.035

1 Introduction

1.1 Background

According to the IPCC special report of October 2018, global CO_2 emissions need to decrease by 45% by 2030 from a 2010 level in order to reach the recommended 1.5-degree target. A target of 2°C requires a 25% reduction in climate gas emissions. Currently we are heading for a 3-degree temperature rise, which will likely have extensive impacts on sea level, biodiversity and weather scenarios [1]. In order to curb climate change and to satisfy the Paris agreement [2], we need tremendous changes in all sectors, including the household and service sectors, industry, transport and energy.

The Nordic countries aim for carbon neutrality[1] by 2050 [3]. Denmark recently adjusted their climate targets and are very ambitious for 2030 [4]. Figure 1 shows the emissions of CO_2 equivalents in the Nordic countries from 1990 to 2017, and the targets for 2030 and 2050.

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[1] Processes, businesses or other economic activity that in total do not lead to an increased CO_2 content in the atmosphere. Forests can absorb carbon and has a negative sign in the climate accounts. Emissions can also be cut in other countries.

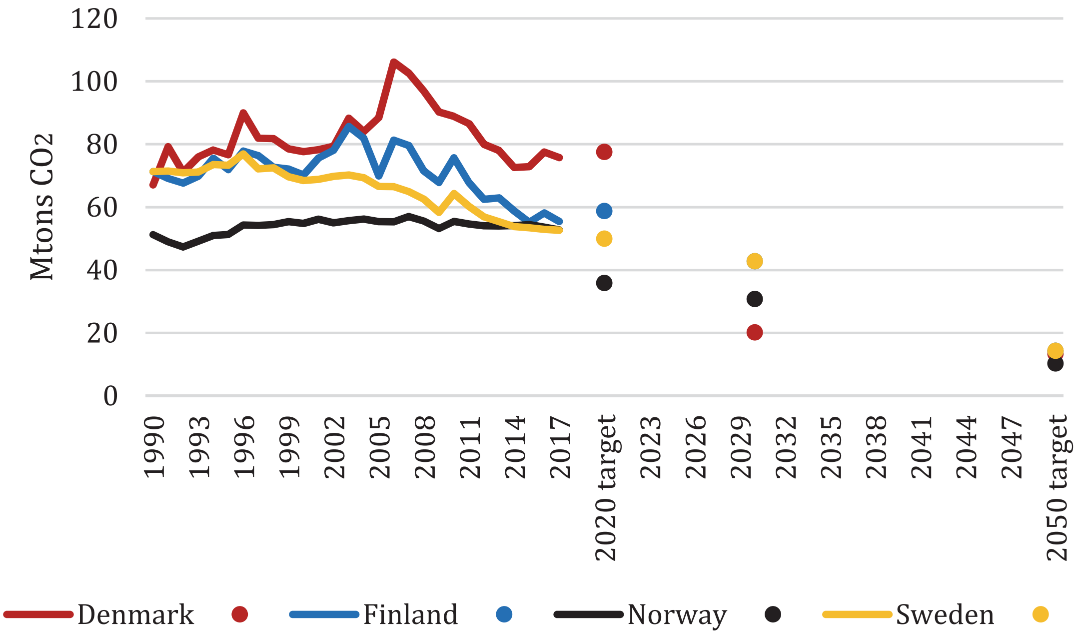


Figure 1. Climate gas emissions 1990-2017 [5, 6, 7, 8] and targets for 2020, 2030 and 2050 [9, 10, 11, 12, 13] in the Nordic countries

Because we are approaching the capacity limit of hydropower with reservoirs, the carbon neutral energy future relies on new renewable energy resources, such as run-of-river, solar and wind to decarbonize electricity generation. These new renewables are non-adjustable and variable. We will be able to produce electricity from wind only when the wind is blowing, and from solar radiation only when the sun is shining. To produce electricity from run-of-river we are dependent on precipitation or meltwater. Electric storage capabilities are currently limited and there is a growing need to balance the power system as the renewable share grows. To be able to integrate the new renewables, maintain the security of supply and avoid large and frequent price fluctuations, energy system flexibility is crucial [14]. There seems to be a broad consensus that there will be a future need for increased flexibility in the Nordic energy system [15]. The electricity grid and energy generation plants are dimensioned according to an expected maximum load. Energy system flexibility is a means to avoid critical peak loads, save investment costs in grid expansion and increased capacity. This means that there may be flexibility options that are more cost efficient than grid expansion and these need to be considered [16]. How to achieve flexibility is, therefore, ambiguous [17].

According to Nordic Energy Technology Perspectives, the energy consumption in buildings constituted one third of the total energy consumption in 2013. They expect energy consumption in buildings to decline towards 2050, with a 2% decline in the four-degree scenario and a 26.5% decline in the carbon neutrality scenario. Energy use for space and water heating, as well as cooling, accounted for 73% of energy consumption in buildings in 2013, and this percentage is expected to fall to 69% in the four-degree scenario and to 63% in the carbon neutrality scenario [18]. The renewable shares for heating and cooling were 47, 55, 31 and 69% in Denmark, Finland, Norway and Sweden respectively in 2017. This calculation method does not include electricity for heating, which in Norway can be very high, up to 80%, depending on the outside temperature [19, 20, 21]. District heating accounted for 44% of the energy consumption for heating in buildings in Denmark, Finland, Norway and Sweden combined in 2013 [22, 23, 24, 25].

The district heating sector serves more than 50% of households with heat in Denmark, Finland and Sweden [26]. District heating can be produced using many different fuels, and the aggregated fossil share in district heating in the Nordic countries was 16% in 2017 [22, 27, 28, 29]. Since the district heating sectors make up a significant share of the energy system in the Nordic countries, are fuel flexible and adaptive, district heating can both contribute to decarbonizing the heating sector and potentially be a large provider of flexibility to the electricity system. The district heating sector can provide flexibility to the electricity system, both as a consumer and as a supplier of electricity. Combined heat and power (CHP) plants produce heat and electricity simultaneously. Power-to-heat technologies use electricity to produce heat through heat pumps or electric boilers. By using electric boilers or heat pumps, the district heating sector can produce heat when the electricity prices are low.

Through CHP plants, the district heating sector can produce electricity when the electricity prices are high. By using heat storage, they can produce heat from electric boilers and heat pumps when the electricity prices are low, and produce heat combined with electricity when the electricity prices are high, even if heat is not needed at that time. This can be a profitable application for district heating producers and a prominent flexibility provider if the technology is competitive at the outset [30]. Kirkerud et al. (2017) found that there is significant potential for flexibility from power-to-heat technologies in the district heating sectors of the Nordic countries [31]. The system operator of the Norwegian power system also regards the district heating sectors in the Nordic countries as a potentially important flexibility provider [32].

In the district heating - electricity interface it can be more efficient to deploy several flexibility options simultaneously. Blarke (2012) found that electric boilers and heat pumps, combined with existing CHP, can increase variability-friendliness in the energy system [33]. Lund and Clark (2002) point out that both heat storage and heat pumps are necessary flexibility options [34]. Figure 2 summarizes some of the flexibility options given by district heating (in red).

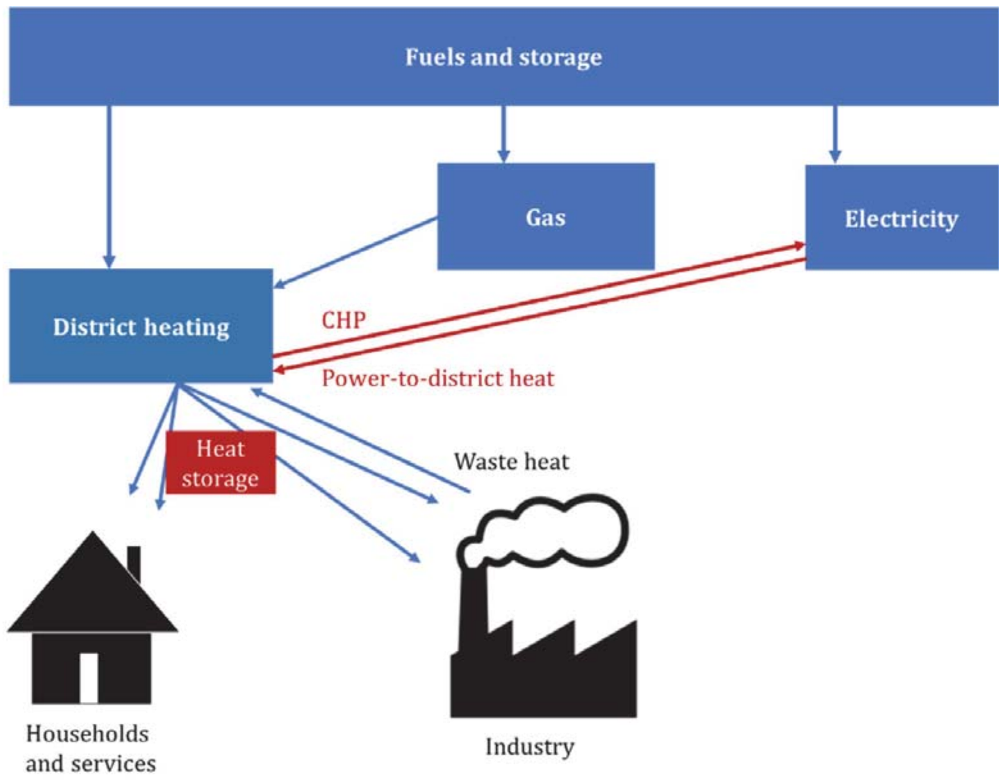


Figure 2. Flexibility options and sector coupling in the district heating – electricity interface

For the district heating sector to be able to provide flexibility to the electricity market, the district heating sector itself needs to incorporate flexible technologies. Additionally, the technology that is used needs to be a technology that connects the district heating sector to the electricity sector. This could be through CHP or power-to-heat technologies. Both the potential and capacity need to be present to be able to deploy flexible technologies. The flexibility potential is currently much larger than the installed flexible capacity and actual deployment. There is a gain to make from additional flexibility capacity if it is used and applied only when needed [35].

Last, but not least, the flexibility provided needs to be sufficiently large to be able to affect the electricity price and relieve the electricity transmission grid. The current flexibility capacities in district heating related to electricity are indicated through the CHP and power-to-heat shares. Figure 3 summarizes key characteristics of the district heating sectors in the Nordic countries related to flexibility.

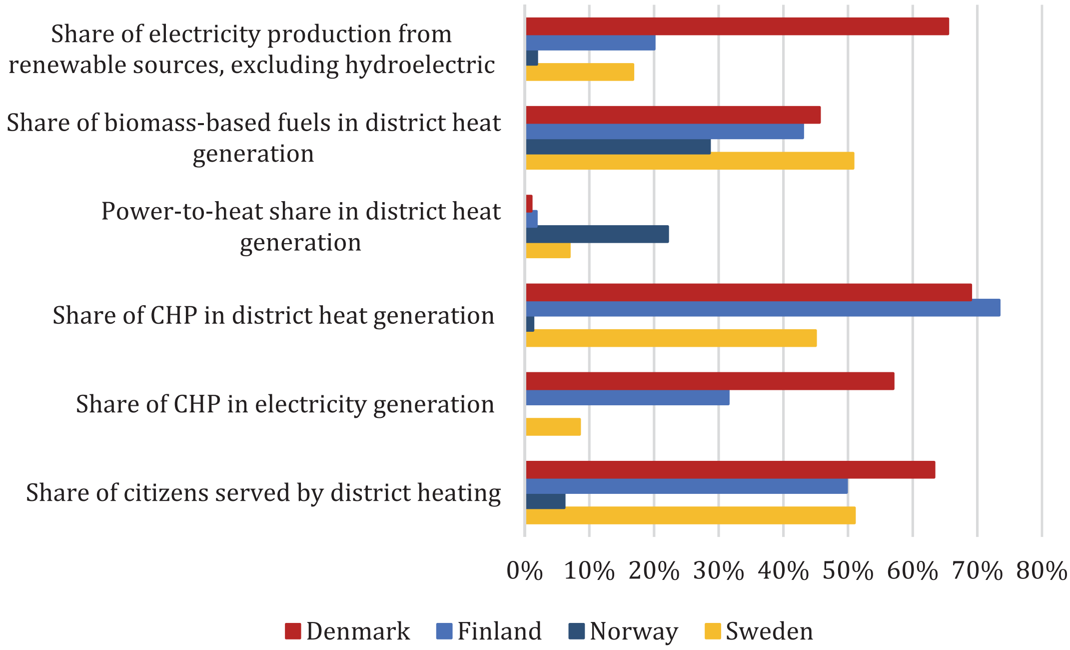


Figure 3. Comparing the district heating sector's position and the key characteristics related to flexibility in the Nordic energy system 2017 [22, 26, 27, 28, 36, 37]

1.2 Objectives

The main objectives of this work are 1) to describe the framework conditions for Nordic district heating and 2) to describe the flexibility opportunities and constraints in the district heating – electricity interface in the Nordic region.

An overview of framework conditions in Nordic district heating is presented in paper I *Framework conditions for Nordic district heating – Similarities and differences, and why Norway sticks out*. This paper covers a wide range of framework conditions for district heating in the Nordic region and analyse why district heating in Norway is very limited compared to the other Nordic countries. Paper II *Policy incentives for flexible district heating in the Baltic countries* and paper III *Economic incentives for flexible district heating in the Nordic countries* investigate how the framework conditions may impact investment in flexible solutions in Nordic and Baltic district heating. Paper IV *Energy system impacts of grid tariff structures for flexible power-to-district heat* focus on electricity grid tariffs and how the structure of the electricity grid tariffs can be a barrier for district heating producers to operate flexibly in the district heating – electricity interface.

This thesis describes the empirical and theoretical background for regulation, fuels and technologies for district heating and flexibility in Nordic district heating. It presents arguments for and against regulation of district heating, including flexibility options through power-to-heat technologies, CHP and heat storage.

1.3 Thesis outline

Chapter 2 describes Nordic district heating and flexibility in the district heating – electricity interface, including arguments for and against district heating and central framework conditions. Chapter 3 presents theoretical framework behind regulation of the district heating sector and flexibility. Flexibility options, both in chapter 3 and 4 are divided into power-to-heat, CHP and heat storage. Chapter 4 gives a general description of the methods used for the four papers included in the thesis. Chapter 5 gives a summary of the four papers, including the main objectives, a more specific description of the method used, and the main results and points of discussion of the papers. Chapter 6 gives an overall discussion of the thesis results, concentrating on methods, impacts of policies and future research. Chapter 7 concludes.

1.4 Related work

Mazhar et al. (2018) give a broad overview of the development, ongoing technological enhancements, social and economic factors as well as regulation of district heating globally [38]. Werner (2017)$_1$ also considers the entire world when reviewing district heating and cooling but focuses on the reasoning and driving forces behind the development of district heating [39]. Sayegh et al. (2017) review district heating in 22 European countries in terms of current technologies and future trends [40]. Lake et al. (2017) review case studies on district heating and cooling systems in a sustainability perspective. They include topics as history, arguments for and against district heating, technologies, efficiency, fuels, economic feasibility and energy policy [41]. Wissner (2014) uses economic theory to explain the regulation of district heating in general, but with a focus on price regulation and with examples from German district heating [42].

There are no comparative studies for district heating in general for the Nordic countries, but there are many studies addressing specific countries, specific framework conditions, or specific fuels or technologies within district heating. Sernhed et al. (2018) summarized recent studies of Swedish district heating [43]. Werner (2017)$_2$ presented the status of Swedish district heating in terms of the market position, technologies, environmental impact, as well as identifying the main driving forces for the development of Swedish district heating and proposed how the district heating sectors will look in the future [44]. Paiho and Saastamoinen (2018) describe challenges and opportunities for the further development of Finnish district heating [45]. Low-temperature district heating is a prioritised research area in Denmark, pointing in the direction of future district heating [46]. Prosumers [47] and low temperature district heating [48] are features of future district heating also studied in Norway.

The literature on energy flexibility and flexibility in the district heating – electricity interface is also extensive when it comes to specific means, technologies and forecasts for specific countries. Paiho et al. (2018) describe promising flexibility options in the Finnish energy systems [15]. Skytte et al. (2017) discuss policy measures that may hinder a flexible coupling of the thermal and electricity sectors [49]. Sneum (2019) has identified 33 barriers to flexibility in the district heating - electricity interface that he is categorizing. This work is in progress and described in the HotCool magazine [50].

2 Nordic district heating

2.1 The development and status of district heating in the Nordic countries

District heating is energy that is transported as hot water or steam in pipes and is used for heating buildings and tap water. To distinguish district heating plants from central heating plants, Statistics Norway defines a district heating plant as a heating system that supplies heat to external customers and has an installed capacity of at least 1 MW [51]. District heating is commonly mentioned as an urban energy option because it is mostly found in densely populated areas.

Figure 4 shows how the district heating sectors in the Nordic countries, Denmark, Finland, Norway and Sweden, have developed over the years since district heating was established in Norway and in terms of delivered district heat. The district heating sectors are of significant size in Denmark, Finland and Sweden. Norway has very little district heating compared to the other Nordic countries.

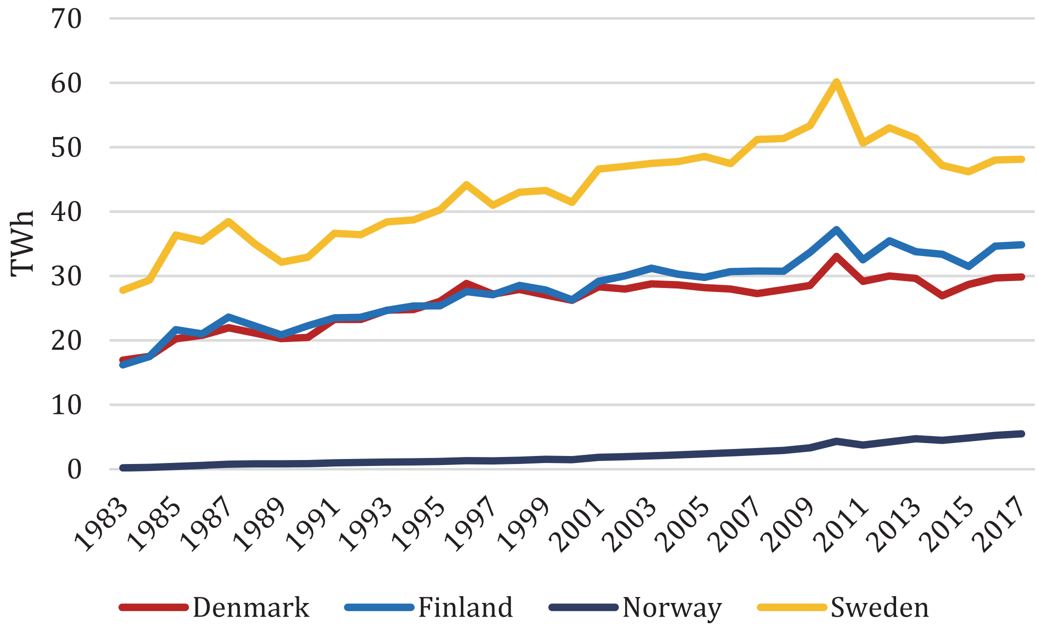


Figure 4. Delivered district heat in the Nordic countries 1983-2017 [22, 23, 24, 25]

Norway undertook massive hydropower development from the 1950s to the 1980s and has since benefited from power surpluses and low electricity prices. This has led to electricity becoming a natural source for heating in Norway. This distinguishes Norway from the other Nordic countries, which have suffered from domestic energy resource scarcity to different extents and at different times. Figure 5 shows how the energy resources for heating are distributed among the Nordic households. For Norway, it is assumed that 60% of the electricity consumption in households is used for heating [52].

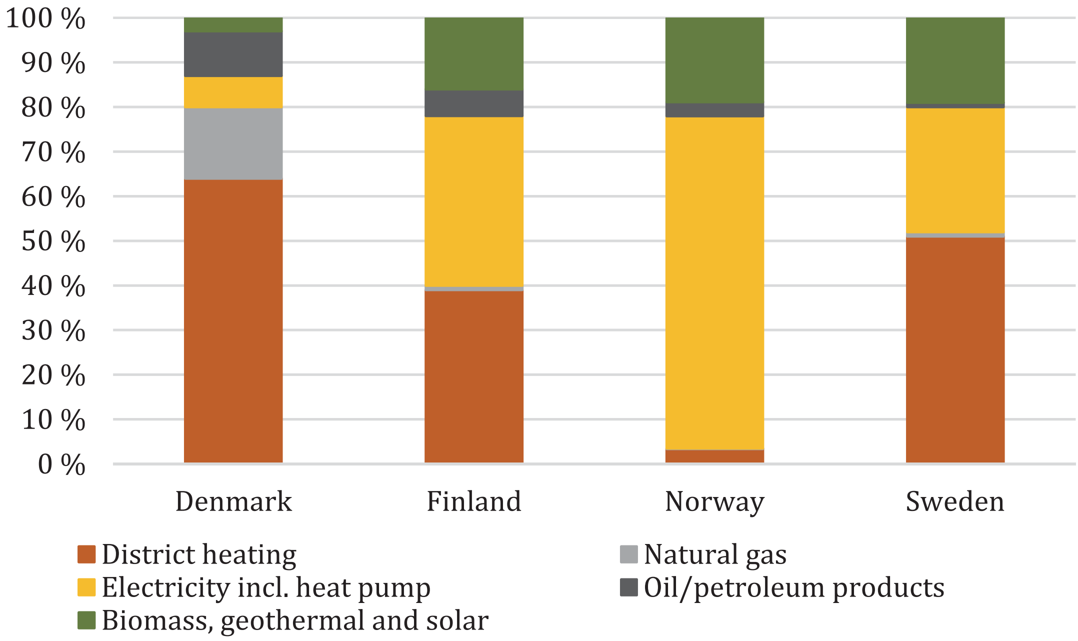


Figure 5. The share of energy consumption for heating in Nordic households 2017 [22, 53, 54, 55]

2.2 Regulating Nordic district heating

District heating has advantages and disadvantages. Historical, economic, political and jurisdictional drivers and barriers are structured and explained in more detail in paper I. The framework conditions may affect producers or consumers, fuels or technologies, and have an indirect or direct impact on investment or operation or use. Some of the arguments for or against district heating may justify policy measures, while the majority must put their trust in the market.

Why district heating?

Werner (2017) emphasizes the use of surplus heat and energy efficiency as strong drivers for introducing district heating. On the demand side, he mentions convenience, that it requires no supervision and that there is no need to obtain fuel as the main driving forces [39]. Lake et al. (2017) highlight higher energy efficiency of district heating compared to individual systems, higher cost efficiency for populated areas and environmental friendliness as the main advantages of district heating [41]. The most prominent arguments for and against district heating are summarized in table 1. The district heating associations and district heating companies of the various countries are, of course, those who promote district heating and present the benefits of district heating. District heating resistance is less visible, especially in Denmark, Finland and Sweden where district heating is more widespread. There are, however, debates concerning framework conditions. In Denmark, a tax has recently been introduced on surplus heat, which the district heating industry wants exemptions for [56]. The secretariat for the tax and grant analysis in the energy field argues that, without a tax, false surplus heat will be produced. False surplus heat means that there will be incentives to use additional fuels to produce excess heat and, thus, more than necessary to obtain the production level [57]. Finland discusses how the share of renewable energy in Finnish district heating should increase and the extent to which biomass is part of the solution [58]. In Sweden, the current debate is largely based on the environmental benefits of import and incineration of waste, since recycling provides valuable gains in relation to combustion, especially when considering emissions from the transport of waste [59]. A tax on waste incineration in Sweden has been proposed, for which potential effects are debated [60]. The price regulation of Norwegian district heating was evaluated in 2010 and 2013, and both reports called for an assessment of the entire framework in order to make recommendations for one specific framework condition. The report from 2013 [61] nevertheless gives a cautious recommendation for a continuation of the rule that the district heating price cannot exceed the electricity price, with taxes and electricity grid tariffs included. The report from 2010 [62] proposed some adjustments to make the pricing more dynamic. In Norway, there is still government support for district heating development, which has been up for debate from time to time. A research report from Norwegian Business School evaluated the framework conditions for district heating in Norway in 2007 and proposed to abolish the investment subsidies because they are not in line with Enova's mandate to take cost efficient measures to reduce greenhouse gas emissions [63]. Enova is a directorate under the Norwegian Ministry of Climate and Environment. They manage the Energy and Climate fund, which aims to induce reductions in greenhouse gas emissions, increase energy efficiency and enhance security of supply.

Security of supply, flexibility in the energy system and increasing the renewable share are socio-economic arguments that have qualified for the Norwegian investment support scheme [64].

The use of biomass [65] and waste [66] for fuels in the district heating sector is disputed in Norway, as in Finland and Sweden. Since district heating is produced in different ways and in different places, it is difficult to conclude on competitiveness and profitability of district heating; this must be calculated for each plant. The district heating sector's ability to reduce national climate gas emissions depends on the district heating sector converting from fossil fuels. The climate effects from incinerated waste and biomass are also in question.

District heating plants also have large buildings with smokestacks that might not be a desired view for the neighbours. District heating production may also generate flue gas that contains polluting substances if the plant does not have flue gas condensation and other measures to clean the flue gas. In addition, activity on the plant may involve some noise and traffic. These are factors that need to be considered before a plant is built and located [67].

Table 1. Arguments for and against district heating [68, 69, 70, 71, 72]

Why district heating?	**Supply side**	**Consumer side**	**For society**
Flexible	A flexible fuel mix	Low probability of interruption	Load reserve
	Possibility of fuel storage		
Energy efficient	By using residuals and waste heat		Saving resources
Climate friendly	By using fossil-free fuels	Better indoor climate	Convert from individual oil boilers
Safe and robust	Less prone to storms	Reliable, little fault	
Convenient	Requires little maintenance	Smooth and stable delivery	
		Little need for supervision	
		Little user management	
		The heating centre and heat exchanger require little space, are clean, quiet and odourless	
		No need for fuel, boiler, fuel tank and water heater	
		Long technical lifetime	
Competitive		Competitive to other heating options	
Utilizing local energy resources	Reducing transport costs		Regional economic growth and security of supply
Why not?	**Supply side**	**Consumer side**	**For society**

Not competitive		Heat pumps and biomass boilers compete	Dependent on subsidy
		Requires a hydronic system	
Environmental impacts	Carbon price	Conscience	Climate gas emissions, noise, traffic, flue gas, visual pollution
Higher value creation from the use of biomass and waste for other purposes	Local and cheap fuels		A second-best solution to the waste problem

The Nordic fuel taxation schemes

The district heating sector faces a mix of framework conditions. Paper I focuses on framework conditions for heat-only generation, based on biomass and fuel oil as peak load, and the economic framework conditions the model plant is facing. Table 2 summarizes the taxes on different fuels in the Nordic countries and shows how the tax level differs not only between countries, but also according to quota obligations and whether the district heating plant also produces electricity or not.

Table 1. Taxes (in €/MWh) for different fuels and different technologies for district heating plants in the Nordic countries (2019) [73, 74, 75, 76]

		Full tax		Heat-only EU ETS		CHP Heat EU ETS		CHP El EU ETS	
		Energy tax	CO_2 tax	Energy tax	CO_2 tax	Energy tax	CO_2 tax	Energy tax	CO_2 tax
Fuel oil	Denmark	24	6	24	6	24	6	0	0
	Finland	7	14	7	14	7	7	0	7
	Norway	15	12	15	12	15	12	15	12
	Sweden	23	19	23	15	7	0	0	0
Natural gas	Denmark	14	3	14	3	14	3	0	0
	Finland	8	13	8	13	8	6	0	6
	Norway	0	11	0	6	0	6	0	6
	Sweden	0	12	0	10	0	0	0	0
LPG	Denmark	27	5	27	5	27	5	0	0
	Finland	8	14	8	14	8	7	0	7
	Norway	0	12	0	0	0	0	0	0
	Sweden	8	25	8	20	2	0	0	0
Coal	Denmark	21	6	21	6	21	6	0	0
	Finland	8	22	8	22	8	11	0	11
	Norway	0	0	0	0	0	0	0	0
	Sweden	10	42	10	33	3	0	0	0
Bio oil	Denmark	30	0	30	0	30	0	0	0
	Finland	9	0	9	0	9	0	0	0
Electricity	Denmark	118	0	29	0	29	0	29	0
	Finland	23	0	23	0	0	0	0	0
	Norway	16	0	1	0	1	0	1	0
	Sweden	33	0	33	0	33	0	0	0

Liquid fossil fuels and natural gas are taxed in all the Nordic countries. Coal and coal products are taxed in Denmark, Finland and Sweden. In Norway there are no taxes on coal, but there is also a limited use of coal, except in Svalbard [77]. Peat has a lower, fixed energy content tax in Finland. The fuel taxation is divided between an energy tax and a carbon tax in all the Nordic countries. Finland previously had a different design for its energy taxation scheme, with a tax component called a strategic stockpile fee, but this structure ceased from 2017. Denmark, Norway and Sweden also have a sulphur tax and a NOx tax. Denmark has a methane tax that applies for some fuels. Fuels based on biomass are, in general, not taxed in the Nordic countries, but biomass use has a sulphur and NOx tax in Denmark and bio oil is subject to an energy content tax in Denmark and Finland. There is no additional sulphur tax in Finland, but fuel oil is taxed according to its sulphur content. There is no energy tax for producing electricity in Denmark, Finland and Sweden, either in electricity-only plants or CHP plants. The heat production from cogeneration is credited against an energy tax. Both heat and power production in CHP plants get a 50% reduction of the carbon tax in Finland. Power generation in CHP plants subject to quota obligation is exempt from carbon tax in Denmark and Sweden. Power producers without quota obligations need to pay the carbon tax. Heat producers in Sweden with a quota obligation get a 30% discount on the energy tax and an 80% reduction in the carbon tax. In Norway, the tax scheme does not separate heat producers from power producers. In Norway, heat and/or electricity producers with quota obligations face a reduced carbon tax on natural gas. Producers who use fuel oil in Norway must pay the full carbon tax, regardless of whether they are subject to the EU's quota system or not.

While energy taxation has the purpose of reducing energy consumption and carbon taxes aim to reduce climate gas emissions, electricity taxes are mainly fiscally justified. Like the tax schemes for fuels, electricity tax schemes differ among the Nordic countries. Norwegian district heating producers pay a significantly reduced electricity tax, making power-to-heat more competitive in Norway than in the other Nordic countries. The reduced electricity tax also applies to industries and municipalities furthest north in Norway. In Finland and Sweden, electricity used in CHP plants have exemption from electricity tax, while heat pumps and electric boilers in heat-only plants face full electricity taxation. Finnish industries and data server suppliers are also eligible for a lower electricity tax. Certain industries and municipalities in Northern Sweden can claim a partial tax refund. Denmark has by far the highest taxes on electricity consumption among the Nordic countries, even with tax deductions. Electricity consumption used for heating and in district heating plants in Denmark are eligible for a partial refund of the electricity tax. District heating producers under the “Electric boiler scheme” have exemption from the public service obligation (PSO) and may claim a partial refund of the electricity tax.

The refund is dependent on heat production, which makes the use of electric boilers relatively more competitive. The ratio of delivered energy and added energy to the heat pump is called the coefficient of performance (COP). For heat pumps with a COP above 2.66, district heating producers with heat pumps are better off paying full tax, since the tax refund is based on heat production rather than electricity input. The PSO is being phased out since 2017 and, from January 2022, electricity consumption is no longer charged a PSO tariff, which makes the full tax option even more attractive to district heating producers with heat pumps with a COP down to 1.88. In Denmark, electric boilers and heat pumps, thus, have different economic framework conditions. Finland and Sweden have different policies towards cogeneration and heat-only plants. Norway does not distinguish cogeneration and heat-only, or heat pumps and electric boilers. Denmark, Norway and Sweden, however, distinguish between actors with and without carbon quota obligations. Until 2013, Denmark had a carbon tax on electricity [78]. Now, however, there is no carbon tax on electricity in the Nordic countries.

In Sweden and Norway, there is a fixed tax on electricity consumption, in addition to the energy dependent electricity tax. These are included in the fixed component in the grid tariffs. The Danish PSO is an energy dependent tax that comes in addition to the electricity tax. Until 2016, the Finnish strategic stockpile fee had the same function. Now, Finnish electricity taxation only consists of an energy tax. The public tax in Sweden is meant for security of supply purposes and the components are called electrical safety, network monitoring and emergency response fee [79]. In Norway, the fee for the energy fund is a means to promote a shift to environmentally friendly energy consumption and generation. The Danish PSO finances the premium tariff for renewable electricity generation [80]. Consumers also pay for the promotion of renewable electricity generation through the green certificate scheme in Sweden and Norway. Finland also promotes renewable energy generation through a premium tariff and subsidies but finances this trough the State budget [81, 82].

2.3 Fuels in Nordic district heating

District heating can originate from many different energy carriers. Figure 6 shows the fuel distribution in terms of supplied energy for district heat generation in the Nordic countries in 2017. The share of biodegradable waste in Denmark is assumed at 55% [20] and in Norway estimates vary from 47% [83] to 52% [84]. The renewable share of domestic electricity generation was 60, 35, 104 and 66 in 2017 in Denmark, Finland, Norway and Sweden respectively, and when export is included in the calculation [85]. Biomass contains carbon. Combustion of biomass is nevertheless considered climate neutral as sustainable forest management is expected.

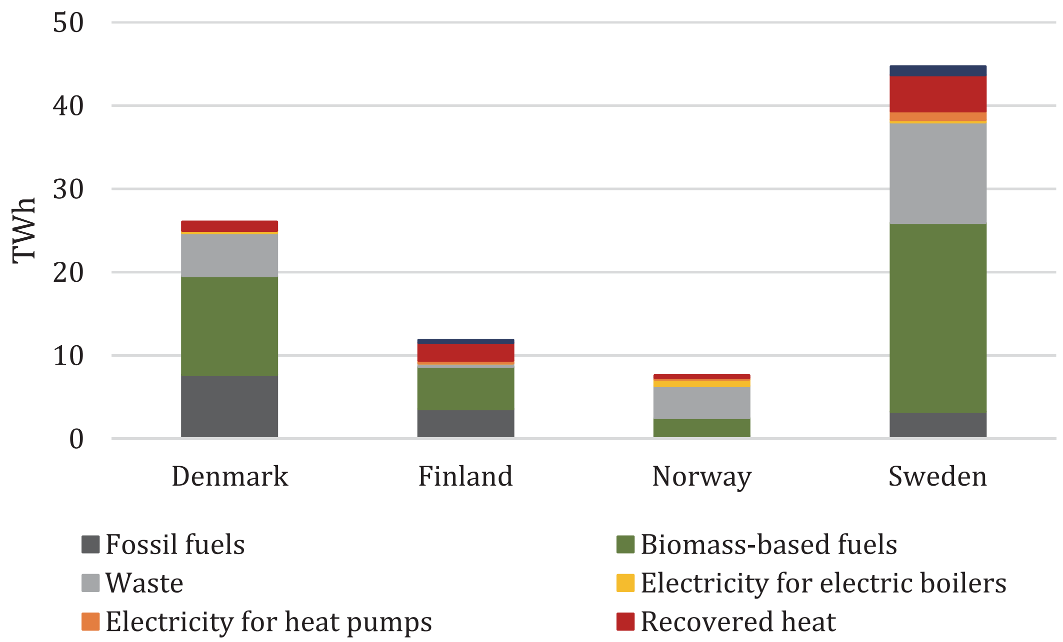


Figure 6. Fuel distribution in Nordic district heating generation 2017 [22, 27, 28, 29]

Fossil fuels

The fossil share of input to district heating generation in the Nordic countries was 31, 38, 5 and 6% in 2017 for Denmark, Finland, Norway and Sweden respectively. For the latter two, and especially for Norway, this fossil part consists of peak load boilers that use fossil oil and gas. 2010, which was a very cold year, had a peak in the fossil share because these oil and gas boilers were used. Bio oil can replace fossil oil and contribute to making the district heating sector more renewable. In Denmark, even though the fossil share is decreasing, a larger share of the fossil fuels used for district heat production is still used for base load. The larger district heating systems typically provide district heating from cogeneration at the central power stations that are based on coal and biomass. During the period 1985-2005, many decentralized CHP plants were built. These are based on different technologies and fuels (e.g. natural gas, waste, straw, wood chips and biogas). The predominant fuel is natural gas, but since 2005, many of the decentralized plants have converted to straw and wood chips at the expense of natural gas. In the early 1990s, coal was the preferred fuel, but since then, the share of oil, natural gas and renewable energy has increased [86]. In 2030, coal fired plants are to be phased out and replaced with biomass [87]. In Finland, fossil fuels are still used for base load, but the fossil share is decreasing. From 2029, coal will be banned for energy production and a support scheme for converting to other fuels is being prepared [88]. Figure 7 shows the distribution of fossil fuels in district heating generation in the Nordic countries in 2017, in terms of supplied energy. Figure 8 shows the development of the use of fossil fuels for district heat generation over the years 2010 to 2017.

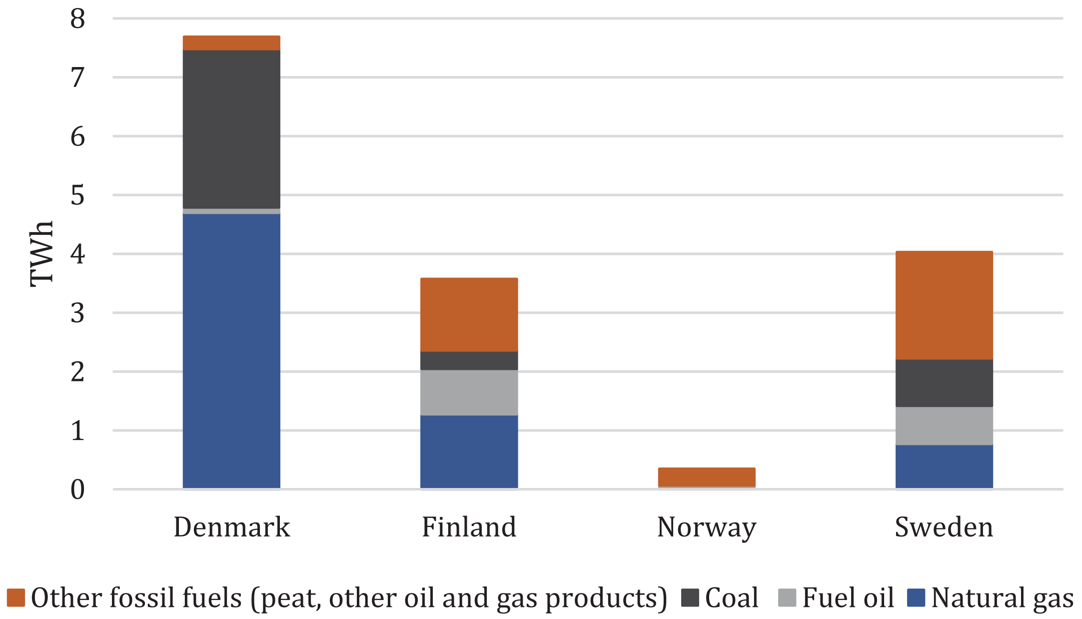


Figure 7. The distribution of fossil fuels in district heat generation in the Nordic countries 2017[22, 27, 28, 29]

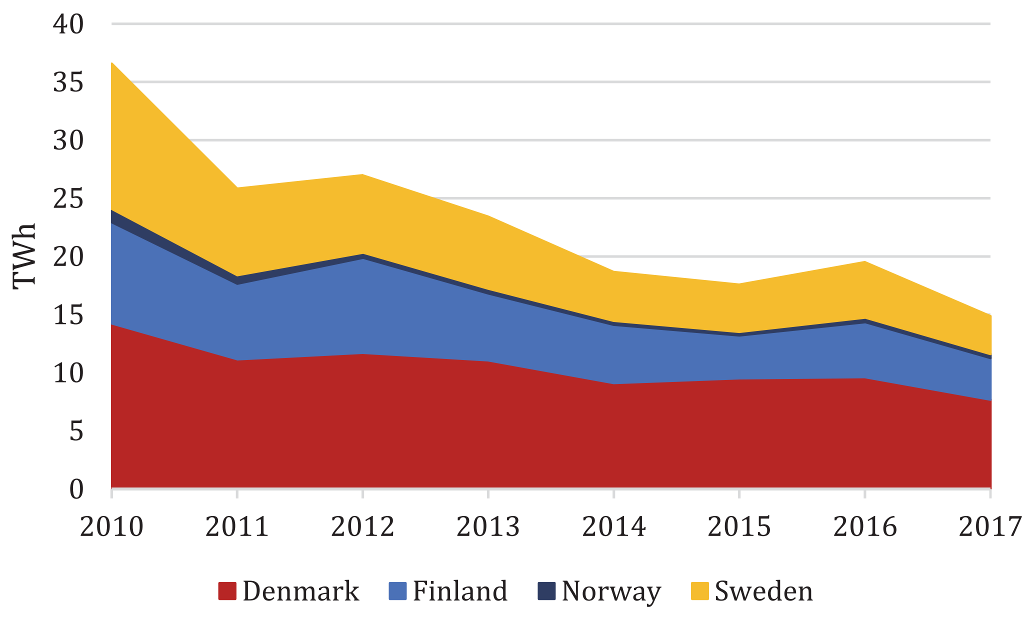


Figure 8. Fossil energy input for district heating generation in the Nordic countries 2010-2017 [22, 27, 28, 29]

Waste to energy and biomass

Around 50% of Norwegian district heating and 20 and 30% of Danish and Swedish district heating is generated from waste incineration [22, 27, 28, 29].

In May 2018, the EU tightened its regulation of waste management and this must be implemented by 2020 [89]. Several measures must then be implemented in the Nordic countries for the recycling and sorting targets to be achieved. Recyclable waste achieves a higher value from recirculation than incineration and the share of the waste that goes to recycling needs to increase. In addition, some of the heat generated from incinerated waste is not utilized. For district heating, this is especially the case during summertime in Norway, when lack of energy storage facilities results in the operational practice of generation following demand. In Norway, unutilized waste accounts for 20% of the waste delivered to waste incineration facilities [90].

More than 40% of the energy consumption for district heat generation originated from biomass in Denmark, Finland and Sweden and close to 30% in Norway in 2017. Almost all of these are residual products, such as wood waste from wood processing, pulp and paper manufacturing and forestry. Finnish and Swedish district heating statistics provide a detailed record of fuel distribution per district heating company. It shows that chips from roundwood and wood residues and bark constitute the largest proportion of biomass consumption in Finnish and Swedish district heating production [27, 29].

Solar heating

Solar collectors are used for water heating in individual buildings in many countries worldwide. However, its integration in urban district heating systems is less common. All the Nordic countries have solar district heating, but it currently only appears in the district heating statistics for Denmark (figure 9). The first large-scale solar heating plant in Europe was developed in Sweden in

1982 [91]. Also, Denmark developed solar district heating in the 80's [92]. Norway's first, and currently only, large-scale solar collector was established in 2011 [93]. In Finland, solar heating is a recurring subject of recent research and might become an important contributor to decarbonizing the Finnish district heating sector [94, 95, 96]. Denmark has invested heavily in large-scale solar heating systems in recent years and is home to the world's largest solar collector [97].

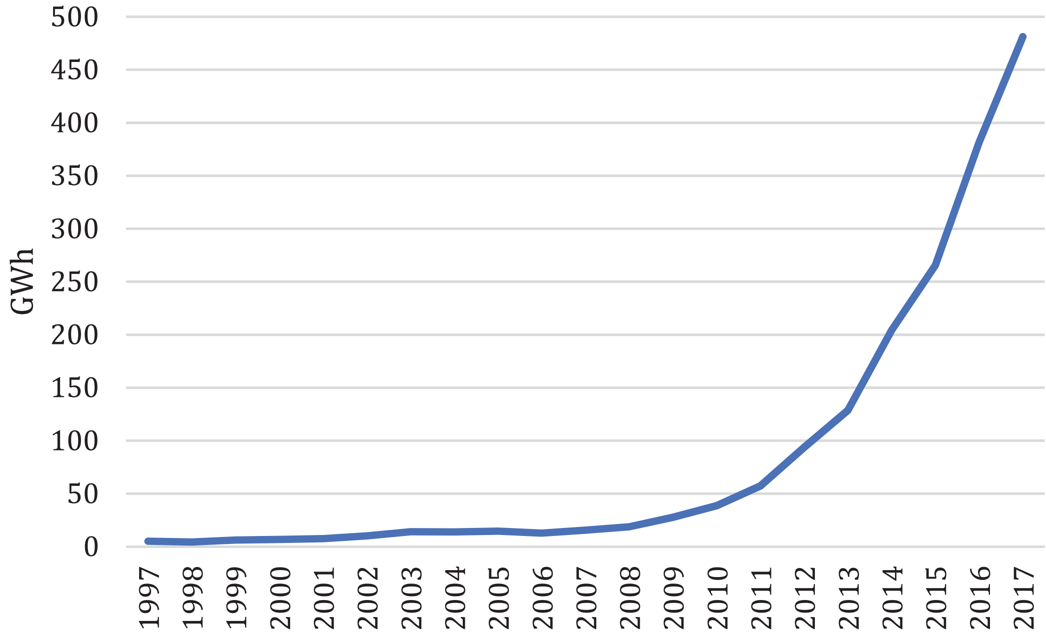


Figure 9. Solar heating generation in Danish district heating 1994-2017

2.4 The future of district heating

According to Nordic Energy Technology Perspectives (2016), there will be a reduction in district heating demand, despite population growth. This is largely due to competition from heat pumps and energy efficiency measures in buildings. District heating will continue to exist in urban areas and is expected to play a significant role in providing flexibility to the energy system. The power-to-heat ratio is expected to increase, while the CHP share is expected to decline and have a less significant role for energy system flexibility. The bioenergy share is not expected to increase. However, in these scenarios, some fossil fuels are allowed. In addition, there is little use of carbon capture and storage (CCS) before 2050. This technology can be used both on biomass-based fuels and natural gas [18].

The district heating sector will face ever stronger competition in the heat market. New business models, fuels and technological development, for instance by expanding the types of use of district heating and utilizing low-temperature residual heat, may be crucial for further development [38].

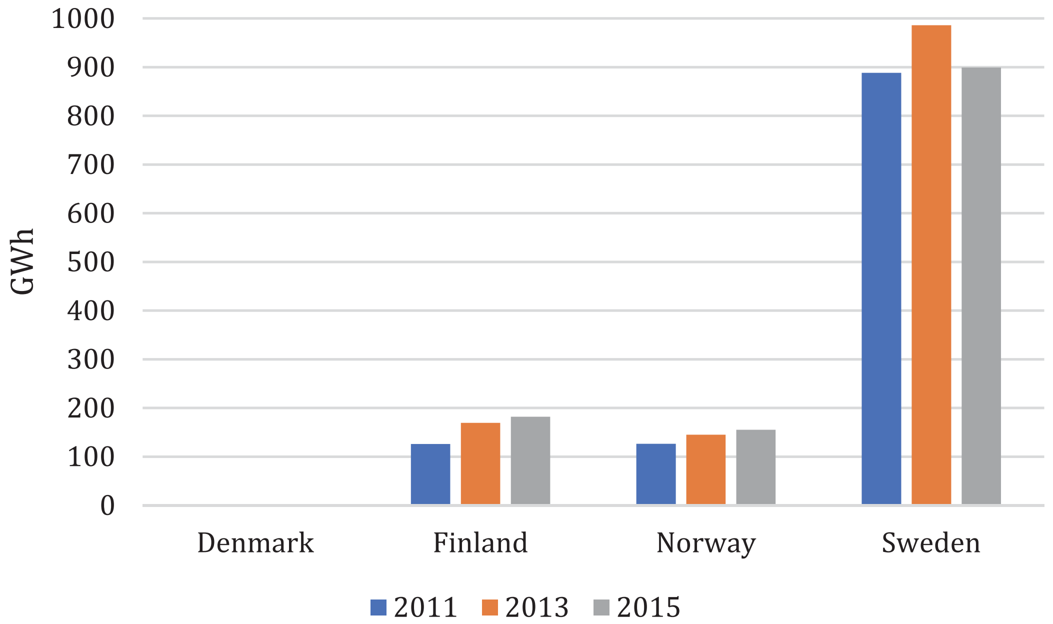
Hydrogen

Hydrogen has a large potential for decarbonizing the heating sector in countries reliant on heating from natural gas, since it seems technically possible to inject hydrogen directly into the natural gas grid [98, 99, 100]. Another interesting feature of hydrogen is that it can couple the electricity, heat and gas sectors. Hydrogen can be produced from excess or trapped wind power and used for heating, as well as transport, and regenerating for power and cooking [101]. The excess heat from electrolysis can also be utilized for district heating. The research project, 'future gas'[2] in Denmark is looking into the possibilities of exchanging gas with hydrogen in the natural gas grid and producing hydrogen from excess wind power generation. Hydrogen for heating is still in a research and development phase and needs further investigation of technical and economic feasibility. DNV GL (2018) predicts that hydrogen for heating will mainly come from steam reformation of natural gas. This further implies implementation of CCS technology [102].

[2] https://futuregas.dk/

District cooling

As with solar heating and heating from hydrogen, district cooling is a less matured distributed energy option. District cooling is the cooling equivalent of district heating. Cooling houses with distributed cold water through pipes can, as with district heating, be traced back to the Romans' aqueduct systems. The first district cooling system as we know it today was developed in the US in 1989 and district cooling was established in the larger cities from the 90's. It is based on the same principles as district heating, but the distributed water is not heated. The source of cooling may come from seawater, which is cheap and energy efficient compared to cooling from air conditioning [103]. Heat pumps are commonly used to achieve the right water temperature. Figure 10 shows how the district cooling market has developed in the Nordic countries, with Sweden taking the lead. In 2017 Sweden delivered 915 GWh of district cooling [104], while Finland and Norway delivered 106 and 173 GWh respectively [22, 105]. Denmark has not yet included district cooling in its public energy statistics, but Euroheat&Power specify a very small installed capacity for Denmark in their country profiles for 2017.



	Denmark	Finland	Norway	Sweden
2011		126	126	888
2013	1	169	145	986
2015	2	182	155	899

Figure 10. Delivered district cooling in the Nordic countries 2011, 2013 and 2015 [26]

4th and 5th generation district heating

Decreasing the water temperature has been in focus for research and development of district heating since steam was substituted with hot water from the 1930s, paving the way for three generations of district heating. Distributing hot water at a lower temperature enables the utilization of such energy resources as solar heat, geothermal heat and residual heat from industrial processes. The lower heat loss makes heat storage less costly and the lower temperature enables the use of less costly components in the pipeline, as well as making it possible to reduce the size of radiators [38].

4th Generation District Heating (4DH)[3] has a research centre in Aalborg, Denmark. Lund et al. (2018) have summarized nearly 200 publications from 4DH. For district heating to be a preferred heating source for energy efficient buildings and for district heating to become an important flexibility provider for the energy system, they argue that the district heating sector needs to develop to a 4th generation level [106]. This implies lower water temperatures and a larger integration of the entire energy system [107].

The research program Flexynets has studied 5th generation district heating systems[4], and claims that such systems exist today. Most of them are established in Germany and Switzerland, but they have also located one in Bergen, Norway. This district heating system uses seawater as a heat source and a heat pump to boost the temperature. 5th generation district heating systems have water temperatures at maximum 35 degrees, heating and cooling systems are integrated through heat pumps and consumers play a more active role, for instance as prosumers [108].

Figure 11 shows the main characteristics of the five generations of district heating in a timeline.

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[3] https://www.4dh.eu/
[4] http://www.flexynets.eu/en/

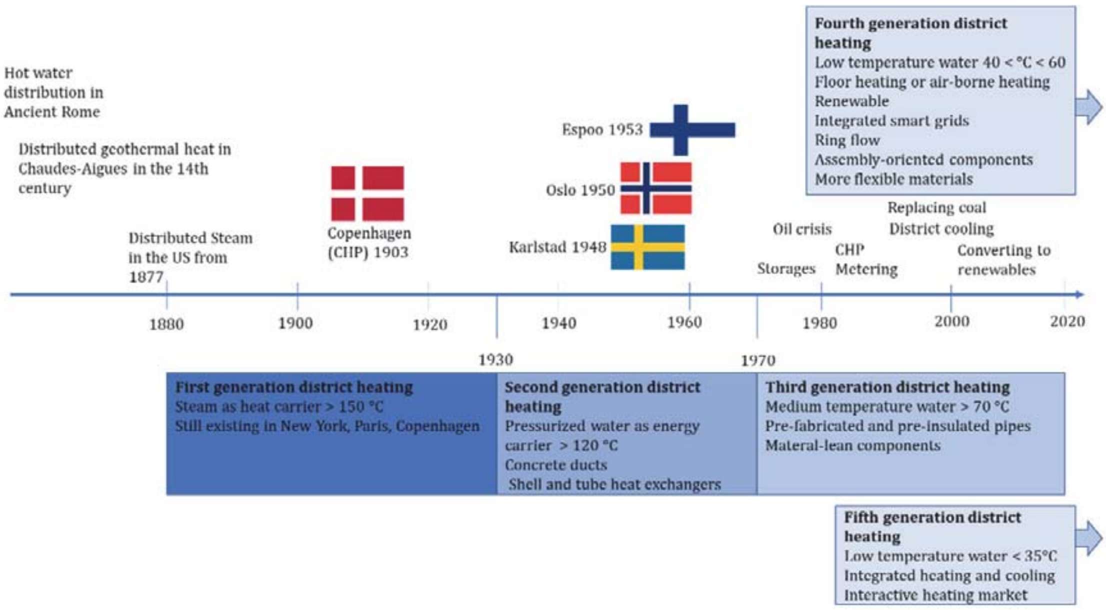

Figure 11. The development of district heating in a timeline and the main characteristics of the five generations of district heating

2.5 Flexibility in the district heating – electricity interface

Denmark has the highest share of wind power generation capacity installed in Europe, amounting to 38% in 2017. Finland, Norway and Sweden had 12, 3.5 and 17% respectively [109, 110]. Denmark occasionally experiences negative electricity prices. This was the case in 51 hours in the two Danish bidding areas combined in 2018; 51 in West Denmark and 40 in East Denmark [111]. Normally, this is due to capacity limits on export to the North of Germany when it is windy in Germany [112]. Germany has the largest installed wind power generation capacity in Europe, and the largest renewable electricity production in Europe in absolute numbers, and consequently has a large impact on the electricity price [113]. Finland, Norway, and Sweden have a larger share of flexible electricity production and have not yet experienced a negative spot price. The standard deviation of the annual average of the spot price is also generally higher in Denmark than in Norway and Sweden. Figure 12 shows the spot price, consumption, production and net import of electricity in week 10, 2019 in West Denmark. In periods of wind, but low consumption, the spot price drops and vice versa. The flexibility from the cogeneration plants, combined with export, is apparently not enough to prevent the price drop of 25 €/MWh from one hour to the next.

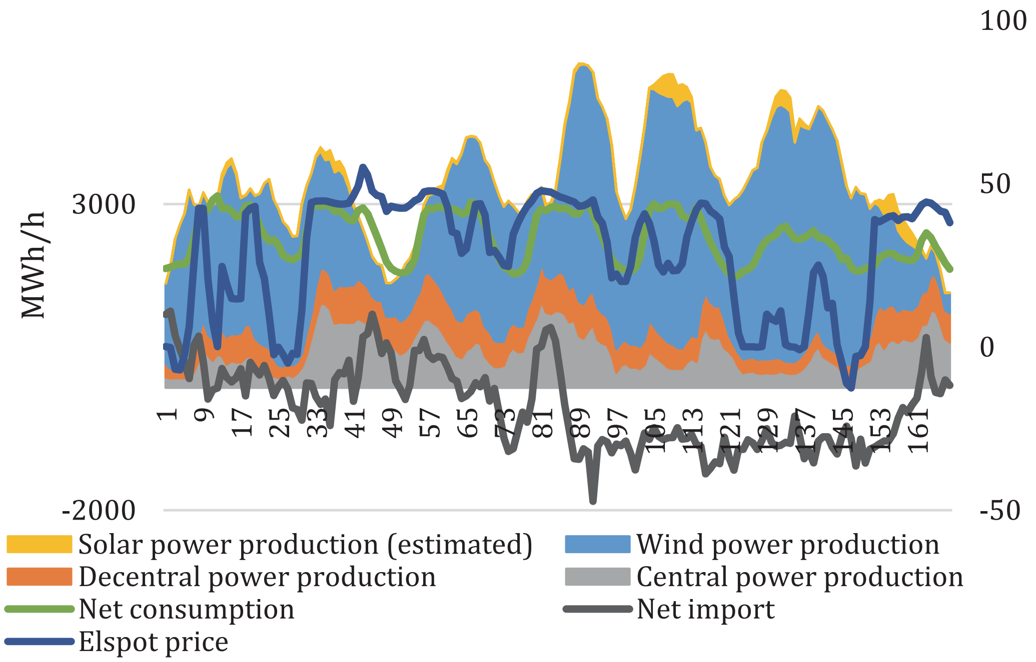

Figure 12. Hourly variation in consumption, production, export and spot prices in week 10 March 2019 in West Denmark [114]

Power-to-district heat

Power-to-heat technologies consume electricity to produce heat. Figure 6 shows that a very small share of the input for district heat generation consists of electricity for heat pumps and electric boilers. The aggregated electricity consumption for power-to-district heat in the Nordic countries amounted to 3 TWh in 2017. The energy efficiency of electric boilers is close to one-to-one, while the heat production from heat pumps can exceed three times the input. Yet, the power-to-heat share in Nordic district heating is 1, 2, 23 and 7% of delivered heat in Denmark, Finland, Norway and Sweden respectively [22, 27, 28, 29] (see figure 3). Heat pumps are mainly used as base load. Electric boilers, and especially in combination with heat storage, can cover peak load and thus contribute to replacing fossil peak load and back-up boilers.

Figure 13 shows electric boiler consumption in West Denmark in week 10, 2019 in relation to the elspot price. It shows that electricity consumption in electric boilers can react quickly to price signals and be switched off when power prices are high and vice versa.

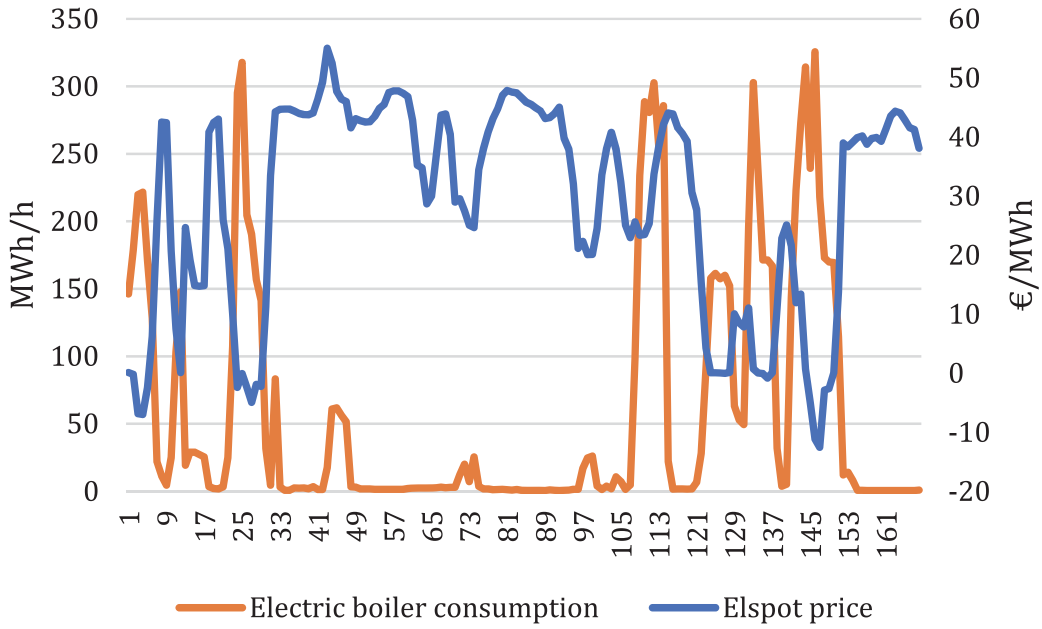

Figure 13. Electricity consumption in electric boilers and the electricity spot price in West Denmark in week 10 2019 [114]

CHP

CHP can produce electricity and heat simultaneously and is thus more efficient than producing heat or electricity separately. There are two main CHP technologies; extraction and backpressure units [115]. Backpressure technology produces electricity and heat at the same ratio. Extraction unit technology can vary the electricity heat ratio and is thus more flexible. Due to falling electricity prices and strong competition from heat-only boilers, the CHP share in Nordic district heating is falling. Figure 14 shows the development of CHP electricity production since 2004. Norway is not included due to the low prevalence of CHP.

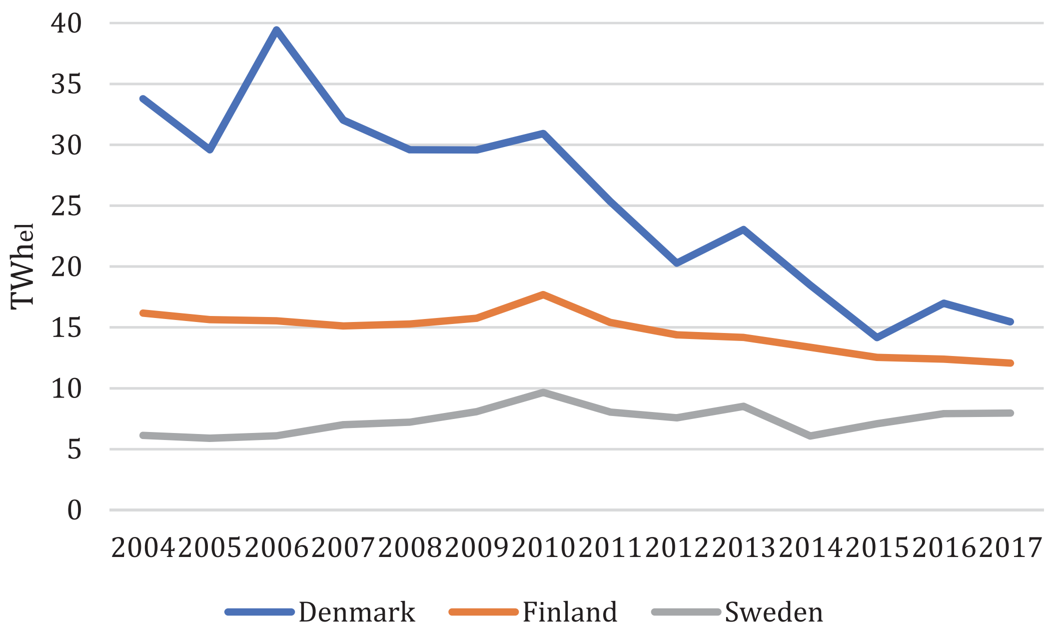

Figure 14. Electricity production in CHP plants in Denmark, Finland and Sweden 2004-2017 [22, 23, 29]

Heat storage

Accumulator tanks for daily storage are common in Denmark, Finland and Sweden. In Norway, currently only a few facilities have installed tank storage facilities [116]. Seasonal storage is a less mature technology than short-term thermal storage, but seasonal thermal storage systems meet a growing interest in the Nordic region [117, 118, 119, 120], considering that the Nordic region has many hours of sunshine during the summer, but low heat demand, and a large proportion of district heating from waste that must be incinerated during the summer months. There are eight seasonal storage facilities in Denmark, seven of which are pit storage systems. Three of these storage pits are commercialized [121], while the others are test facilities. The pit storage facility in Vejle is the world's largest, at 200 000 m^3 [122]. There is one borehole storage facility in Denmark. There are several borehole solutions planned and under testing in the other Nordic countries [123, 124]. The efficiency of seasonal storage is between 60 and 90% [125].

3 Theoretical frameworks

3.1 Why is the district heating sector regulated?

District heating has the characteristics of a natural monopoly [35]. Natural monopolies are characterized by falling average total costs (AC)[5] in the production interval, i.e. large fixed costs, but low marginal costs (MC)[6]. The investment costs for district heating plants are high, but when the infrastructure is in place, the distribution of heat has low costs. Figure 15 shows how a natural monopoly adapts (Marginal costs = Marginal revenue (MR)[7]) and how it can be regulated. An unregulated natural monopoly of a good that is considered beneficial produces too little (x_m), and at too high a price (p_m) in relation to the social optimum (x^*, p^*). For natural monopolies, a profit or price cap such that the costs are covered is considered socially acceptable (p_c, x_c), even though it is not pareto efficient[8] [126].

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[5] Average costs – Total costs divided by the number of units of the good produced
[6] Marginal costs of production – The change on total costs that comes from producing one additional unit
[7] Marginal revenue – The additional revenue from selling one additional unit
[8] A state where resources are allocated such that no one can get better off without anyone getting worse off

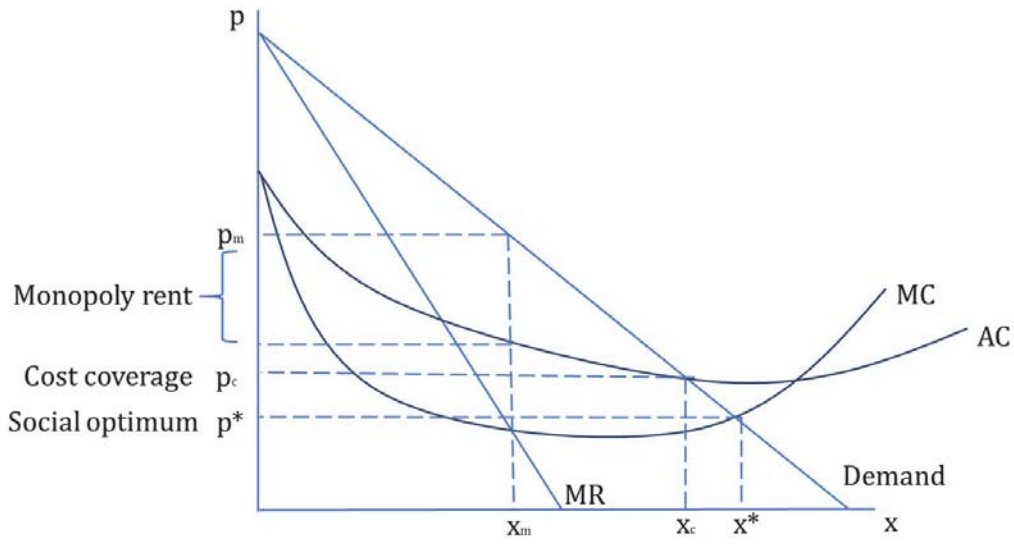

Figure 15. A natural monopoly's market adaptation, optimal solution and possible regulation

Break-even pricing is practiced in Denmark. Asymmetric information, however, makes it difficult to regulate the price or profits of district heating, because marginal costs are unknown to the regulator [38]. When production costs are not known to the regulatory authorities, district heating companies will have incentives to overstate their costs in order to set a higher price. To ensure that companies without competitors nevertheless get an incentive to streamline production, district heating producers in Denmark are required to present efficiency measures in their cost reporting to the authorities [127]. The Swedish district heating sector is regulated to a small extent, but in the district heating legislation there is a provision on transparency, that prices must be publicly available to make their costs visible [128]. Municipal operation of district heating plants is common, where commercial interests are suppressed.

The municipalities in Norway may adopt an obligation to connect to the district heating grid in a concession area. For affiliated district heating customers in a concession area, the district heating price cannot exceed the electricity price, including electricity grid tariffs and electricity taxes [129]. This gives a certain security against unreasonably high prices to customers who are obliged to connect. Due to high electricity prices after 2018's record months of drought, several district heating companies have, however, abandoned the practice of linking to the electricity price and lowered the district heating price [130, 131]. Third party access is a third way to prevent monopoly adaptation. This is done voluntarily in Denmark, Finland and Sweden, and it is established by law in Norway that third party access should be considered [125].

A fourth measure to prevent monopoly adaptation and to ensure investment in district heating is investment subsidies. The Norwegian government offers investment subsidies for investments in district heating plants mainly based on renewables [67]. In the development phase for district heating, investment support was also practiced in the other Nordic countries. An investment subsidy shifts the AC curve down, such that the break-even point is reached at a higher production level, closer to social optimum. Investment subsidies for households enabling district heating, as exist in Norway [132] and, to some extent, in Sweden [133], shifts the demand curve to the right, resulting in a lower equilibrium price and a higher equilibrium quantity.

There may also be external effects from district heating production. External effects are effects of someone's production or consumption that are not reflected in the production costs and market prices. A positive externality leads to a lower production level than the socially optimal and a negative externality leads to a higher production level than optimal, since the external effects are not considered in business-economic optimization or profit maximizing behavior. Examples of positive externalities from district heating include additional benefits and economic ripple effects from local energy generation. Examples of negative externalities are noise, traffic, visual pollution and polluting emissions.

Taxes are a measure to correct for negative externalities from production and production-based subsidies are a measure to stimulate production that have positive externalities. The optimal tax from polluting production is set such that the marginal benefits from reducing emissions equal the marginal abatement costs. For climate gas emissions, a carbon tax should, in theory, reflect this equilibrium. Taxes on fuels, for instance, energy and CO_2 taxes, which are applied in all countries, shift the MC curve to the left, and decrease production from the polluting fuel. Subsidies that are dependent on the produced quantity, such as green certificates for biomass CHP in Norway [134] and Sweden [135] and premium tariffs in Finland [136] and Denmark [137], shift the MC curve to the right, increasing the equilibrium quantity of district heating from biofuels. Taxes make polluting fuels relatively more expensive than renewable fuels. Since district heating producers are not bound to a specific fuel mix, the consumption of fossil fuels can be substituted by renewables. The use of renewable fuels may, however, be reduced as a result of the energy tax. That is due to the income effect, that the total purchasing power of the district heating plant drops when one fuel has become more expensive, but this can be compensated through the tax revenue [138].

Dalen et al. (2007) argue that a district heating plant also has the character of being a public good, because once the infrastructure is in place, new users will not have a negative impact on existing subscribers of the facility. Public goods have non-rivalry in common with natural monopoly. The district heating investors' problem is to gather enough users of the network that can pay for the investment. One way to solve this problem is to apply the obligation to connect [139], which exists in Denmark [140], Norway [129] and in exceptional cases in Finland [141].

Natural monopoly, public goods, externalities and asymmetric information are examples of market failure. Table 3 summarizes means to correct for these market failures applied in the Nordic countries, Denmark, Finland, Norway and Sweden, today.

Table 2. Market failure and current policy measures to correct for market failure in Nordic district heating

Market failure	Measure	Denmark	Finland	Norway	Sweden
Naural monopoly	Profit cap	V			
	Price cap			V	
	Investment subsidy			V	
	Third party access			V	
Public good	Obligation to connect to the district heating grid	V	V	V	
Negative externality	Carbon tax	V	V	V	V
Positive externality	Green certificates			V	V
	Premium tariffs	V	V		
Assymmetric information	Transparency				V
	Required efficiency improvements	V			

When there only exists one market failure in the market, it can be relatively easy for the government to correct for the inefficient outcome. If the district heating producer pollutes in addition to be a natural monopoly, there are several types of market failures in the market. If the government requires a fee that corresponds to the social marginal cost (SMC), where the negative externality is included, the market solution will be even further away from the socially optimal. This is the basis behind the theory of second best [142].

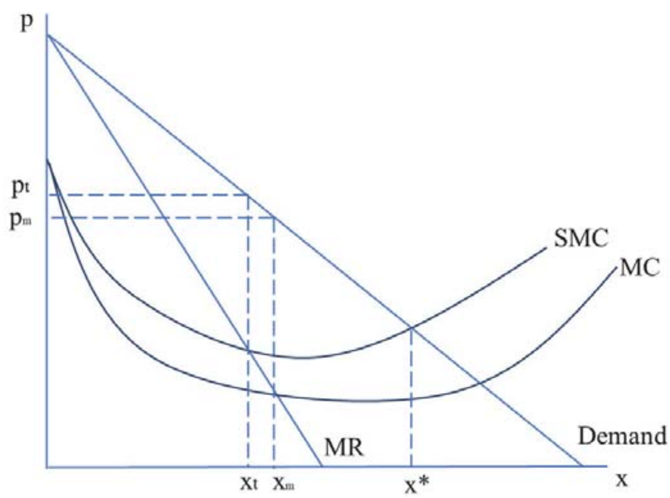

Figure 16. An illustration of a second best-problem with a natural monopoly that also pollutes

3.2 Energy system flexibility

Flexibility is an expression that can be applied to many different things. Flexibility is defined in the Cambridge dictionary[9] as the ability to change or be changed easily according to the situation, and the ability to bend or to be bent easily without breaking. Both definitions are applicable to energy system flexibility. Energy system flexibility can be defined as the ability to quickly increase or reduce electricity consumption and increase or reduce electricity production when needed [143, 144]. Energy system flexibility can come from many different sources, such as electricity grid expansion, flexible electricity generation, and flexible electricity storage and consumption. Flexibility in the energy system has gained increasing attention during this century, and the literature sources on flexible technologies, opportunities and limitations are extensive. Lund et al. (2015) have reviewed almost 400 literature sources and give a comprehensive overview of the flexibility measures enabling integration of renewables in the energy system [145]. Figure 17 shows different flexibility options in the energy system (in red) and the sector coupling for energy. There are large amounts of fossil energy resources to be replaced with renewables. Several types of flexibility options will probably need to work simultaneously to integrate the growing renewable share such that we will be able to meet the climate targets [146].

[9] https://dictionary.cambridge.org/

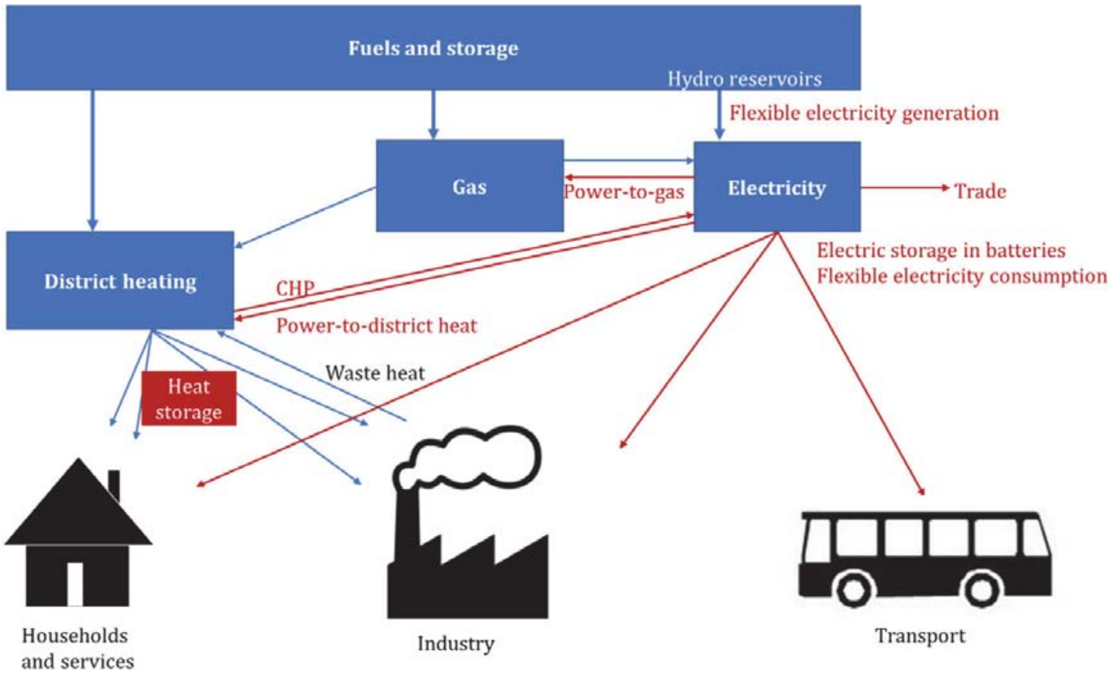

Figure 17. Flexibility options and sector coupling for the electricity market

The flexibility providers that currently result in the highest shifted volume of electricity in the Nordic electricity system are the hydro reservoirs, the transmission lines between countries and regions and plants with low ramping costs [147]. The domestic household sector, industry, transport and service sector can provide additional energy system flexibility by demand response. They can act flexibly through responding to price signals in the electricity market by consuming electricity when there is a power surplus and refraining from using electricity when there is a power shortage in the market; that is, when power prices are low and high, respectively. Technology development and digitization give us increased opportunities to control our consumption. Roll-in of smart electricity meters is a measure to increase consumer flexibility. For electricity, use and purchase are usually tantamount. You may not be hungry for dinner or need light in the middle of the night when the power is cheapest, but you may want to put on the washing machine or dishwasher just then. Digital tools can help to find a proper utilization of the power when it is purchased and switch the devices on and off for you. Paterakis et al. (2017) give a state-of-the-art summary of the existing demand response technologies [148]. For the electrified part of the transport sector, the time of purchase and time of use are separated. The transport sector may thus be a major flexibility provider through batteries in electric vehicles [149]. Battery technology is evolving and may become an important provider of short-term electricity storage [150]. Another, less mature, way to store electricity is to transform electricity to gas. Gas, for instance hydrogen, can be stored long-term, and may thus serve different flexibility needs from other flexibility options; for instance, as back-up [151].

Figure 18 shows a simplified load distribution for an electricity grid for 24 hours. There is low electricity demand at night, and demand is highest when we come home from work. To use electricity when the electricity prices are low and refrain from using electricity when the electricity prices are high contributes to valley-filling and peak-shaving respectively. Electrification contributes to load growth and energy efficiency measures, while substitution with other energy carriers contributes to electricity conservation. Moving consumption from peak load periods to low load periods is called load shifting. Load shifting contributes to a smoother load curve. Network costs are high when the load is high, but close to zero when the load is below a critical peak load. The ideal load curve is, thus, a straight line, which implies that the electricity grid capacity is utilized perfectly [152].

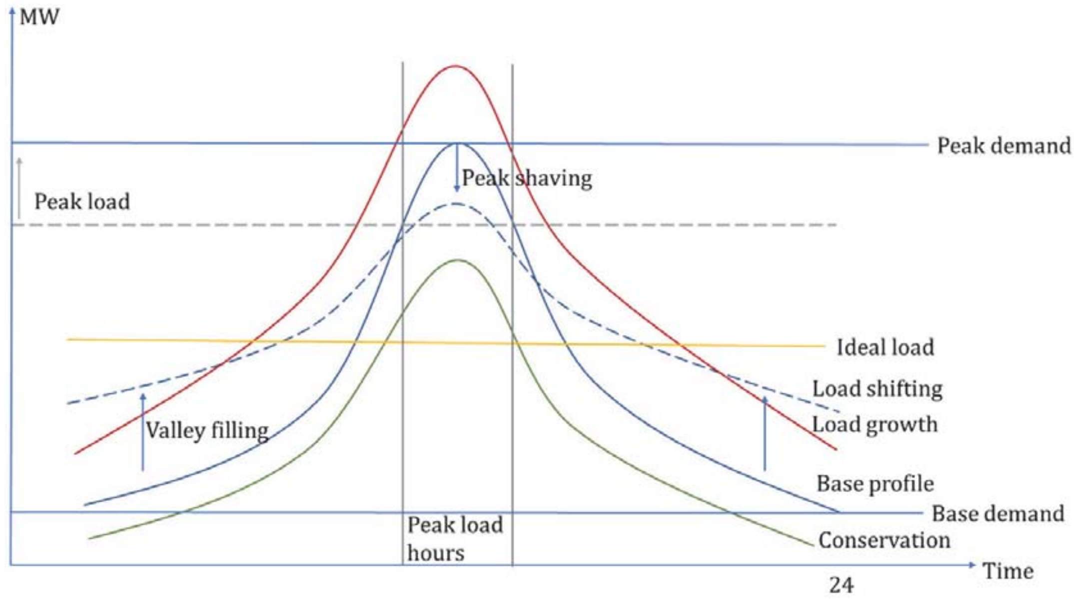

Figure 18. Flexible electricity demand illustrated with examples of 24-hours load curves

The electricity supply curve is called the merit order curve. There are various technologies that use different fuels and have different efficiencies that produce power on the market. The producer that generates electricity with the lowest marginal costs is the first producer to enter the market. As market demand increases, capacity constraints at the various manufacturers allow new manufacturers with other technologies, fuels and efficiencies to enter the market. The electricity price is determined by the marginal cost of the last manufacturer who entered the market. Figure 19 shows how the price in the market is determined in a low-demand period and a high-demand period. The figure also shows how flexible electricity demand can affect the price by increasing the electricity price by valley-filling and reducing price spikes through peak-shaving. In this way, flexibility helps increasing the value of the base load capacity. The electricity demand in the short term is considered perfectly inelastic [153].

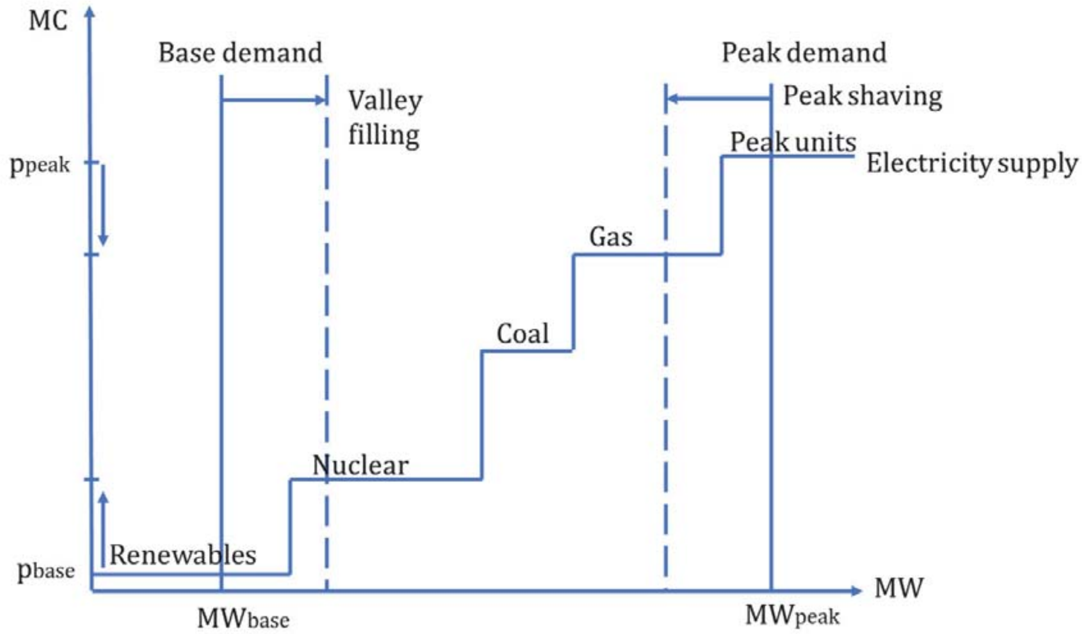

Figure 19. The merit order curve and how flexible demand may affect the power price

The Nordic electricity market is an unregulated market, and the current electricity market is not able to increase the incentives for flexible electricity demand further beyond the signals from variation in the spot price. A way to incentivize flexible electricity demand is through peak load pricing. This is quite common for electricity transmission, because the grid operators are natural monopolies and because of the characteristics of electricity - non-storability and that it is used at the time of purchase. To steer consumption away from the peak load hours, the consumer price can be set higher for peak hours than base load hours. This is 3rd degree price discrimination[10] [124] and is done through the electricity grid tariffs, either through the energy component or through the load demand component.

Different technology options can address different flexibility needs. The technologies applied depend on the response time from when the flexibility

[10] Different pricing for different consumer groups, here according to time of use

need occurs to when the flexibility option comes into effect, and the duration of the flexibility need. Energy system flexibility exists in three time dimensions - short term, medium term and long term [17]. According to the common time resolution in socioeconomics, however, energy system flexibility only applies for short term, for a maximum period of from one season to another. The term flexibility only applies for the period until new investments are realized. Long-term flexibility should, thus, not be confused with security of supply. One important aspect of security of supply is, however, system flexibility. Energy system flexibility may be crucial for system stability, and thus the security of supply [154].

3.3 Flexibility in the district heating – electricity interface

Considering the district heating sector seasonal heat storage may be one example of long-term flexibility, while accumulator tanks may satisfy the medium-term flexibility need. An immediate interruption of electricity transmission to heat pumps and electric boilers may be one option to satisfy the short-term flexibility need. Figure 20 shows the time dimensions of energy system flexibility, with examples from flexibility in the district heating – electricity interface.

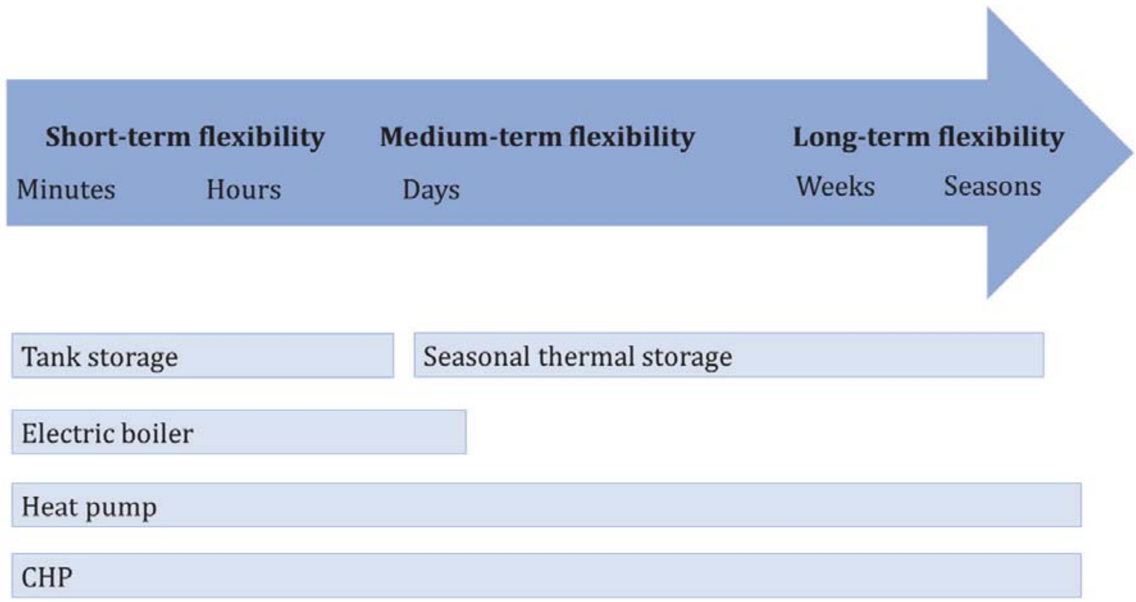

Figure 20. The three time dimensions of energy system flexibility and examples of flexibility options in the district heating – electricity interface

The incentive for district heating producers to operate flexibly towards the electricity system is triggered by the electricity price. District heating companies can contribute to a more efficient utilization of the grid capacity by increasing the load when it is low and contribute to reducing peak loads [155].

This can, however, only happen if it is economically viable for the flexible technology to enter the market. In paper III, the connection between marginal costs of heat production and the electricity price is called the preferred unit of dispatch. The preferred unit of dispatch can be compared to the merit order curve. Figure 21 shows how the current electricity price determines which district heat generation technology is economically feasible at that point in time. The thick line represents the preferred unit of dispatch. The framework conditions for district heating are important in this respect. Tax exemption for biomass-based fuels moves the marginal cost curve for the heat-only boiler down and makes this technology relatively more competitive compared to other district heating technologies. Electricity tax and electricity grid tariffs shift the marginal cost curves for power-to-heat technologies upwards, and these may not be able to enter the market if this makes the marginal costs for competing heat production technologies relatively lower.

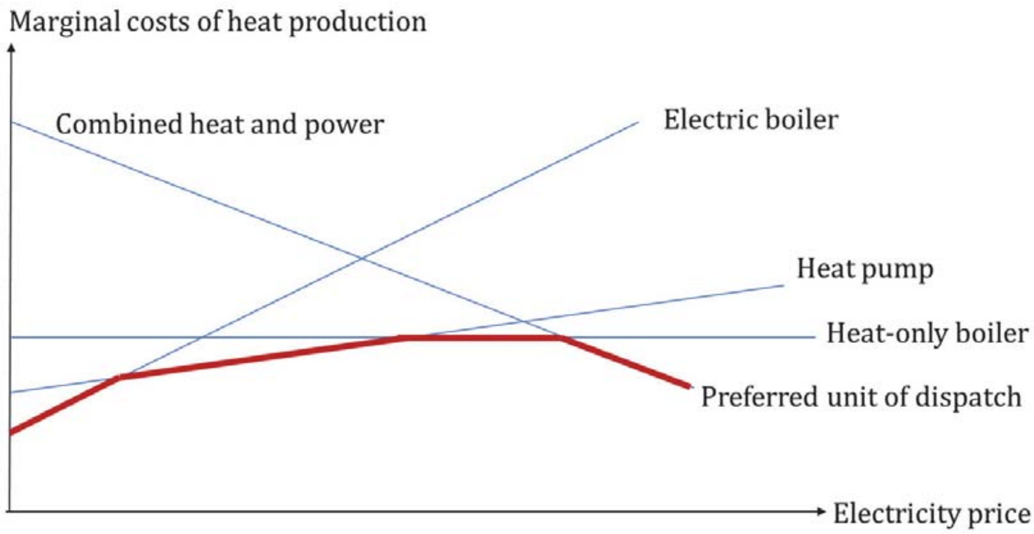

Figure 21. The relation between the marginal costs of heat production and the electricity price in terms of deployed technologies in district heat generation [49]

Power-to-district heat

Power-to-heat technologies can contribute to balancing the power system and increasing the uptake of renewable electricity in the energy system [156]. Even though heat pumps are used for base load, they have a potential to be operated more flexibly. For district heating producers with electric boilers [157] and heat pumps [158], it will be worthwhile to operate these when the electricity price is low. This will contribute to valley-filling. When the electricity demand is high, district heating companies can turn off heat pumps and electric boilers and, rather, produce heat from energy sources other than electricity. This could contribute to peak-shaving. By only using other production methods than those connected to the electrical system, by producing district heat through heat-only boilers, the district heating producer will contribute to conservation. By increasing the number of electric boilers and heat pumps in operation, one can get load growth in the system. If, however, these supplements operate flexibly, the peak load will not necessarily be moved upwards, but the load curve will become smoother.

CHP

Cogeneration is a promising flexibility provider. The higher the price of electricity, the higher the profitability of CHP facilities. The CHP plants can be a useful flexible resource when wind power resources and solar radiation fail and thus satisfy the need for medium- or long-term flexibility. In this way, both the electricity sector and the thermal sector can benefit from this kind of flexibility. The flexibility capacity increases with heat storage and for extraction plants with low ramping costs and plants that can operate on partial load [108].

Heat storage

Accumulator tanks for short-term heat storage make it possible to disconnect the supply and demand for district heating, so that district heating producers can produce heat at lower operating costs, even if the demand for heat does not correspond to the production at that time. District heating producers can, for example, produce district heating using heat pumps and electric boilers during the night, when the electricity price is low. The heat can be stored till the morning, when the demand for heat is higher and the marginal cost of production is also higher. In this way, accumulator tanks increase the flexibility capacity of the system. Accumulator tanks can, thus, contribute to meet the demand for short-term flexibility.

Accumulator tanks can also be used to store heat produced from other energy sources. This will not contribute to the flexibility of the electricity system, but to conservation, and can be profitable for the district heating producer by achieving a higher utilization of the base load capacity that has lower fuel costs at the expense of peak load capacity that both has higher fuel prices and currently is often based on fossil fuels. The use of accumulator tanks can, thus, help to decarbonize the district heating sector and increase profitability [159].

With seasonal storage, the district heating producer can increase the utilization of base load energy sources, such as waste and solar heat. During the summer, much of the heat that is produced from waste incineration in Norway and Sweden is not used to heat buildings and tap water but goes to waste. This is because the demand for heat is low in the summer (see figure 9). With seasonal storage, it is possible to store the hot water for more than a week, and even from summer to winter, and thus serve the medium- and long-term flexibility need, combined with CHP.

There is a growing prevalence of solar heating, as figure 9 displays, and solar heating varies greatly with seasons in the Nordic region. Figure 22 shows a common annual load profile for a district heating plant. There is a potential to produce heat from waste, electricity and solar heating and store it for the heating season. This will both increase the renewable share in the generation of district heat and increase efficiency, by producing heat at lower costs and distributing the capacity utilization more evenly throughout the year.

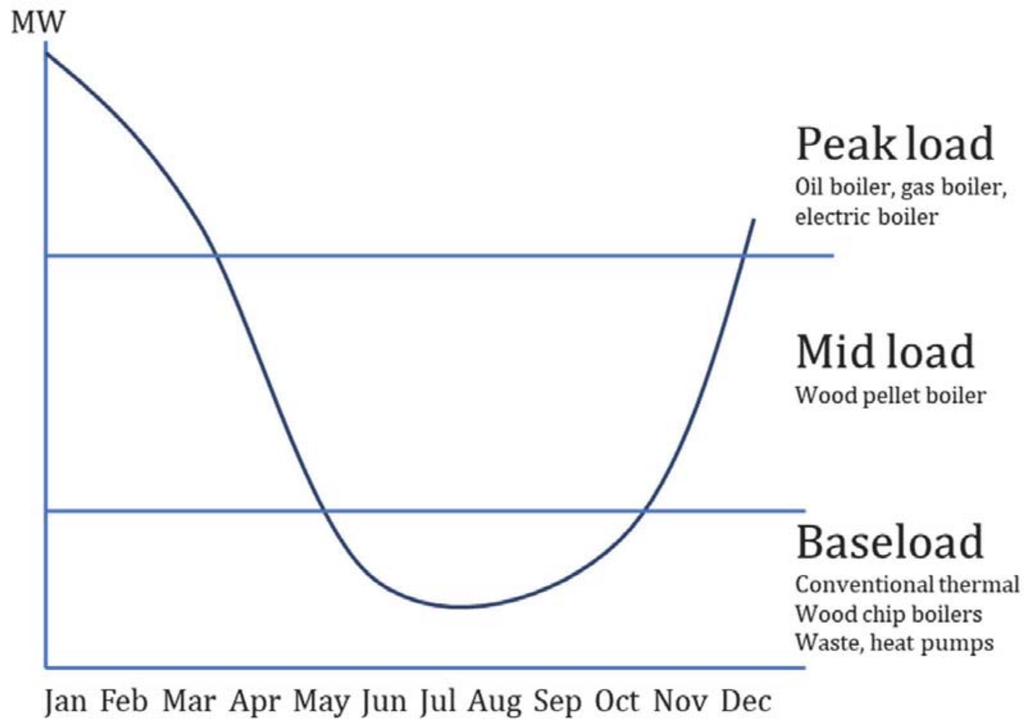

Figure 22. Annual energy demand curve and typical technologies for baseload, mid load and peak load

4 Method

4.1 Data collection and analysis

A large proportion of this work has involved obtaining comparable data for the energy system and district heating in the Nordic and Baltic countries. Background material, historical factors, prices, cost components, fiscal policy instruments and other political guidelines in the different countries are brought in through conversations with experts, questionnaires, literature searches, legislation, public statistics and reports, as well as press releases. The tax systems in the different countries differ, they are complicated and have many exceptions. Prices that are not included in public statistics, such as fuel prices for households and electricity grid tariffs, are taken from companies, and an average is calculated. The prices have been changed to €/MWh, and the exchange rate used is the average over the current year. Public statistics are often aggregated, and it has been important to find categories that contain the same variables in order to be able to compare the different countries. The same goes for the definitions being the same for the same variables in the different countries. One example is that, in the statistics for fuel-distributed district heating production, heat pumps for some sources may mean heat produced from heat pumps, while in other sources it may mean input of electricity into heat pumps.

In the Nordic countries there is much available information in English or a Scandinavian language. With the exception of some material on electricity grid tariffs and the historical development of district heating in Finland that has only been found in Finnish, there has been little need for translation. Data for the Baltic countries has required more help from experts in the respective countries.

Cagno et al. (2013) [160] categorized barriers for energy efficiency in industry, and their work was used for inspiration for the categorization of framework conditions and flexibility options carried out in this study.

4.2 Energy system analysis

There are many energy system model tools. Jebaraj and Iniyan (2006) reviewed more than 250 models, model systems and related work regarding energy models. From this, they divided their reviewed energy system models according to their purpose; for instance, energy planning, forecasting and emission reductions [161]. Connolly et al. (2010) considered 68 tools that can be used to analyse the integration of variable renewable energy but ended up presenting only 37 in their paper [162]. Pfenninger et al. (2014) built their work on previous reviews of energy models and grouped energy system models into four main categories: 1) Optimization models, 2) Simulation models, 3) Power systems and electricity market models and 4) Qualitative and mixed-method models [163]. Ringkøb et al. (2018) reviewed 75 different energy system models. They divided energy system models into three main categories. They share the first two with the study by Pfenninger et al. (2014), and the third category is equilibrium models [164]. Ferrari et al. (2019) reviewed 17 models that can be used for energy planning and classified them according to time resolution, user friendliness and whether the use of the model requires a subscription. Among these models were those used for studies of single systems, groups of systems and integrated sectors [165].

Energy system models vary from optimization models of individual systems to energy market models at a regional or even global level. Some models are adapted to short-term analysis, while others are meant to investigate long-term effects. The number of energy system models or energy system model tools increases with the energy transition, where new models are created as new needs arise. An important driver for this development has been to model an energy system with a large share of variable energy resources [164]. Such models need to include energy flexibility options and a higher temporal resolution. Because prices of certain fuels and electricity vary according to where the resources are located, energy system models should have a relatively high spatial resolution. The computational time of the models increases with resolution, so when this is suitable for solving the particular problem, one option is to have a high temporal resolution and limit the analysis to just one specific location. For example, the effects of local bottlenecks will disappear when the system is aggregated to electricity spot areas or countries [163]. Another important factor affecting computational time is the presence of binary variables in the energy system model. To introduce stochasticity to a model also increases complexity. One way around a stochastic model is to have a deterministic model but run different scenarios.

Furthermore, when energy system flexibility is an important factor of the model, Connolly et al. (2010) emphasize the importance of also including the household sector, the industrial sector, the transport sector and the heating sector in an electricity market model; flexibility can be underestimated if the possibilities of sector coupling are not included [162].

Some energy system models only include the electricity system, while others include other sectors that are energy producers and/or consumers. Many sectors are energy consumers. The TIMES Norway model includes all energy supply and demand, such as the biomass sector, hydrogen, transport and buildings [166]. The Balmorel model has add-ons for including the transport sector, waste and hydrogen. It has also been coupled with a forestry model [167].

The macroeconomic model, SNOW (Statistics Norway's world model), has a business classification of 49 sectors [168]. This general equilibrium model is designed for long-term analysis of climate gas emissions and climate policy. The regional economic model, REMES, has 43 goods and 47 industry sectors [169]. General equilibrium models can be thus be used to study other topics than energy. Both SNOW and REMES have a temporal resolution of one year. To reduce the computational time of models with an hourly resolution, one can run the model for specific hours or periods during the year.

Energy system models can be a combination of the models characterised in Pheffinger et al. (2014) and Ringkøb (2018). Models can also be linked through soft linking, hard linking or complete integration. By linking the degree of detail, a bottom-up model can be kept. By linking a general equilibrium model and a partial equilibrium model, one can, for instance, analyse the ripple effects of political instruments or changes in the energy system, such as increased electricity demand, on other parts of the economy [170].

Techno-economic models are typically limited to one specific plant or production unit. What is technically feasible may not necessarily be economically viable, so techno-economic studies investigate whether technical solutions are also economically feasible under current and expected market conditions. Fischer et al. (2018) list jurisdictional, market and technical constraints to consider the ability to find the techno-economic feasibility of different options for energy generation [171].

The levelized cost of energy (LCOE) is a common measure for determining techno-economic feasibility. Levelized cost of electricity or levelized cost of heat are also terms that are used, dependent on the energy product. The concept is a measure of the lifetime energy costs divided by energy production. The method calculates the present value of the investment, given a specified discount rate and includes operating and maintenance costs. Calculation of

LCOE is given in the formula below. For fuel cost, parameters such as efficiency rates and expected price increase need to be determined. Projections for the operation pattern over the expected lifetime of the plant or unit considered also need to be undertaken. By using the LCOE designation, the cost of different technologies can be compared, regardless of differences in technical lifetime. There are various calculators available online that calculate LCOE [172]. There are also guidelines for how to calculate LCOE for various energy storage options [173] (e.g., batteries) and energy efficiency measures [174]. A simplified equation for LCOE is found in the formula below:

$$\text{LCOE} = \frac{\sum_{t=1}^{n} \frac{(K_t + D_t + F_t)}{(1+r)^t}}{\sum_{t=1}^{n} \frac{q_t}{(1+r)^t}}$$

K_t – Investment expenditures in year t

D_t – Operations and maintenance expenditures in year t

F_t – Fuel expenditures in year t

q_t – Energy generation in year t

r – Discount rate

n – Longevity

Investment subsidies are included in the investment expenditures. Taxes and subsidies that are dependent on the production level or fuel consumption are included in the fuel costs. Operation and maintenance costs can also be divided into fixed and variable costs. In papers II and III, (K_t + D_t + F_t) is exchanged with TC_t (total costs), which includes investment subsidy, fixed and variable operation and maintenance costs, fuel costs, electricity price included electricity grid tariff cost components, the different taxes, as well as revenue components, such as electricity sales for CHP plants and energy dependent subsidies.

Techno-economic analyses may provide a basis for assessing socio-economic profitability. Techno economic models can, for instance, serve cost-benefit analysis of energy projects. There will be winners and losers from energy policy measures. Techno-economic models can exemplify the winners and losers, since the energy market models aggregate plants according to region and technology groups according to averages and example plants. Energy system models are also useful for evaluating the impact of energy policy measures, by, for instance estimating system costs and revenues [171].

Socio-economic analysis includes environmental concerns, policy measures that are not easily quantifiable and geographical characteristics. To give a price on non-priced effects, such as visual pollution and degradation of biodiversity, a scoring method is used. Figure 23 illustrates the scale energy system models can have, the research areas they can be applied to, model types and examples of models that can be used for energy system analysis.

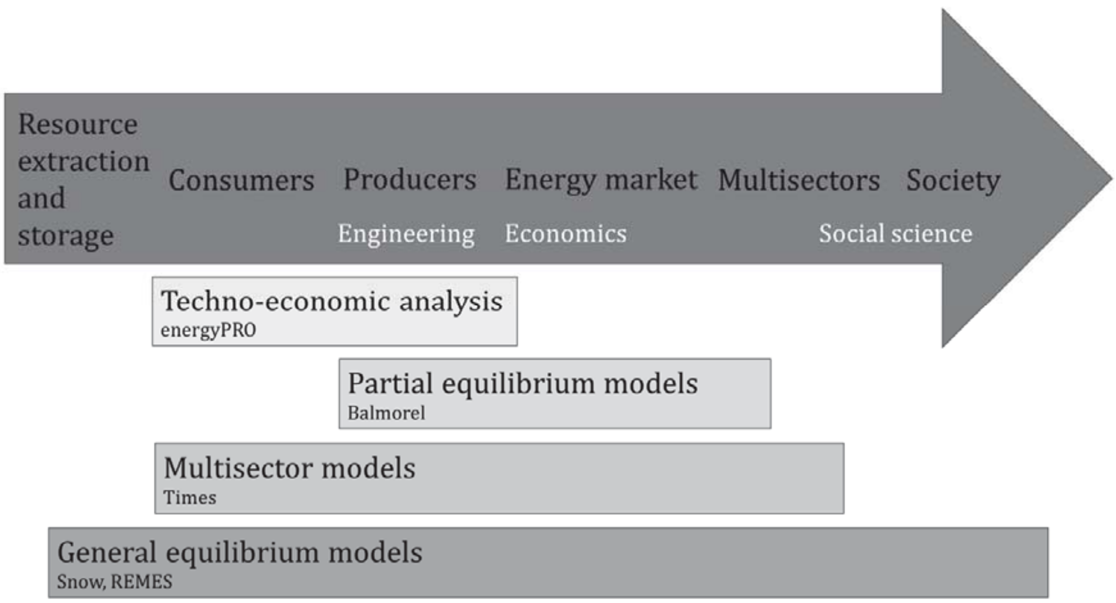

Figure 23. Examples of energy system models, which sectors or parts of the value chain they can cover, and for which disciplines they can be used

5 Results

5.1 Framework conditions for Nordic district heating – Similarities and differences, and why Norway sticks out

Objective

The main objective of this paper is to describe the development and the current position of district heating in the Nordic countries. We compare historical, economic, jurisdictional and political framework conditions for Nordic district heating, with the background of Norwegian district heating being very small compared to the district heating sectors in the other Nordic countries. We analyse the differences in costs and revenues affecting the profitability of investment in and operation of district heating and assess the economic and operational impacts of the differences in costs and revenues. We also analyse the competitiveness of district heating in the market for heat by comparing the household sector's costs of heating in the Nordic countries. Additionally, we discuss the impacts of framework conditions that are not quantifiable.

Method and data

The main method of this paper is qualitative, by collecting framework conditions, interpreting and categorizing them. The collection of data has been conducted through a questionnaire to Norwegian district heating suppliers and communication with industry representatives, academia, the authorities and those responsible for public district heating statistics. The survey attempted to collect investment costs, which are not publicly available data, and to get input on the ranking of framework conditions. We were also given temporary access to data from the district heating statistics in Norway, Excel sheets for calculating levelized costs of energy for different energy generation technologies from The Norwegian Water Resources and Energy Directorate [174] and data from a survey done by Thema Consulting for a report on the role of Norwegian district heating in the energy system, with permission from the respondents [175]. Collected data from respondents is not used directly as results but used as background information for this study. Much of the work consists of getting to know the district heating industry, with its associated technologies, politics and economics. The method also involves desk research for gathering information from technology descriptions, legislation, public reports, academic literature, district heating associations, energy authorities, district heating companies and public debate. To exemplify the impacts of economic framework conditions, we have used an example plant and an example building. Simple Excel calculations of annual costs are applied to show possible impacts of differences in costs and revenues. The equation for annual energy costs is given below.

$$AEC = \frac{K \times a}{q} + \frac{Df}{q} + Dv + F$$

$$a = \frac{r(1+r)^n}{(1+r)^{n-1}}$$

AEC – Annual energy costs per MWh
Df – Fixed operation and maintenance costs
Dv – Variable operation and maintenance costs
F – Fuel costs
K – Investment costs
a – Amortization factor
q – Energy production
r – Interest rate
n – Longevity

Results and discussion

Unlike the electricity sector, the framework conditions for district heating vary a lot between the Nordic countries and even within the countries. When we compare the impact of the economic framework conditions on the profitability of investment and costs of operation of one model plant during its lifetime, however, we find that the differences in the economic framework conditions cannot explain the large difference in the extent of district heating in Norway compared to the other Nordic countries.

This is the case when the investment subsidy in Norway is included. Norway has higher labour costs than the other Nordic countries, but the investment subsidy outperforms the impact of the wage differences. Denmark has higher fuel prices, especially for biomass fuels, since Denmark has less forest resources. Sweden has relatively high taxes on fossil fuels, which make the oil boiler in the model plant expensive to use. Finland has the lowest costs, but also lower prices, so the differences in the annual energy costs converge.

When we look at the framework conditions for district heating consumers, however, there are differences that make Norway stand out. Electricity is more competitive for heating in Norway than in the other Nordic countries. Also, most buildings in Norway do not have a hydronic system. By having to add the cost of investing in a hydronic system to the total cost of individual heating, the competitiveness of heating systems requiring a hydronic system weakens. The most important reasons for the less developed district heating sector in Norway are the historical dependence on electricity and the lack of infrastructure that district heating requires. An important enabler of district heating development is the municipalities. The important role of local authorities is also mentioned for the further development of district heating [176].

5.2 Policy incentives for flexible district heating in the Baltic countries

Objective

An increasing renewable share and its impacts are important subjects in the Baltic countries, as well as in the Nordic countries, as they are trying to become less dependent on imports. District heating is significant in the energy systems in the Baltic countries and district heating's future role as a flexibility provider is a relevant issue. The objective of this paper is to analyse the feasibility of flexible district heating technologies in a future electricity system including a large share of variable renewable energy in Estonia, Latvia and Lithuania. We apply current economic framework conditions in the Baltic countries and look into how policies in the form of taxes and subsidies incentivize investment in flexible technologies that increase the coupling of the district heating and electricity systems.

Method and data

We analyse the impacts of taxes and subsidies on investment incentives by using the analysis tool, energyPRO. energyPRO is a modelling software for techno-economic optimization and analysis of district heating systems. The software optimizes the operation of the modelled system in accordance with preconditions, such as storage capacity, and restrictions on partial load and input data as fuel costs, maintenance costs, investment costs, taxes and subsidies. The operational optimization of system operation is performed at an hourly basis with perfect foresight, minimizing heat production costs based on day-ahead electricity spot prices [177]. The users of energyPRO do not have access to the code and the use of the model requires a subscription. The software has recently been applied to a feasibility study of a small-scale district heating system with a heat pump and heat storage [178], to analyse the use of micro cogeneration plants for peak-shaving [179], the costs of booster heat pumps for different low-temperature heating sources for district heating [180], and the costs of different renewable alternatives for a district heating plant [181]. In this study, the operational optimization is conducted hourly across a 20-year timescale from 2016 to 2035.

In energyPRO, we developed four model district heating plants with different degrees of coupling to the electricity system and thus different potentials for providing flexibility. Three of the four different model plants have different coupling to the electricity system, and one is without any coupling. The peak load boiler for all four plants is an oil boiler. The coupling can be on the demand side, on the supply side, or both.

The most flexible plant is a cogeneration plant with an electric boiler. The two medium-flexible plants are a cogeneration plant with a wood chip boiler, and a plant with both a wood chip boiler and an electric boiler. The plant that has no connection to the electricity market is a plant with a large woodchip boiler in addition to the peak load boiler. We modelled the different compositions of the district heating systems under current policies in terms of taxes and subsidies to find the resulting heat production costs, measured as levelized cost of heat. We included a heat storage system and compared the results with and without heat storage capacity. The feasibility of the model plants was also tested with and without taxes and with and without load demand components of the electricity grid tariff.

The framework conditions were collected through a detailed questionnaire for district heating experts from academia in the different countries, communication with experts and through desk research.

Results and discussion

Current policies in the Baltic countries are not directed at increased flexibility from the coupling of district heating and electricity systems. Through techno-economic modelling, we found that current policies incentivize investment in flexible consumption and inflexible production in Estonia and Latvia, which is the opposite of the stated policies that promote cogeneration of heat and power.

The model plant with a wood chip boiler and an electric boiler has the lowest levelized cost of heat in Estonia and Latvia. This is a medium-flexible plant in capacity through the electric boiler. However, the electric boiler is only used in Estonia and to a limited extent, and only in the no-taxes case.

The electric boiler has low competitiveness compared to the oil boiler due to high electricity prices with taxes and electricity grid tariffs. Heat storage resulted in a lower levelized cost of heat for all model plants, compared to no heat storage. That is because of a higher utilization of the baseload technologies, at the expense of the peak load boiler which has higher marginal costs of heat production. This may also have a positive environmental impact, as the baseload boiler is based on biomass and the peak load boiler on fossil fuels.

The impact of the framework conditions on flexible operation cannot be measured through this study. The effect of heat storage on the electric boiler is small, due to the low deployment. The oil boiler is not competitive relative to the CHP capacity, resulting in full utilization of the baseload. Since the electric boiler is rarely used, the effect of electricity grid tariffs cannot be measured. Allowing for partial load of the biomass boiler reduces the need for storage, indicating that ramping rates are important flexibility measures.

5.3 Economic incentives for flexible district heating in the Nordic countries

Objective

In this paper we study the economic incentives for investment in flexible district heating and flexible operation of district heating in the Nordic countries, Denmark, Finland, Norway and Sweden.

Method and data

The methodical approach is to analyse investment costs distributed over the tecno-economic lifetime and optimize the operation of model plants with different coupling to the electricity system. We analysed four different model plants with different coupling to the electricity system by using energyPRO. We used the same model plants and the same modelling software as in paper II, but the inputs are the economic framework conditions for the Nordic countries, in the form of taxes, subsidies and electricity grid tariffs. The input data is a result of extensive reviews of the levels, design and exemptions for taxes, subsidies and electricity grid tariffs for each country. The prognosis for heat demand and the price levels of wood chips, electricity and oil is from the carbon neutral scenario of the Nordic Energy Technology Perspectives [18].

Results and discussion

The lowest levelized cost of heat in Finland, Norway and Sweden was found for CHP with an electric boiler. This result is mainly driven by subsidies. In the no-taxes and subsidies scenario, the CHP is outperformed by the electric boiler, oil boiler and wood chip boiler. The investment with the lowest levelized cost of heat in Denmark was for the biomass heat-only boiler. Biomass, which is exempt from taxes, is the most preferred fuel, while, also in this study, electric boilers have low deployment. In the no-tax case, however, there is some deployment of the electric boiler in Finland, Norway and Sweden.

As with the Baltic study, heat storage is a no-regret investment for all four model plants. In Norway, electric boilers are more competitive due to the low electricity prices. The modelling results show that fixed load demand tariffs hinder the entrance of electric boilers. There is baseload operation of the cogeneration plant and biomass outcompetes electric boilers in all scenarios, such that flexible operation cannot be assessed much further than to capacity.

The model results are consistent with the current trend that CHP loses in competition with biomass heat-only boilers, due to the tax exemption for biomass-based fuels [182].

5.4 Energy system impacts of grid tariff structures for flexible power-to-district heat

Objective

In paper IV, we analyse how different structures of the electricity grid tariffs affect flexible use of electricity in future Nordic district heating at an aggregated market level in 2030. In the paper, we also study the impact on fuel consumption and investments in the district heating sectors in the Nordic countries, including investments in heat storage, and the impact on electricity prices, fuel consumption and investments in the electricity sector. Additionally, climate gas emissions for the different grid tariff structures are measured.

Method and data

The energy market model Balmorel[11] is applied for the analysis. The Balmorel model is briefly explained in the paper, and thoroughly explained in Wiese et al. (2018) [183]. There are several recent studies where Balmorel has been applied. Jensen and Skovsgaard (2017) used Balmorel to study potential effects on the Nordic and Northern German energy markets of a biogas target in Denmark in 2025 [184]. Alonso et al. (2018) used Balmorel integrated with a waste optimization model to predict climate impacts and value added from importing waste for incineration in Denmark from 2014 to 2035 [185]. Baldini and Trivella (2018) used Balmorel to test the impacts of different energy efficiency measures in Danish households on the Northern European energy

[11] http://www.balmorel.com/

system [186]. The industry sector is not included in the Balmorel model; Wiese and Baldini (2018), however, suggest how to integrate the industry sector into the model [187]. Balmorel has generally been used to study the Northern European energy market from the perspectives of the Nordic and Baltic countries, but from 2015 a bottom-up model of the Mexican energy system has been built for projections for the Ministry of Energy in Mexico. This structure is based on the Balmorel structure and the model, called Balmorel-MX, has most recently been used to study the potential effects of carbon pricing in Mexico [188].

In this study, five different electricity grid tariff structures that are applied in the Nordic system today are applied in the Balmorel model. In addition to energy system modelling, the study includes data collection on tariff structures and levels in the different countries. In Norway and Sweden, the structures vary more, and data on the various tariff structures can only be found from the grid companies, who are obliged to provide their tariffs to the public. This is done through their websites.

Results and discussion

The results of the model run show that the difference in the structure of the electricity grid tariffs is of great importance for the use of power-to-heat technologies in the district heating sectors in the Nordic countries. There is a significant fossil share in the electricity system in 2030, which means that a carbon price of €35 per tonne of CO_2 pushes the electricity price up and makes electric boilers less competitive.

The power-to-heat share in this study largely consists of heat pumps. Heat pumps are more competitive, due to higher energy efficiency and exemption from quota obligations. A low energy component of the grid tariff scheme is the most attractive for heat pumps. Under tariffs with a high heat pump share (power-to-heat share), electricity prices are higher, investments in wind power are also higher and carbon emissions are lower. For this tariff structure, the share of electric boilers is at its lowest. Heat pumps usually run to cover the base load, with electric boilers for peak load. Heat pumps will, therefore, have more operational hours to distribute the load demand component of the electricity grid tariff scheme, while electric boilers will avoid the load demand tariff.

An electricity grid tariff scheme with a fixed load demand component will, as also shown in paper III, give very low electric boiler deployment. However, electric boilers are the most flexible power-to-heat technology. We are moving towards an extended use of load demand tariffs, which provide a fairer distribution of costs for network usage [189]. To increase the number of electric boilers entering the market, the load demand tariff must be such that it occurs only at certain hours or on certain occasions. Then, electric boilers get the opportunity to operate outside these hours and will, to a greater extent, be able to contribute to flexibility for the electricity system.

This flexibility can also be enhanced using heat storage. The model results show that investment in heat storage follows investment in electric boilers. The largest investment in heat storage is in Denmark, indicating that the need for flexibility triggers investment in cost-effective flexible solutions, without other incentives than the existing market signals. That there are investments in heat storage in all scenarios suggests that heat storage is a profitable investment, which is in line with the findings in papers II and III.

6 Discussion

Method

For the techno-economic studies, the energy system model, energyPRO was chosen. It optimizes the operation by minimizing the costs of an energy generation plant, given its predetermined technologies. We set up four model plants with different flexibility capabilities. The main research question was whether the economic framework conditions for district heating companies prevent incentives to invest in flexible technologies. This could, however, only be answered indirectly, based on which of the four plants provides the lowest costs over their technical lifetime (LCOH). An alternative method would be to build a bottom-up optimization model for investments, for example in GAMS. Then, we would be able to suggest a solution to the problem more directly. The model itself would have selected dimensioning and composition of fuels and technologies based on, for example, a predetermined energy demand.

energyPRO is a simulation model where the processes between the entering of data and output of results are less documented. Its use also requires a subscription and a subscription fee. By building the model from scratch, we would have had more control over the calculation and any errors that might arise. We would also be able to further develop the model for further research. By making the code open source, all interested users can develop the model and help validating the results. Balmorel is an open source model, which is mentioned as one of the main advantages of the model [183].

Another disadvantage of energyPRO is that the model is not yet able to solve the optimization problem of the power-to-heat technologies facing load demand tariffs. The load demand component of the electricity grid tariffs is calculated per month, based on the highest load demand for one hour during the month. An aspect of optimization that is not included is that the dispatch of the electric boiler may be dependent on the time of the month. The choice of dispatch can be expected to differ according to whether the decision takes place early in the month or late, if they have not used the electric boiler during the month, even though there is a low electricity price at that time. Load demand tariffs require the optimization to go in loops, which energyPRO does not yet handle. The Balmorel model was upgraded for paper IV to be able to take the load demand tariff into account.

All energy system models have advantages and disadvantages and are more suitable to solve some problems others. As presented in chapter 5.2, energyPRO is widely used, not only by engineers and consultants for energy planning, but also within research. EnergyPRO is intuitive and has a good graphical interface. Ferrari et al. (2019) highlight energyPRO as a very user-friendly model [165].

Building a bottom-up energy system model from scratch would require a lot more input on technological details and investment and operational cost components and preferably cover more technologies than the predetermined four model plants. Fuel and labour costs are publicly available, although aggregated over regions and for a family of fuel types or groups of businesses or consumer groups. Technical details and investment costs are possible to obtain through experts, or through academic literature and public reports giving examples.

There are large differences in the setup of the different plants and local conditions matter. Both operational and investment costs may vary according to time and location. Due to lack of data on investment costs, we assumed in papers I, II and III that the same investment costs were valid for all the countries that were compared but adjusted for differences in the labour costs. This might be very simplistic. However, when the main purpose is to compare countries, simplification is necessary; with too many details, the factors that make up the differences may be blurred in this type of analysis.

The quantitative method used in paper I is even more simplified, in that the operational profile of the plant was predetermined. This can be justified by the fact that it was an additional analysis, that the main method is qualitative and that the fuel type used in the sample plant does not vary much in price over the year. It was, therefore, considered sufficient to determine an operation profile in advance and not to use an optimization model.

If we were to consider the costs of using an electric boiler, the time the boiler would be used would be at least as important as the total operational hours over the year, and the analysis would require an optimization model or an hourly consumption profile over the year. Consumption profiles for electricity consumption can be obtained. The consumption profile for the electric boiler at the former district heating operator in Oslo Hafslund's (current Fortum Varme) district heating system over the year was used to compare the tax costs of the power-to-heat technologies in paper IV. However, this must also be done with caution. Hafslund's electric boiler is subject to an interruptible tariff, and its operating profile will probably look different from one for an electric boiler that meets another tariff structure.

To show how different tax systems may affect the cost of using electric boilers compared to heat pumps for a secondary analysis, it was considered best to use a simplified Excel analysis. In an optimization model, the profile would also be different, and it would be more difficult to distinguish which differences the tax system can make. With an equal consumption profile and identical facilities, the differences become clearer, although it is somewhat artificial to assume equal profiles when the costs are different, especially when the tariffs are designed to affect the consumption profile.

Results

The main results common to papers II, III and IV are that heat storage seems to be a profitable investment and that the use of electric power is low. This is in line with Paiho et al.'s (2018) findings, which emphasized heat storage as an important flexibility provider in Finland [15]. The techno-economic studies show that CHP is dependent on subsidies in order to compete against pure heat-generating technologies, while the model runs show that the CHP share also competes with heat pumps. The public statistics show that the share of CHP is decreasing and that the share of electric power is low in today's district heating sector. Helin et al. (2018) also describe a demanding competitive situation for CHP in the Nordic countries [182].

Increased electrification is expected in the district heating sector as a result of the need for increased flexibility that comes with an increasing renewable share. Our results, however, show that electricity taxes must be reduced considerably in Denmark, Finland and Sweden if the share of electric boilers is to increase. A load demand component of the electricity grid tariff can also be an obstacle to increased use of electric boilers, in particular. In order to provide incentives for flexible use of electric boilers, the tariffs should have a flexible design; for example, according to time-of-use. Investment in heat storage may be profitable because it increases the utilization of the base load technologies and does not necessarily increase the flexibility of the energy system. The Balmorel runs showed substantial investment in heat storage in Denmark and that investment in heat storage followed investment in electric boilers, suggesting that the market gives incentives to invest in flexible capacity if needed. There will be different flexibility needs in different regions. Norway has a large proportion of regulated power generation and will, during normal periods, likely be able to meet the need for flexibility with the installed hydroelectric power capacity with reservoirs [190].

There is great resistance to onshore wind development in Norway. There are regions with a high proportion of unregulated power production where the need for increased flexibility capacity is greatest. A breakthrough for CCS technology can mean that there will be less wind power development and that the energy system can keep flexible thermal systems in the future. This also shows the importance of having a holistic picture as a starting point when making projections. Attitudes and technological development are factors that are difficult to include in a model, but it is important to include them in the analysis. Sovacool (2018) points out pitfalls to avoid when trying to incorporate social science into analysis of the energy market [191].

Energy system models may serve as important guidelines for policy makers [161]. Some of the existing framework for district heating are justified by market failure. Several characteristics of different types of market failure have been identified in the energy market. Asymmetric information can be a key to understanding why overlapping applied policy tools occur. There are few framework conditions with the purpose of increasing the flexibility of the energy system. However, there are many framework conditions that indirectly affect flexibility. The introduction of framework conditions to increase flexibility depends on both the need for flexibility and whether the market is able to solve it on its own. The best option may exist if the market signals are clearly visible to the actors. The theory of second-best shows that overlapping policy means and attempts to regulate a type of market failure can lead to suboptimal solutions. The fact that the authorities do not provide taxes, tax cuts or subsidies that are sufficient to obtain a certain production level indicates that asymmetric information exists. In Norway, several framework conditions have been introduced with the same objective.

Models that include binary variables, for instance for investment (either invest or not), will have results where a technology is suddenly in place, or not at all. In reality, it is often somewhere in between; when a new technology emerges, it is not established overnight. Early adopters may invest before the technology is profitable and are able and willing to take a higher risk to grasp an eventual early-mover advantage. These are optimistic about the new technology. These types of uncertainties are also not included in deterministic models. This underlines the importance of both sensitivity analyses and qualitative assessments.

Future research

Taking this work a step further, it would be interesting to take a holistic perspective and study the socioeconomic impacts of flexible options, flexibility needs and framework conditions for energy system flexibility. Such a study would need a more detailed categorization, as well as ranking of the framework conditions. Paiho and Saastamoinen used interviews to identify the most important challenges and opportunities for Finnish district heating [45].

Proposals for specific analyses in Balmorel can be the impacts of a wide implementation of 4th-generation district heating on the power-to-heat and CHP share. Impacts of an energy tax on waste and/or biomass fuel would be relevant follow-up studies. Including the power-to-gas sector, CCS, regulating markets and capacity markets in the energy system model, can indicate the role district heating will have in the future and its potential contribution to energy system flexibility.

7 Conclusions

The district heating sector can help reduce greenhouse gas emissions and increase energy system flexibility. Reducing climate gas emissions and increasing energy system flexibility are arguments supporting the investment subsidy for district heating in Norway.

The largest contributors to flexibility in the district heating - electricity interface are power-to-heat technologies and CHP, combined with heat storage. Increased flexibility enables an increased uptake of renewable energy resources. The Balmorel model showed that an increased power-to-heat share increases the deployment of wind power in the system. In terms of reduction in climate gas emissions, district heating may thus contribute in two ways; through flexibility and by converting to renewable fuels.

For the Nordic countries, the need for flexibility will be greatest in Denmark and results from the Balmorel model showed that the largest share of investment in heat storage is in Denmark.

The current state of district heating in the Nordic countries is the result of both past and present regulations and policies, as well as resource availability. The district heating sector is subject to elements of several market failures that require regulation. The Nordic governments have chosen different approaches to correct for market failures. There are major differences in the regulation of district heating in the Nordic countries and the tax schemes are complicated, with many exemptions.

There are no political framework conditions designed to increase the flexibility of the energy system. Interruptible tariffs, which are common in Norway, and of which there are a few examples for electric boilers in Sweden, will have a positive effect on the use of power-to-heat technologies that can potentially operate flexibly. However, it is the grid companies that set prices for electricity grid tariffs. The main purpose of pricing is to steer consumption away from peak load periods, where transmission costs are high. Price discrimination in the form of peak load pricing shows signs of moving consumption away from peak load periods. The electricity price itself shows signs of moving production or consumption. In Denmark, however, the flexibility provided is currently not enough to avoid price falls below 0.

The need for flexibility in the Nordic energy system is not clear. In Norway and Sweden, we have a lot of flexible hydropower and the need is less urgent. However, Norway with its large share of hydropower from reservoirs, has proved to be vulnerable to periods of low rainfall and high prices. With increased renewables from wind and sun, the need for flexibility might increase. However, how increased flexibility should be achieved is also ambiguous.

The techno-economic models show that investment in heat storage is profitable. This is not primarily due to the need for flexibility, but that it enables increased utilization of the technologies with the lowest operating costs. The techno-economic analyses also indicate that up and down regulation are important technical properties for flexibility in the energy system.

CHP plants are thus potentially important flexibility providers, but in recent years, CHP has lost ground in favour of heat-only biomass boilers that operate on base load. The techno-economic analyses showed that, under the current framework conditions, investment in CHP is largely driven by subsidies. High electricity prices when taxes and electricity grid tariffs are included, make the potentially very flexible electric boilers less competitive in the market for heat. The Balmorel model showed that heat pumps have better conditions but are also commonly used as base load and are less flexible.

District heating has historically proved to be adaptable to changes in the energy system and policy requirements. We will continue to have district heating in densely populated areas. Technological developments are taking the direction of exploitation of waste heat sources with decreasing temperatures. The future of district heating will also be characterized by a growing renewable share. District heating can be an important factor in reducing greenhouse gas emissions from the heating sector. There is particularly great interest in solar energy in Finland. Challenges for the district heating sector will be reduced energy demand and competition from individual heat pumps. Expanding the business area, for example with cooling, is a possible development.

In future, district heating could play an important role as a flexibility provider for the electricity sector. This may happen through increased electrification and increased use of heat storage and is probably related to electricity markets other than the spot market. Hydrogen is a flexibility alternative that can be used in the future, and perhaps especially in Denmark. The CHP share is likely to continue to decline.

In order to increase the electricity-to-heat share, barriers such as energy taxes and the level and structure of the electricity grid tariff may be crucial. Nevertheless, it appears that the competitive conditions for electric boilers are currently poor, and that the conditions for heat pumps are better. The low cost of biomass is one of the main reasons. It also appears that heat pumps tend to run as a base load, and do not contribute to energy system flexibility, and that heat storage is used to increase the use of base load technologies.

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