NUCLEAR DISTRICT HEATING

Lappeenranta–Lahti University of Technology LUT

Master’s Programme in Energy Technology, Master's thesis

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ABSTRACT

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The purpose of this master's thesis is to discuss the implementation of nuclear energy to district heating. With climate change being a challenge to the modern world, there is a goal of reducing carbon emissions. A large portion of global carbon dioxide emissions comes from district heating. Almost 90% of district heat is produced from fossil fuels globally, and the use of nuclear energy in district heating can replace the need for fossil fuels.

District heating networks are generally more developed in countries with cold climate, where there is a large demand for district heating. In general, around Europe, the share of fossil fuel in district heat production is quite high. These countries can become the trailblazers for deployment of nuclear reactors for district heating purposes. There are a few possible types of nuclear reactors that can be used for district heating, mainly small modular reactors, and dedicated district heating reactors.

There are constraints for nuclear district heating in regulations and legislation. The first one is the distance from densely populated areas at which nuclear reactors can be sited, which can greatly affect the nuclear district heating competitiveness. The second constraint is the licensing process which can significantly slow down the process of reactor deployment and make it more costly. The current regulations and legislation were made with large conventional nuclear reactors in mind, which leads to the possibility of their reconsideration, as small modular reactors and dedicated district heat reactors can provide the same level of safety as large reactors, while sited closer to the consumers.

Nuclear energy is a good candidate for replacing fossil fuels in district heat production. Small modular reactors can be used for cogeneration of district heating and electricity. Dedicated district heating reactors can also be used, especially in countries with more uniform temperature throughout the year, as it improves the economics of heat production.

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ABBREVIATIONS

DH	District Heating
NPP	Nuclear Power Plant
SMR	Small Modular Reactor
PWR	Pressurized Water Reactor
BWR	Boiling Water Reactor
HWR	Heavy Water Reactor
LWR	Light Water Reactor
LMFR	Liquid Metal Fast Reactor
IEA	International Energy Agency
IAEA	International Atomic Energy Agency

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Abstract

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Symbols and abbreviations

1 Introduction

Climate change is a big challenge in the modern world. In order to counteract the climate change, a big shift towards the decarbonization is needed. The energy for heating people's houses and workplaces is one of the highest contributors to carbon emissions. According to International Comparisons of Heating, Cooling and Heat Decarbonisation Policies report, the heat generation is accounted for around 40% of global annual carbon dioxide emissions that are related to energy. More than 85% of district heating energy sources in 2021 were fossil fuels, such as coal, natural gas and oil (IEA 2022b) In order to reduce emissions, energy sources with low carbon footprint should be considered for district heat production. A potential solution for this is the use of nuclear power for district heating.

The idea of using nuclear energy for district heating is not new. There are examples of successful implementation of nuclear reactors for heating purposes which were implemented over 60 years ago. The Ågesta Nuclear Plant was the first commercial NPP built in Sweden, which construction began in 1957 and operation lasted from 1964 to 1974. For 10 years the Ågesta NPP produced 10 MW(e) and initially 50 MW(t) power, later increased to 70 MW(t) to the residential area of Stockholm (Farsta). Ågesta was a valuable experience for future studies and projects in Nuclear District Heating, even though it didn't provide good economics due to its size (Peter Margen 1978, 1-28).

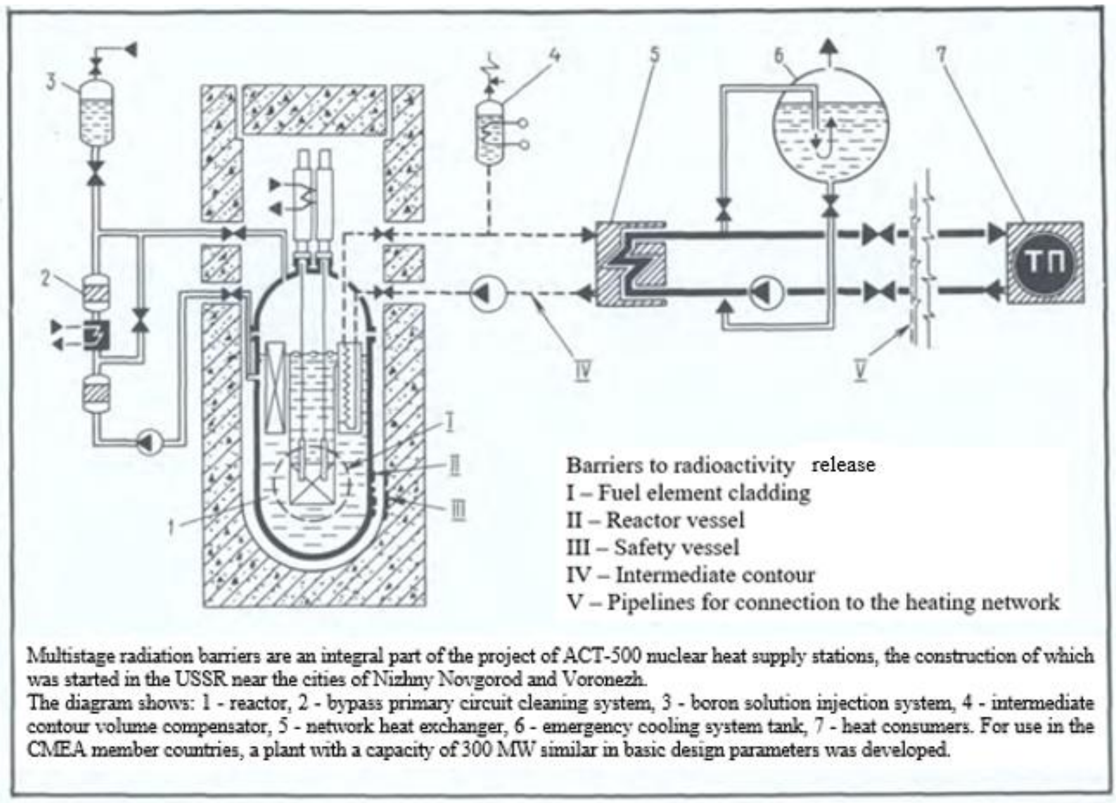
One of the next successful projects in this area was the Soviet AMB reactors with an implemented scheme for unregulated steam extraction from condensing nuclear power units at the Beloyarsk NPP, which in the late 1960s supplied 25 MW of heat not only for its own needs, but also for the nearby village of Zarechny. With the advent of RBMK reactors in the Soviet Union, a similar practice was transferred to them - unregulated extraction of saturated steam began to be used at the Leningrad, Chernobyl, Smolensk and Kursk nuclear power plants. The same practice has been transferred to VVER power units. VVER-440 units with standard turbines could provide 58 MW for heating due to unregulated extractions; VVER-1000 units with specially adapted turbines had the potential to produce 233 MW of heat.

Bilibino NPP is another example of the use of cogeneration. This nuclear power plant is located in the Far East and supplies both electrical and thermal energy to the city of Bilibino.

The Bilibino NPP produces about 80% of the electricity generated in the local isolated power grid, making it an indispensable source of energy in this remote area.

The concepts of nuclear power plants that produce exclusively thermal energy have become much less widespread. The process of producing heat for heating has a higher efficiency than the production of electricity; heating without cogeneration does not require expensive equipment such as turbines and generators. Reducing the heat output and coolant parameters improves the efficiency of natural circulation both in normal and emergency operation, which has a positive effect on NPP safety. This would potentially make it possible to revise the requirements and regulations for the location of nuclear power plants, thereby allowing the nuclear power plant to be closer to the settlement, reducing the length of communications for water supply, and reducing the cost of transporting heat.

ACT reactors (nuclear heat supply station) were developed as part of the project of nuclear heat supply stations designed to generate thermal energy, provide hot water and heat residential and industrial facilities. The ACT design was based on pressurized light water reactors, however, ACT had fundamental differences from VVER reactors. The ACT-500 reactor has an integrated circuit: the core, the heat exchangers of the primary and secondary circuits and the pressure compensator are located in the reactor vessel. This made it possible to minimize the branching of the circuit and avoid the use of large-diameter pipes, potentially dangerous in terms of the possibility of large circuit breaks (Panasenkov et al. 1984). Since the reactor is not designed to generate electricity, there was no need to generate steam with rigid thermodynamic parameters, but only hot water, which made it possible to reduce the energy intensity of the core and fuel rods, which eliminated the need for powerful circulation pumps and made it possible to use natural circulation coolant. It also simplified the design of the reactor and increased its reliability and safety. In the ACT-500 reactor, the pressure in the first circuit is 2 MPa, in the second circuit it is 1.2 MPa, and in the third circuit it is 1.6 MPa. The pressure in the network circuit stays higher than in the second circuit, which makes it possible to prevent the ingress of water from the second circuit into the network circuit if the network heat exchangers are leaking. In addition to containment, the reactor used a safety vessel - a containment adjacent to the reactor vessel near the core, which could withstand the pressure in the event of a break in the primary circuit and maintain a minimum level of coolant, preventing the fuel assemblies from being exposed (Panasenkov et al. 1984).



Barriers to radioactivity release
I – Fuel element cladding
II – Reactor vessel
III – Safety vessel
IV – Intermediate contour
V – Pipelines for connection to the heating network

Multistage radiation barriers are an integral part of the project of ACT-500 nuclear heat supply stations, the construction of which was started in the USSR near the cities of Nizhny Novgorod and Voronezh.
The diagram shows: 1 - reactor, 2 - bypass primary circuit cleaning system, 3 - boron solution injection system, 4 - intermediate contour volume compensator, 5 - network heat exchanger, 6 - emergency cooling system tank, 7 - heat consumers. For use in the CMEA member countries, a plant with a capacity of 300 MW similar in basic design parameters was developed.

Figure 1. ACT-500 reactor barriers to radioactivity release, translated from Russian (Panasenkov et al. 1984).

These and other design features of the power unit, due to which the number of protection barriers and reliability increased (three independent security channels), gave grounds for revising the standards for the location of some nuclear facilities: NPP was allowed to be built at a minimum distance of about 2 km from large settlements instead of ~ 25 km, taken for conventional nuclear power plants.

For large cities (heat load above 1100 MW) it was planned to use stations with ACT-500 reactors, for medium-sized cities it was planned to use reactors of lower power ACT-300. So, in 1982-1983, the construction of two nuclear power plants with two ACT-500 reactors began near the cities of Voronezh (population in 1985 - 0.85 million people) and Gorki (population in 1985 - 1.4 million people, modern name - Nizhny Novgorod). It was assumed that these nuclear power plants would take over most of the base heat load of these cities. The construction of these stations was stopped in 1990 as a result of increased anti-nuclear sentiment in society after the accident at the Chernobyl nuclear power plant, despite the fact that the construction of these stations at that time was 50-70% completed (Shulga 2018).

Table 1. Comparative characteristics of the VVER-1000, ACT-500, and ACT-300 reactor plants (Shulga 2018).

	VVER-1000	ACT-500	ACT-300
Thermal power, MW	3000	500	300
Thermal energy supply, MW	1000*	1800	1000
Specific energy intensity of the active zone. MW/m3	110	27	23
Coolant pressure in the 1st contour, MPa	16	2	2
Temperature at the inlet/outlet of the core	289/321	126/204	120/200
Number of fuel assemblies	163	121	85
*In the version of the power unit of a nuclear combined heat and power plant			

At the moment, this practice has become common for Soviet-designed reactors, in particular, in Russia, almost all the VVER reactors are also used for heating. Despite this, the contribution of nuclear power plants to the production of heat in district heating in Russia is still insignificant and amounts to less than a percentage of the total production, from which we can conclude that for the more extensive use of nuclear power plants in district heating in Russia, it is necessary to implement fundamentally new approaches to avoid combustion of organic fuel for central heating.

The Swedish-Finnish concept SECURE (Safe Environmentally Clean Urban Reactor) was another example of a district heating reactor. SECURE is a low-pressure, low-temperature LWR that was developed in collaboration between Finland and Sweden in 1976–1977 (Leppänen 2019). The design of the reactor included a base load for medium to large population centers with 200 MW(t) at temperature of 95 degrees Celsius temperature, as well as the larger variant with 400MW(t) at temperature of 160 degree Celsius.

One of SECURE's main design criteria was to get rid of large emergency area. This was achieved by relying on passive cooling and various inherent safety features. The underground location provides physical protection. The reactor core, safety systems and cooling circuit are located underground that also serves as the primary containment. Heat exchangers connecting the DH network are located above ground. The plant was built for remote operation without any personnel present on the site. Reactivity control is achieved by adjusting the boron concentration in the coolant. There were no control rods in the reactor, and the negative reactivity during shutdown was ensured by injecting boron steel spheres in the moderator channels. (Leppänen 2019).

The SECURE reactor was designed around 40 years ago, but it can still be relevant even today. Passive safety features that do not depend on any outer power supply are a big advantage. However, the underutilized application of defence-in-depth principles and the handling of serious accidents in design vividly reflect outdated safety concepts of the 1970s (Leppänen 2019, 8-10).

1.1 Key issue and methodology of research

The goal of this master's thesis is to analyze the existing market for district heating, discuss the potential of nuclear energy in district heating, involving different approaches, such as using currently existing large conventional reactors for cogeneration, building smaller nuclear reactors dedicated to district heating and utilizing the currently largely discussed concept of Small Modular Reactors for cogeneration or direct heat production.

As of today, nuclear energy is rarely used for district heating purposes, where most of the examples are the large conventional reactors that produce both electricity and heat for district heating networks. There are many designs of heat-only reactors that have been developed for the last few decades, as well as many designs of SMRs that are suitable for the district heat implementation. These concepts could become the solution for reducing the emissions in the district heating market, with main concern being safety, as producing district heat often assumes siting near the consumers.

Nuclear safety is a very important criteria for implementing nuclear energy into district heating networks, which includes both public opinion on nuclear power and the regulations from the nuclear regulation authorities. Can the modern concepts for nuclear district heat production provide a level of safety similar to conventional reactors, considering their siting being closer to the consumer is the question that has to be evaluated.

The actual demand and competitiveness of nuclear power in district heating market is another important question to be answered here, concerning the demand for district heating in European countries in general and how much of the produced district heating comes from fossil fuels.

Current regulations and legislations of many different authorities across the world for the use of nuclear power were made with large conventional nuclear reactors in mind. District heating, in general, requires the heat source to be located near the consumer to mitigate heat losses. Modern designs for nuclear reactors of smaller power, such as SMRs with inherent safety features can provide a level of safety similar to large reactors, while being sited near population areas. Possible changes in legislation and regulations to allow closer siting should be considered.

1.2 Structure of the thesis

The introduction contains a review of the historical experience of nuclear district heating, both implemented projects and concepts that have not reached practical application. The practice of using nuclear reactors for district heating dates back to the 1960s, but this has not become widespread.

Chapter two considers different technical options for nuclear district heating, such as large reactors with cogeneration, small modular reactors with cogeneration and dedicated heating reactors. Different reactor designs are considered, both modern and designs of past decades, which may still be relevant at the present time.

Chapter three is dedicated to the discussion of regulatory constraints that limit the possibility of implementing nuclear reactors for district heating. Mainly regulations and legislation for siting, as well as licensing of nuclear reactors is considered. Nuclear district heating application might be not worth considering if some regulatory issues are not resolved.

Chapter four presents the market analyzes of samples of several countries, primarily around the Baltics, but including Poland, as it has a developed district heating network, while most of its fuel for heat production is coal. This chapter contains an attempt to assess the size of district heating networks and what share of fuel do fossil fuels consist in different countries. Based on that a decision of how reasonable the use of nuclear district heating in individual countries can be made.

Chapter five contains a review of modeling done in a "Nuclear District Heating in Finland" report (Partanen 2019) that assesses different configurations of nuclear reactors for Finnish district heating networks of varying demands based on load factor and share of produced heat in annual demand. This chapter also contains a similar modeling done for the Denmark case, that only considers dedicated district heating reactors, in order to compare the load factors and annual share of Finland and Denmark case, since these two countries have very different annual heat demand profile.

Chapter six includes general considerations on the use of nuclear district heating in the current situation with worldwide regulations and legislation, as well as the use of different types of nuclear reactors for district heating.

Chapter seven consists of considerations regarding why the implementation of nuclear energy for district heating is important and what can be done to overcome the current obstacles.

2 Technical options

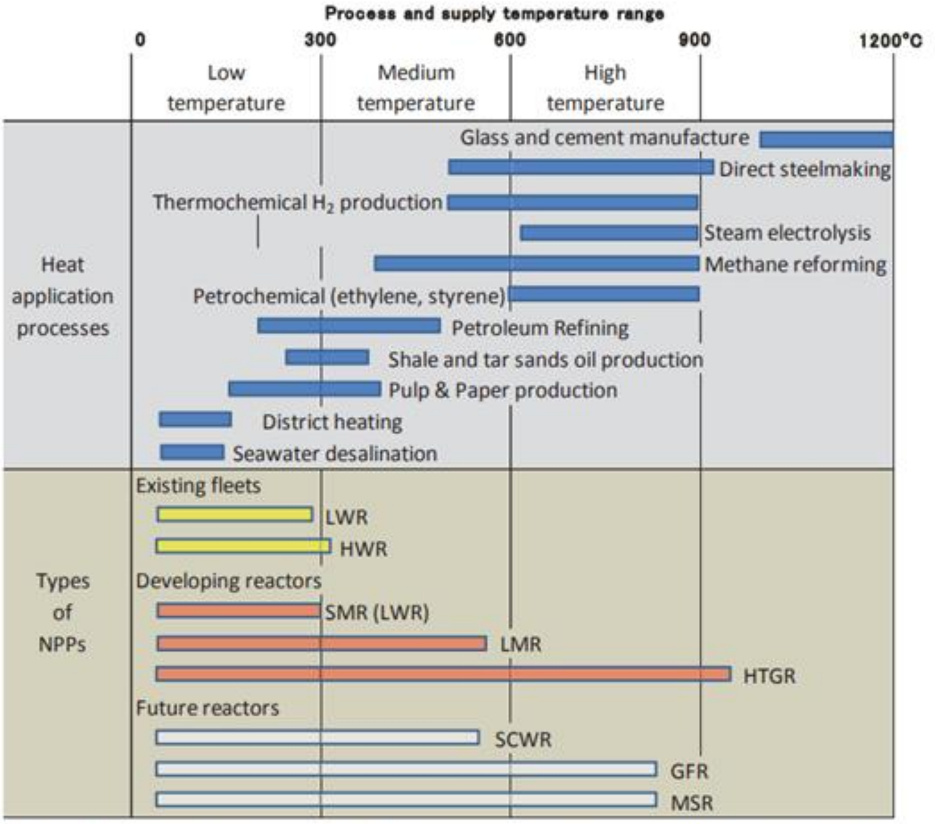
From a technical point of view, there are three main areas of nuclear heating:

- Large nuclear reactors with cogeneration.
- Nuclear reactors designed specifically for heating.
- Small Modular Reactors (SMRs) with cogeneration.

In this chapter, the above options are reviewed and the state and prospects of different approaches to nuclear heating are assessed.

2.1 Large reactors with cogeneration

Nowadays, the most widespread use of nuclear power plants for heating nearby settlements or industrial facilities. Such heating in large reactors is usually carried out by extracting steam from turbines specially equipped for this purpose. Strictly speaking, any type of reactor can be used for cogeneration. The different types of reactors can be divided according to the supply temperature range. The picture below shows temperature ranges for different applications of heat, along with the temperature which different reactor types can produce.



Note: GFR — gas cooled fast reactor; HTGR — high temperature gas reactor; HWR — heavy water reactor; LMR — liquid metal reactor; LWR — light water reactor; MSR — molten salt reactor; NPP — nuclear power plant; SCWR — supercritical water reactor; SMR — small modular reactor.

Figure 2. Temperature ranges of different types of nuclear power plants and heat application processes (IAEA 2017, 12)

As can be seen from this figure, the most suitable reactor types for district heating are LWR, HWR and SMR (LWR). Most existing cogeneration reactors are used in district heating with process operation temperatures under 150°C. The worldwide experience of DH using nuclear energy is over 500 reactors years (IAEA 2000). The table below shows nuclear cogeneration plants for district heating purposes.

Table 2. Nuclear Power plants with cogeneration used for district heating (IAEA 2017, 16).

Country and plant	Location	Start of operation: reactors (heat)	Reactor type	Power (MW(e))	Heat output (MW(t))	Temp. (C) at interface (feed/return)
Bulgaria						
Kozloduy-5,6	Kozloduy	1987 (1991)	PWR/WWER	2 x 953	2 x 20	150/70
Hungary						
Paks-2,3,4	Paks	1983 (1987)	PWR/WWER	3 x 433	3 x 30	130/70
Russian Federation						
Bilibino- 1 -4	Bilibino	1974 (1981)	RBMK/EGP	4 x 12	4 x 19	150/70
Novovoronezh-3,4	Novovoronezh	1972 (1973)	PWR/WWER	2 x 385	2 x 33	130/70
Balakovo-1-4	Balakovo	1986-93	PWR/WWER	4 x 950	4 x 200	130/70
Kalinin- 1,2	Udomlya	1985-87	PWR/WWER	2 x 950	2 x 80	130/70
Kola-1-4	Apatit	1973-84	PWR/WWER	4 x 410	4 x 25	
Beloyarsk-3	Zarechny	1981	LMFR/BN-600	560	170	130/70
Leningrad-1-4	St. Petersburg	1974-81	RBMK	4 x 925	4 x 25	130/70
Kursk-1	Kursk	1977	RBMK	3 x 925	128	130/70
Kursk-2-4	Kursk	1979-86	RBMK	3 x 925	3 x 175	130/70
Smolensk- 1,2	Desnogorsk	1983-90	RBMK	2 x 410	2 x 173	130/70
Slovakia						
Bohunice-3,4	Trnava	1985 (1987)	PWR/WWER	2 x 365	2 x 240	150/70
Switzerland						
Beznau- 1,2	Dottingen	1969-71 (1983-84)	PWR	365, 357	2 x 80	128/50
Ukraine						
Rovno- 1,2	Rovno	1981-82 (1982)	PWR/WWER	950	2 x 58	130/70
Rovno-3	Rovno	1987 (1987)	PWR/WWER	2 x 950	233	130/70
South Ukraine-1,2	Yuzhnoukrainsk	1983-85	PWR/WWER	950	2 x 151	150/70
South Ukraine-3	Yuzhnoukrainsk	1989	PWR/WWER	950	232	150/70
Romania						
Cernavoda- 1	Cernavoda	1996	HWR/CANDU-6	660	47	150/70

Light Water Reactors currently make up for the most experience with district heating reactors, but there are also examples of LMFR and HWR use. We will separately consider each of these types of reactors and their application for district heating.

2.1.1 Light Water Reactors in District heating

Light water reactors are the most common type of reactors used in district heating.

One notable example of cogeneration using LWR is the Bilibino NPP, four power units of which were launched in 1974-1977. Initially, the Bilibino NPP consisted of four power units of the same type. At each power unit of the station, EGP-6 channel water-graphite reactors are used as steam generating units, generating saturated steam according to a single-loop scheme. One power unit has an electrical capacity of 12 MW and a simultaneous heat supply of 19 MW. Reactor Bilibino-1 has been shut down permanently in January 2019, and for the Bilibino-2 power unit, a license was issued for the extended operation of power unit No. 2 until December 31, 2025 (Rosatom 2019). Thus, after the decommissioning of power unit No. 1, the total installed capacity of the Bilibino NPP is 36 MW and 57 MW of heat supply. At the same time, the maximum heat supply to consumers, with a decrease in the electric power of the station to 30 MW, is up to 116 MW (Sarkisov 2011).

Beznau NPP, located in Switzerland, is another current example of cogeneration. This nuclear power plant is the first commercial nuclear project in Switzerland. This NPP has 2 identical PWRs Beznau-1 and 2, with net electrical power of 365 MW each. Their commercial operation began in December 1969 and March 1972 respectively. The Beznau NPP started supplying district heat to the Refuna system in 1984, each unit providing 80 MW of heat output.

2.1.2 Heavy Water Reactors in District Heating

Heavy Water Reactors, in general, are less common in the nuclear industry, which also makes their use in district heating extremely rare. In Europe there is an example of district heating using a heavy water reactor for cogeneration, specifically located in Romania Cernavoda-1 and 2, a Canadian CANDU-6 heavy water reactor, which has electrical power of 660 MW(e) (net) and provides 47 MW of district heat to the grid of the city Cernavoda.

2.1.3 Liquid Metal Fast Reactor in District Heating

Currently, all Liquid Metal Reactors are fast-neutron reactors, and most of them are breeder reactors (LMFBRs). The supply temperature range of LMFRs is beyond that is required for district heating purposes so their use for heating purposes is quite limited.

Beloyarsk-3 and 4 are two reactors at Beloyarsk NPP, supplying 70% of heating and 50% of hot water to the neighboring city of Zarechnoye. The Beloyarsk NPP originally had two reactors, AMB-100 and AMB-200, launched in the 1960s and decommissioned in the 1980s. In 1981, the BN-600 (Beloyarsk-3) reactor was commercially launched, which was a sodium-cooled fast neutron reactor with an electric power of 600 MW. The reactor was connected to the district heating system and supplied 170 MW of thermal energy to the city of Zarechny (population 28,000). In 2015, the BN-800 (Beloyarsk-4) reactor was connected to the network. Both Beloyarsk-3 and Beloyarsk-4 are fast neutron reactors.

Both power plants are built according to the three-contour scheme. The reactor coolant is liquid sodium, which circulates in the primary and secondary loops. In terms of physical parameters, the BN-600 and BN-800 reactors are characterized by natural safety: in case of exceeding the permissible operating parameters, the nuclear reaction is self-extinguished, and the reactor is shut down without human intervention and automation. The BN-800 project offers an additional (compared to the BN-600) security system. The power plant is designed to significantly expand the nuclear fuel base at the expense of natural uranium isotopes not used today and to reduce radioactive waste by organizing a closed nuclear fuel cycle. In September 2022, the Unit 4 reactor was loaded with MOX fuel at full capacity for the first time (Rosatom 2022).

2.2 Small Modular Reactors with cogeneration

Interest in small modular reactors has grown in recent years. SMRs are one of the promising energy sources for nuclear district heating and cogeneration. In this section, commercially mature proposals that currently exist will be considered.

Small Modular Reactors (SMRs) are usually defined as a class of nuclear reactors that are smaller than conventional large nuclear reactors and can be built at a certain location (factory), then shipped and operated at a separate site. SMRs’ power is limited to 300 MW(e) by IAEA characterization.

Even though SMRs lose economics of scale to large reactors, they have a number of important advantages due to their small size and power. There are a wide variety of different designs of SMRs, but some of the benefits are the following:

- Increased passive safety. Since SMRs capacity is lower than that of a large reactor, reactors are designed with extended passive safety life. This allows the use of fewer active safety systems and the placement of reactors closer to cities. (Partanen 2019)
- Suitable for localized use-cases. The low power allows SMRs to be used for district heating in isolated grids, and as consumer demand increases, the small size of the reactors allows more units to be built on the same site.
- Initial investments are much smaller than that of large reactors, making the construction shorter and more reliable for potential investors.

SMRs have significant advantages for district heating, as they have increased inherent security, which allows them to be located closer to consumers, which can be one of the decisive factors, since the costs of pipelines, as well as losses in transporting water to consumers, are significantly reduced. SMRs, due to their modular nature, also make it possible to adjust the amount of energy produced on one site by adding or reducing the number of modules used.

In this section commercially mature proposals for SMRs with cogeneration for district heating purposes are reviewed.

2.2.1 SMART

South-Korean integral PWR design SMART (System-integrated Modular Advanced ReacTor) has 330 MW(t) and 100 MW(e) power output. In 2012 SMART became the first SMR design that has obtained a standard design approval from the Korean Nuclear Safety and Security Commission (Partanen 2019).

The main feature that differentiates SMART from traditional large PWRs is that all the main primary components (such as core, pressurizers, steam generators, main coolant pumps) are all installed in a single vessel. This integral design allows to enhance the performance and safety of the nuclear reactor. The integral design has proven itself in the operation of existing nuclear reactors (IAEA 2017). The design parameters are presented in the following table:

Table 3. Design parameters of SMART reactor (IAEA 2017, 25)

Item	Specification
Reactor type	Integral PWR
Thermal power	330 MW(t)
Design lifetime	60 years
Electric power	100 MW(e) (80-90 MW(e) at cogeneration)
Cogeneration	Seawater desalination 40 000 m^3/d or district heat (628 GJ/h)
Fuel and reactor core	
Fuel type	UO_2 square fuel assembly
Enrichment	4.95wt%
Active fuel length	2.0 m
No. of control element banks	57
No. of control banks/material	62.6 W/cc
Burnable poison material	3 years
Reactor pressure vessel	
Overall length	49
Outer diameter	49/Ag-In-Cd
Average vessel thickness	Al_2O_3 - B_4C, Gd_2O_3 - UO_2
Vessel material	SA508 CL-3
Reactor coolant system	
Design pressure	17 MPa
Operating pressure	15 MPa
Core inlet temp.	270°C
Core outlet temp.	310°C
Steam generator	
Type	Once through with helically coiled tubes
No.	12
Design temp.	350°C
Design pressure	17 MPa
Main coolant pump	
Type	Canned motor pump
No.	4

Flow rate	2006 m^3/h
Water head	17.5 m
Control element drive mechanism	
Type	Linear pulse motor driven
No.	49
Step length per pulse	4 mm
Make-up system	
No. of trains	2
Operating mode	Active
Secondary system	
Feedwater pressure	5.2 MPa
Feedwater temp.	180 ℃
Steam pressure	3.0 MPa
Steam temp.	274 ℃
Degree of superheating	40 ℃

SMART was developed to be a multipurpose energy source, suitable for district heating as well. It can cogenerate electricity and district heating at around 80 MW(e) and 175 MW(t) capacity.

2.2.2 NuScale

NuScale is a United States company developing Integral Pressurized Water Reactors (IPWR). Among Western SMRs this design is closest to the commercialization. In 2017, NuScale's design certification application (DCA) has been accepted by US nuclear regulator. The first phase of the certification review has been completed in 2018, which is the most difficult and long phase. The first demonstration of the NuScale Power Module is planned to be done by 2024, with a commercial 12-reactor plant planned to be built soon after in 2026 (Partanen 2019).

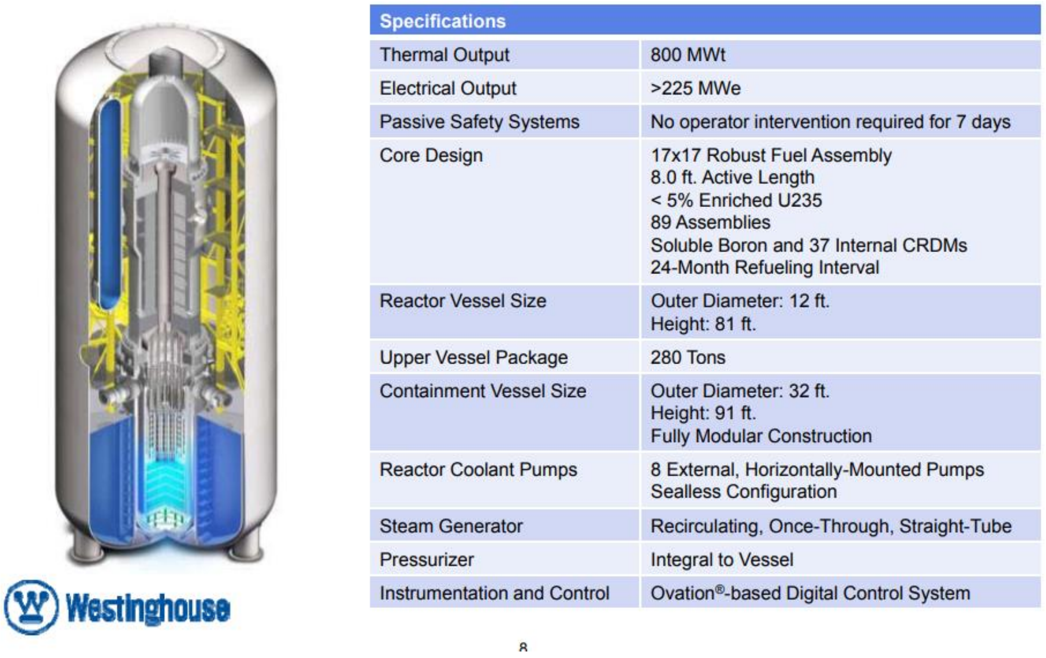
NuScale designs small modular nuclear reactors that are projected to be commercially available around 2025 by Department of Energy. NuScale reactors take much less space than conventional large reactors, generating 77 MW(e) of power output (NuScale 2021). In this design light water scheme used, similarly to large conventional nuclear plants.

The NuScale design isn’t utilizing water pumps or any circulation equipment. In most accidents the reactor can shut down and to cool down for an indefinite amount of time. The reactor is designed to be stored in an underground basin for protection against earthquakes, with a concrete cover above it. In the case of the power of the cooling system outage, the pool water will absorb the reactor heat. The pool contains enough water to cool the reactor core for an indefinite time without the need to refill the pool (Power 2013).

2.2.3 Westinghouse SMR

The Westinghouse small modular reactor produces 225 MW(e) output. Components of the reactor are enclosed in the pressure vessel. The SMR only requires 30% of the site area for larger AP1000. Estimated construction time is 18 months, which is smaller compared to the constructing time of AP1000 (IAEA 2017, 19).

One of the advantages of this SMR design claimed by Westinghouse is that it utilizes already proven technology basis with passive system that are conceptually similar to their AP1000 plant, as well as using digital Instrumentation and Control systems that are based on AP1000 plant design, which is supposed to facilitate the licensing process (Westinghouse 2014).



Specifications	
Thermal Output	800 MWt
Electrical Output	>225 MWe
Passive Safety Systems	No operator intervention required for 7 days
Core Design	17x17 Robust Fuel Assembly 8.0 ft. Active Length < 5% Enriched U235 89 Assemblies Soluble Boron and 37 Internal CRDMs 24-Month Refueling Interval
Reactor Vessel Size	Outer Diameter: 12 ft. Height: 81 ft.
Upper Vessel Package	280 Tons
Containment Vessel Size	Outer Diameter: 32 ft. Height: 91 ft. Fully Modular Construction
Reactor Coolant Pumps	8 External, Horizontally-Mounted Pumps Sealless Configuration
Steam Generator	Recirculating, Once-Through, Straight-Tube
Pressurizer	Integral to Vessel
Instrumentation and Control	Ovation®-based Digital Control System

Figure 3. Westinghouse SMR specifications (Westinghouse 2014).

The specifications of Westinghouse SMR are presented in the figure 3.

2.3 Dedicated district heating reactors

Reactors whose only job is to produce low temperatures for district heating, and which do not involve the production of electricity, can get rid of the need for high pressures. This gives them the opportunity to simplify the design and reduce the cost of construction. With all this, such reactors offer good safety features due to the absence of a pressure vessel or a decrease in pressure in the circuits. The absence of electricity production also eliminates the need to accommodate expensive turbogenerator equipment, which also takes up a lot of space (Partanen 2019, 27).

Nuclear power plants that produce heat only for district heating are much less common. They have undeniable advantages, most importantly, allow you to make projects more compact with the same heat capacity. First, because almost three times more thermal energy is consumed to produce electricity, the heating heat generation process is significantly more efficient. Second, heat supply (if not cogeneration) does not require expensive equipment, such as turbo-generators, bulky equipment and large amounts of condensate, and the principle of an integrated arrangement of equipment can be used in the reactor (regardless of whether there is a vessel or another type of reactor). The reduction of the thermal power together with the parameters of the coolant and the multiple reduction of the energy intensity of the reactor, in turn, facilitates the use of natural circulation in normal and emergency operating modes and generally increases its safety. All this allows for changes in nuclear power plants. The requirement for a location that brings it closer to largely populated areas reduces the length of water (or steam) supply lines and thus reduces the cost of transporting heat, which is the biggest obstacle to nuclear district heating. Thanks to this, nuclear power plants for heating open up additional markets that are not available to large nuclear power plants.

2.3.1 RUTA-70

The RUTA pool reactor project was developed in the USSR in the late 1980s for use as part of a nuclear power plant for heat supply to small remote isolated cities and / or settlements, as well as in seawater desalination plants.

The RUTA-70 reactor has a thermal power of up to 70 MW and is designed for municipal district heating systems and low-grade heat generation in the form of hot water with a temperature not exceeding 95 °C. The environmental effect from the use of this plant is high - when one RUTA reactor replaces gas-fired boilers, the reduction in carbon dioxide emissions will be 80,000 tons per year (Rosatom 2016).

The heat supplied from the RUTA reactor has a lower price than the heat from boiler houses and thermal power plants running on fossil fuels. Simplicity of design, low parameters of the pool reactor coolant ensure its high reliability and safety, which allows the nuclear plant to be located in close proximity to consumers, minimizing transport losses in the heat supply system (Rosatom 2016).

2.3.2 SECURE

Safe and Environmentally Clean Urban Reactor or SECURE is reactor designed specifically for district heating. It was developed by the Swedish company ASEA-ATOM in 1970s. The project has since been canceled due to growing anti-nuclear sentiments, despite it good economic performance. In 2012, a review of SECURE's "applicability" in current conditions and regulatory requirements was conducted. Overall, although many changes such as on "Defense in Depth" would be necessary to modernize the design, it is still easier than designing a new reactor (Partanen 2019).

2.3.3 DHR-400

The DHR-400 is a 400 MW(t) pool reactor. It is designed to produce hot water at 90 °C (inlet water temperature is 60 °C). This reactor is intended to produce district heating. This reactors price per kilowatt is estimated to be very low – 500 euros with total construction cost of 200 million euros.

One of the main drawbacks is that the output temperature is somewhat low, since, for example, many Finnish district heating networks are designed for temperatures up to 120 degrees Celsius when demand for heat is high. This creates the need for reactor to be accompanied with another heat source of higher temperature during the winter. Modern district heating networks are designed to work with lower temperatures to utilize heat pumps and excess heat, making them suitable to harness the power from this reactor that provides low temperature water (Partanen 2019).

2.3.4 NHR-200

In the 1990s, the NHR-200 thermal power plant with a thermal power of about 200 MW was developed. Its features are: three-circuit scheme with increased pressure in the intermediate circuit (3 MPa versus 2.5 MPa in the primary circuit); all-mode natural circulation of the coolant; integral layout of the reactor plant; low power intensity (~36 MW/m3). The design passed the safety assessment and was approved by the regulator, but only recently has a real prospect of its implementation emerged: in early 2018, INET and one of the largest investors in the Chinese nuclear industry, CGN, agreed to jointly carry out preparatory work for the construction of a unit based on a modified reactor - NHR-200-II.

3 Regulatory constraints

In recent years, the issue of energy decarbonization has become more and more acute. Half of the energy consumed by mankind is for heating for homes, industry and other applications, and the fossil fuels share in heating was 64% in 2021 (IEA 2022a).

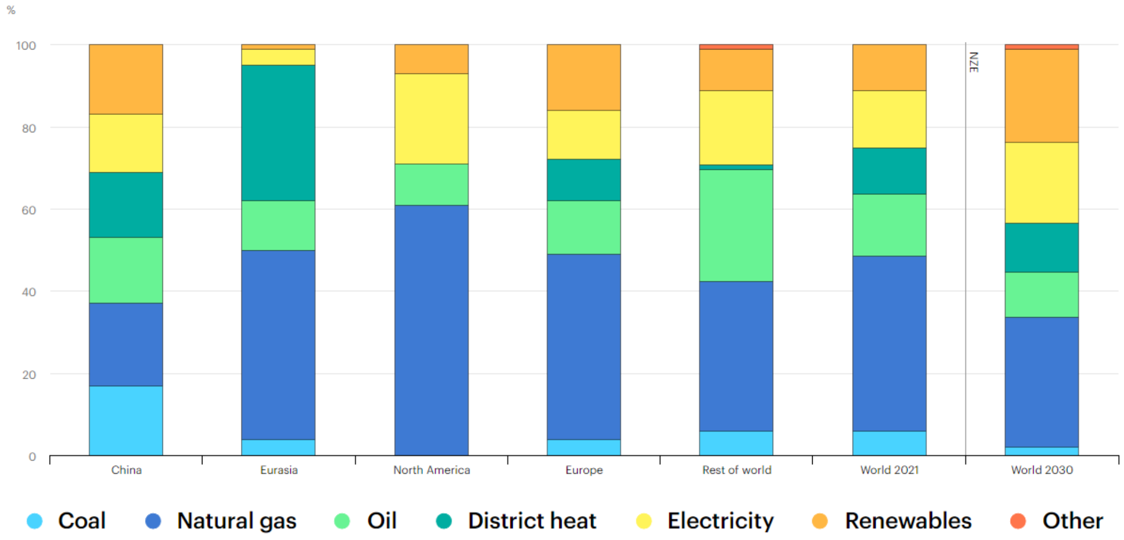


Figure 4. Energy demand for heating related to buildings and fuel share in the Net Zero Scenario, 2021-2030 (IEA 2022a).

Nuclear heating is one of the most promising options for heat decarbonization. However, the construction of nuclear power plants, in particular SMRs for heating, encounters many obstacles from the regulation and legislation that have been developed for large conventional reactors, which raises the question of their revision when it comes to SMRs or small reactors for heating or cogeneration. This chapter will cover current regulations and limitations they pose in Finland, as well as discuss the way other countries work towards the regulation changes to allow for easier implementation of nuclear energy in district heating, where two main concerns are simplification of the licensing process for standard reactor designs, instead of licensing each new plant, as well as changes in requirements for the siting of nuclear reactors.

3.1 Finland Nuclear Energy Regulations

In Finland, as in many other European countries, the nuclear power plant licensing process has been developed for large conventional NPPs. Currently in Finland, each reactor requires a separate license, and this process can be time consuming and costly.

Basic requirements for the safety of the use of nuclear energy are presented in the Nuclear Energy Act (990/1987) with general guidelines for a nuclear facility operation and Nuclear Energy Decree (161/1988) with more specific guidelines and instructions.

The licensing process consists of two main parts - the energy policy part, where decision-in-principle is made by the government, and the nuclear safety part, with government approval and STUK's safety assessment (Polin 2020). The licensing process is presented in the figure 5:

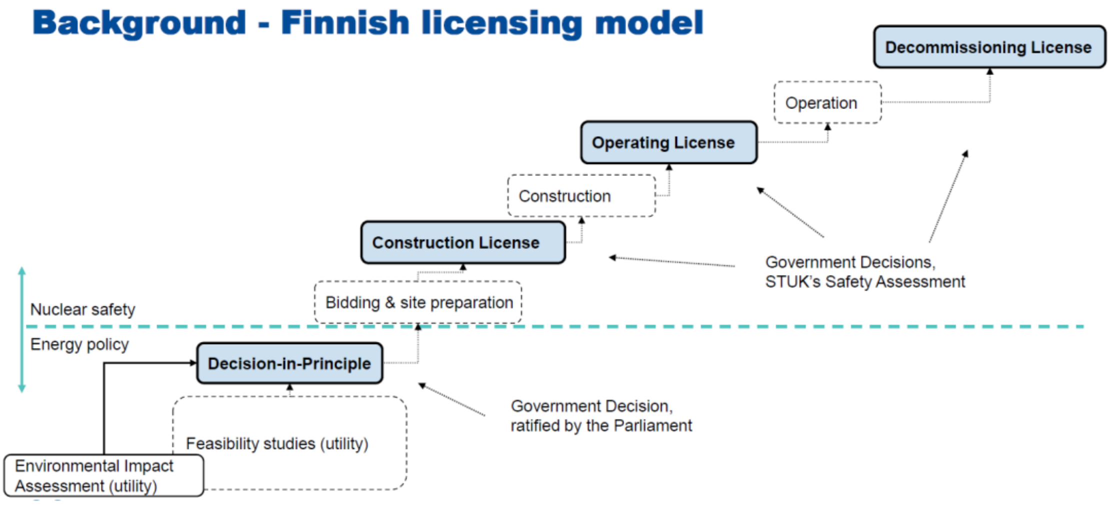


Figure 5. Licensing model of Finland (Polin 2020, 65).

In Finland, construction of a nuclear power plant always requires a Decision-in-Principle from the Parliament.

One of the most important factors at the moment is the definition of the emergency zone. By regulations, nuclear power plants must always be built away from cities. The location of nuclear heating facilities near the consumer is one of the factors affecting efficiency. That is why the existing approach, in which emergency zone the solution is universal for all nuclear facilities, as for large reactors, is not suitable for modern reactor designs that are used for heating. Legislation should be adopted considering the size and specificalities of the reactor, as well as the fact that some types of accidents cannot occur due to the design features of a particular reactor.

The emergency and reactor evacuation zones in Finland are 5 and 20 km. This distance comes from the STUK rules which was written with large conventional nuclear power plants in mind. Reducing this zone, given that the safety of new designs of nuclear reactors remains at the same level, could make nuclear heat production more efficient.

3.2 Legislation in other countries

With the growing popularity of the idea of using nuclear energy for heating, as well as SMRs, efforts have been made in some countries to research the prospects for this direction. Thus, Canadian Nuclear Laboratories or CNL carried out a study on SMRs that was published in 2017 with a request to the government to support commercialization of SMRs. In 2018 four requests from different SMR developers to build demonstration plants have been received by CNL. Canadian Nuclear Laboratories have also performed a stakeholder study, which showed that many of them expected SMRs to be beneficial, safe, clean, acceptable by the public opinion and licensable (Partanen 2019).

In the UK in 2017 new policies regarding the help for SMRs to get into the market have been announced. The government has announced a funding for building a system to assess and license SMRs better. Funding towards the support of development of advanced reactor designs, as well as to create market conditions suitable for bringing new reactor designs to the market and seeking for funding (Partanen 2019).

4 Market Analysis

This section presents an analysis of the demand and supply of the heating market in the Baltic countries - Finland, Sweden, Norway, Estonia, Denmark, and Russia. All of the above countries have a well-developed district heating system, making these countries good candidates for nuclear district heating.

District heating is more energy efficient and can allow to reduce emissions. That is why many countries have embarked on the development of district heating systems, which is confirmed by the statistics of consumption growth through district heat networks.

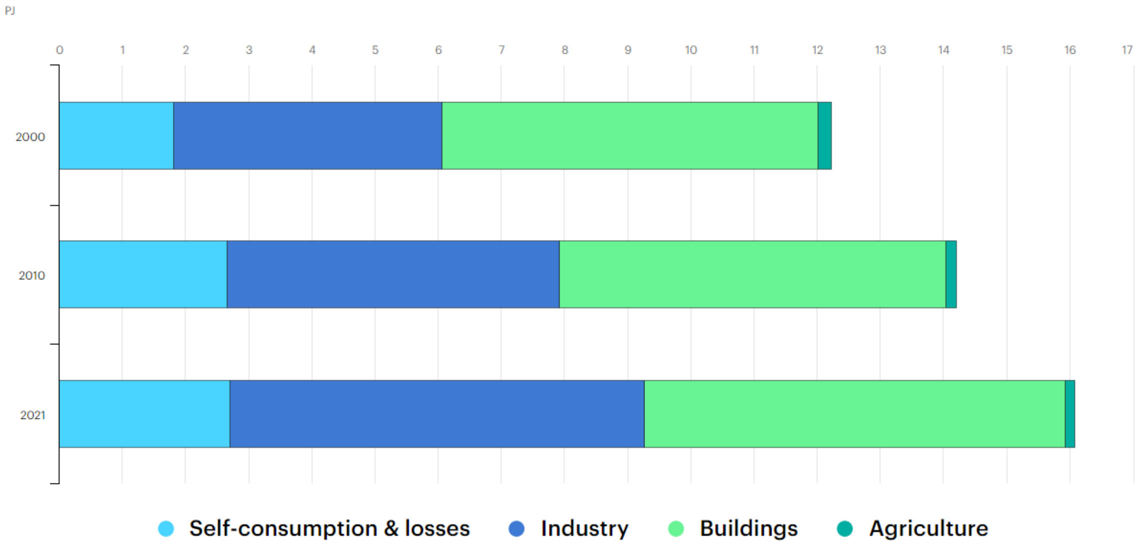


Figure 6. Global yearly heat delivered through district heat networks by to end-use sectors 2000-2021 (IEA 2022b).

From the graph of world heat consumption, one can observe an increase in energy consumption through district heating networks by 10% over 10 years. Specifically in Europe, the length of district heating networks has also grown, as can be seen from the following graph.

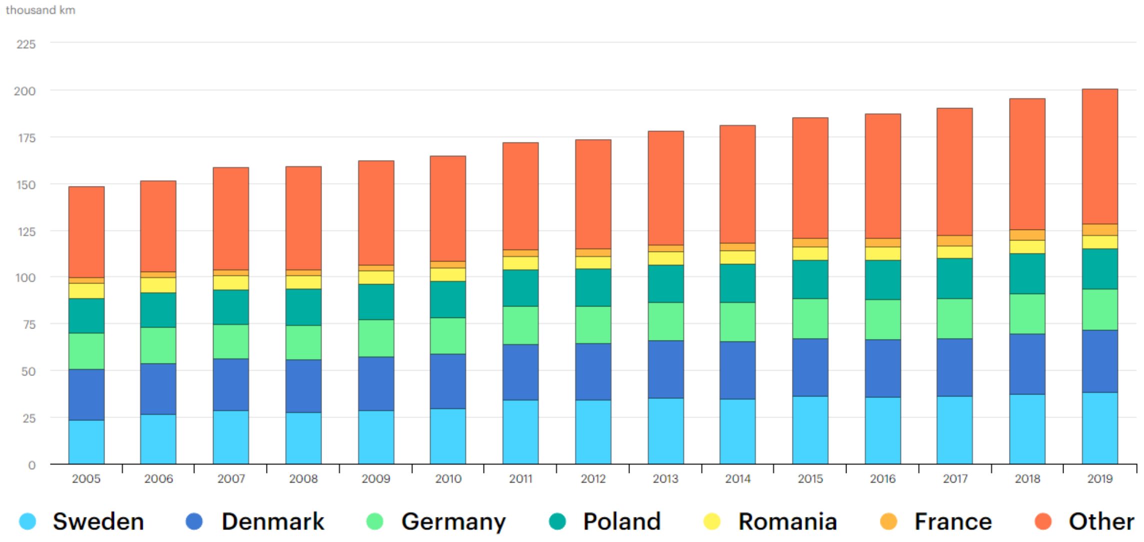
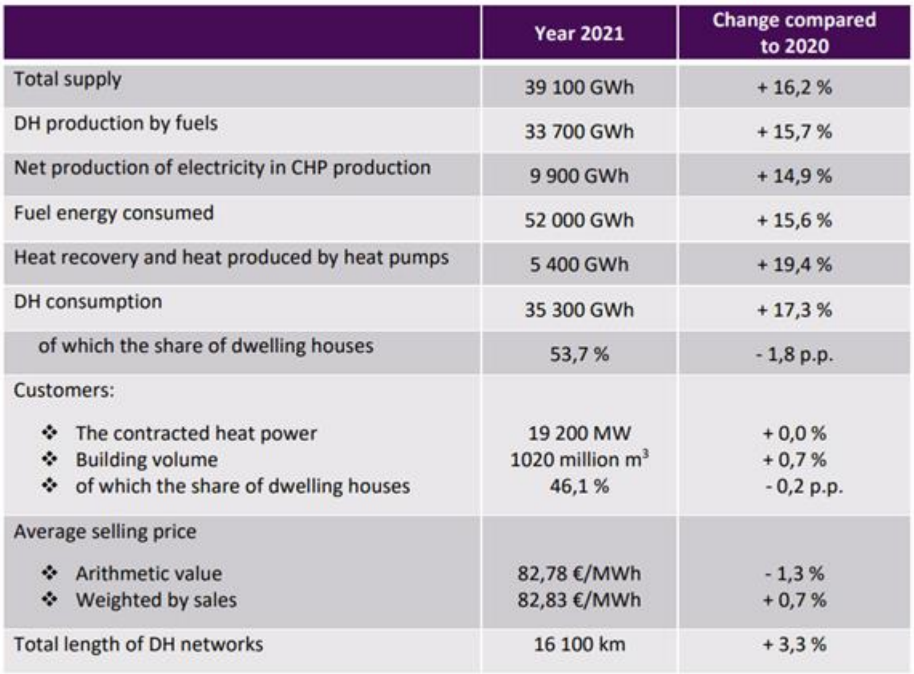


Figure 7. District heating operating pipeline length growth, 2005-2019 (IEA 2020)

4.1 Finland

The heating demand in Finland is one of the highest in Europe due to long and cold winters, which makes the issue of decarbonization of fuel used for heating even higher.

Based on Energy Finland 2021 report, the total district heat supply of the was 39 100 GWh. The general information on district heating in 2021 is presented in the figure below. In Finland district heating takes almost 50% of the total heating market. It should be noted that 2020 was a record warm year, so the growth of energy supply is higher than average over the last years.



	Year 2021	Change compared to 2020
Total supply	39 100 GWh	+ 16,2 %
DH production by fuels	33 700 GWh	+ 15,7 %
Net production of electricity in CHP production	9 900 GWh	+ 14,9 %
Fuel energy consumed	52 000 GWh	+ 15,6 %
Heat recovery and heat produced by heat pumps	5 400 GWh	+ 19,4 %
DH consumption	35 300 GWh	+ 17,3 %
of which the share of dwelling houses	53,7 %	- 1,8 p.p.
Customers:		
❖ The contracted heat power	19 200 MW	+ 0,0 %
❖ Building volume	1020 million m³	+ 0,7 %
❖ of which the share of dwelling houses	46,1 %	- 0,2 p.p.
Average selling price		
❖ Arithmetic value	82,78 €/MWh	- 1,3 %
❖ Weighted by sales	82,83 €/MWh	+ 0,7 %
Total length of DH networks	16 100 km	+ 3,3 %

Figure 8. District heating statistics for year 2021 in Finland (Energy Finland 2021)

One of the main concerns of the district heating is its fuel source. Today, heating remains one of the biggest contributors to greenhouse gas emissions.

Statistics by energy source for Finland show that more than 30% of the fuel used for heating is not carbon neutral.

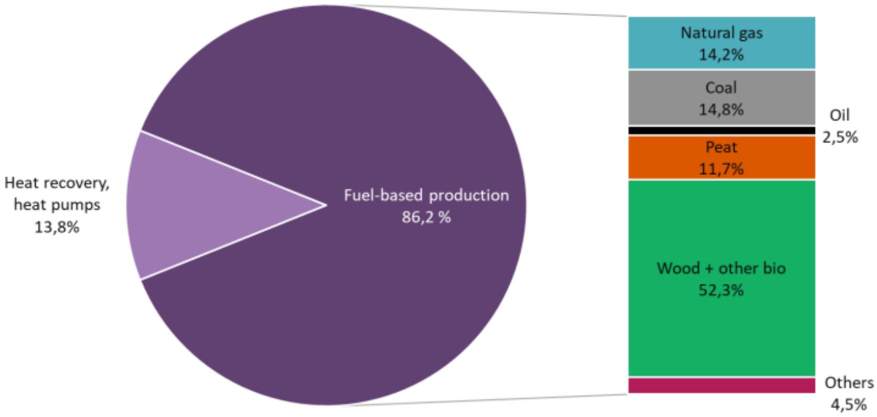


Figure 9. Energy source share in Finland (Energy Finland 2021)

Over the past decades, the amount of energy consumed supplied through district heating networks has been gradually increasing.

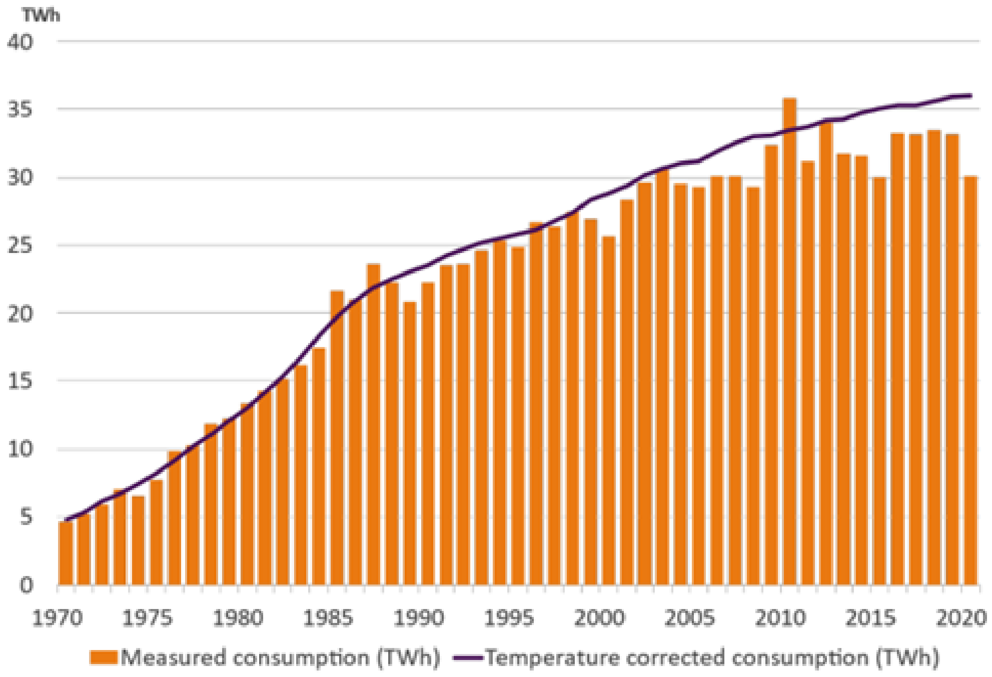


Figure 10. Measured DH consumption and temperature corrected consumption (Energy Finland 2021)

From the statistics presented above, we can conclude that the district heating market in Finland continues to develop, and the share of not carbon neutral fuel used in the production of the energy is still high, which allows for future considerations to replace this share with nuclear energy.

4.2 Sweden

Swedish district heating statistics published by the Swedish Energy Agency shows that the district heat consumption has been steadily increasing over the decades:

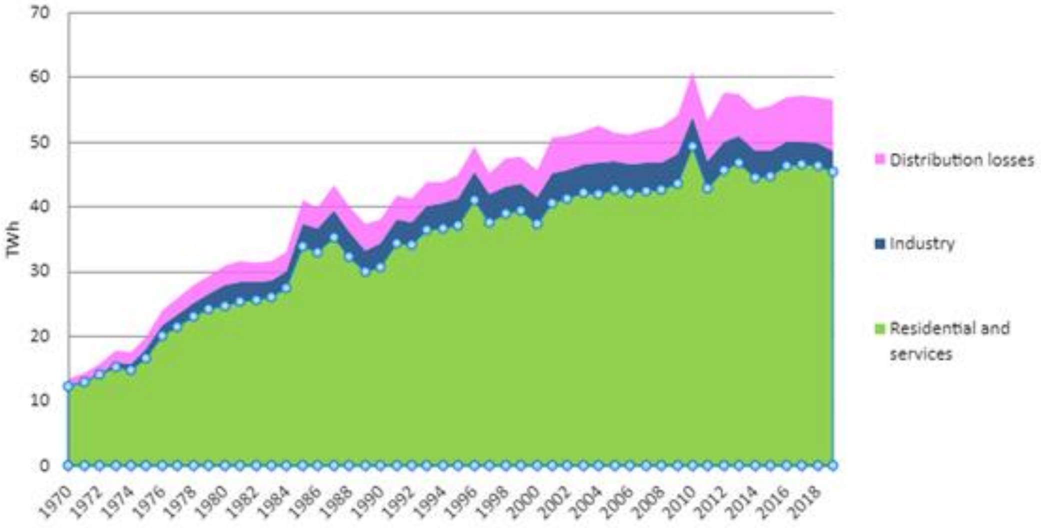


Figure 11. District heating consumption in Sweden, from 1970, TWh (Swedish Energy Agency 2022).

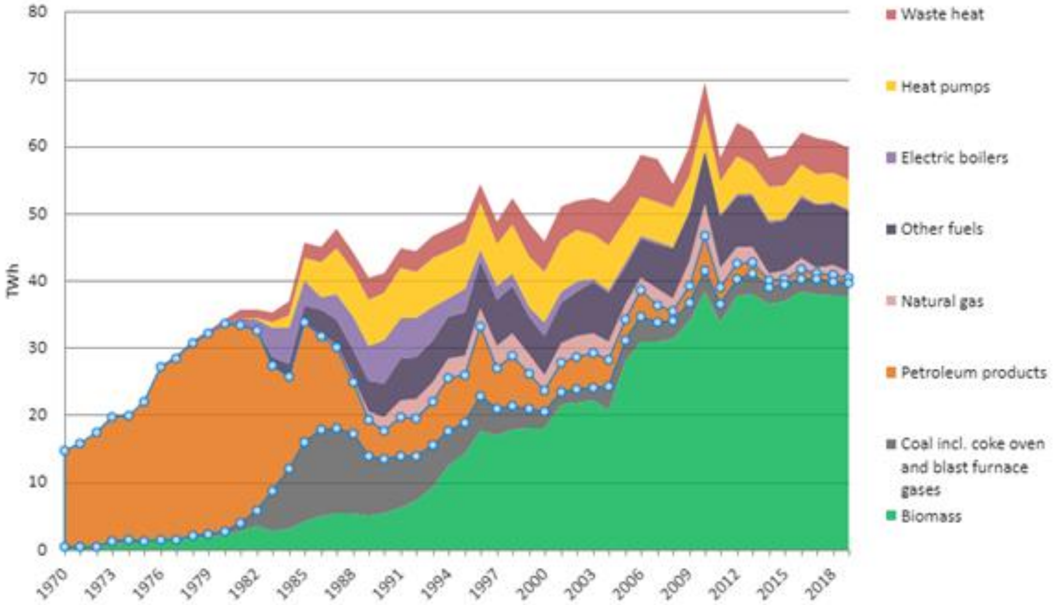
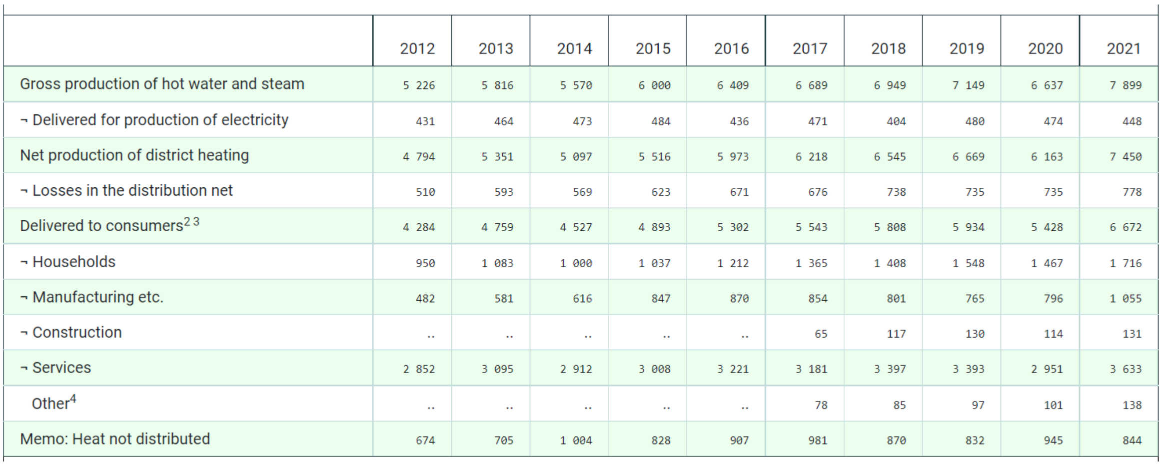


Figure 12. Input energy used in the production of district heating in Sweden, from 1970, TWh (Swedish Energy Agency 2022).

For the last 20 years the usage of biomass has been rapidly growing in the district heating production, greatly reducing the carbon dioxide emissions.

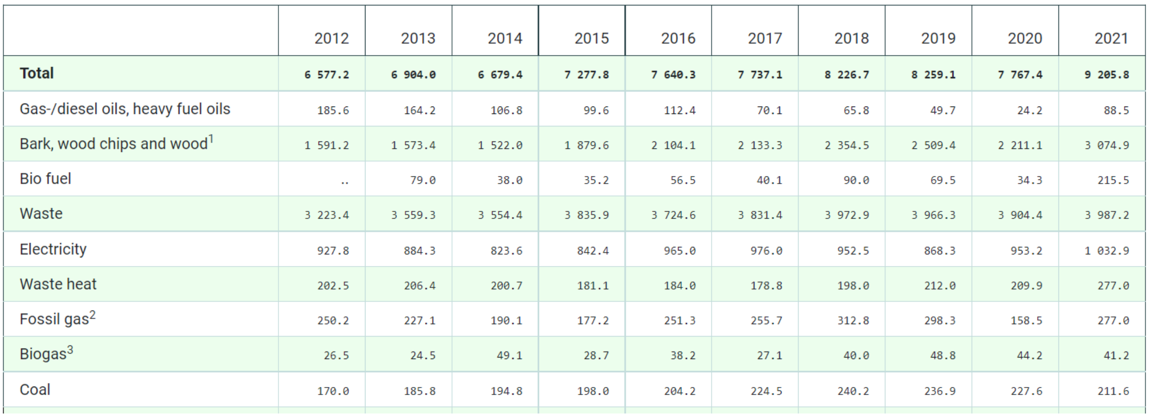
4.3 Norway

Unlike Finland and Sweden, Norway’s district heating only makes up about 2% of energy demand for heating, which is very low compared to other Baltic countries. The reason for this is that in Norway a lot of population has access to hydroelectricity and 80% of electricity is used for heating (Habibollah Sadeghi et al. 2022).



	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Gross production of hot water and steam	5 226	5 816	5 570	6 000	6 409	6 689	6 949	7 149	6 637	7 899
¬ Delivered for production of electricity	431	464	473	484	436	471	404	480	474	448
Net production of district heating	4 794	5 351	5 097	5 516	5 973	6 218	6 545	6 669	6 163	7 450
¬ Losses in the distribution net	510	593	569	623	671	676	738	735	735	778
Delivered to consumers[2 3]	4 284	4 759	4 527	4 893	5 302	5 543	5 808	5 934	5 428	6 672
¬ Households	950	1 083	1 000	1 037	1 212	1 365	1 408	1 548	1 467	1 716
¬ Manufacturing etc.	482	581	616	847	870	854	801	765	796	1 055
¬ Construction	..	..	..	..	..	65	117	130	114	131
¬ Services	2 852	3 095	2 912	3 008	3 221	3 181	3 397	3 393	2 951	3 633
Other[4]	..	..	..	..	..	78	85	97	101	138
Memo: Heat not distributed	674	705	1 004	828	907	981	870	832	945	844

Figure 13. Balance of district heating in Norway, GWh (Statistics Norway 2022).



	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Total	**6 577.2**	**6 904.0**	**6 679.4**	**7 277.8**	**7 640.3**	**7 737.1**	**8 226.7**	**8 259.1**	**7 767.4**	**9 205.8**
Gas-/diesel oils, heavy fuel oils	185.6	164.2	106.8	99.6	112.4	70.1	65.8	49.7	24.2	88.5
Bark, wood chips and wood[1]	1 591.2	1 573.4	1 522.0	1 879.6	2 104.1	2 133.3	2 354.5	2 509.4	2 211.1	3 074.9
Bio fuel	..	79.0	38.0	35.2	56.5	40.1	90.0	69.5	34.3	215.5
Waste	3 223.4	3 559.3	3 554.4	3 835.9	3 724.6	3 831.4	3 972.9	3 966.3	3 904.4	3 987.2
Electricity	927.8	884.3	823.6	842.4	965.0	976.0	952.5	868.3	953.2	1 032.9
Waste heat	202.5	206.4	200.7	181.1	184.0	178.8	198.0	212.0	209.9	277.0
Fossil gas[2]	250.2	227.1	190.1	177.2	251.3	255.7	312.8	298.3	158.5	277.0
Biogas[3]	26.5	24.5	49.1	28.7	38.2	27.1	40.0	48.8	44.2	41.2
Coal	170.0	185.8	194.8	198.0	204.2	224.5	240.2	236.9	227.6	211.6

Figure 14. Consumption of fuel used for gross production of district heating in Norway, GWh (Statistics Norway 2022).

Even though district heating is such a small part of Norway's total heat production, the production of district heat has been on the rise in the last decade. Mostly district heating networks in Norway operate in large cities. Only a small part (about 4%) of the fuel used to produce district heating is not carbon neutral.

Thus, district heating networks in Norway are very underdeveloped, which makes it difficult to use nuclear reactors for district heating purposes.

4.4 Poland

Poland is second in Europe by the amount of district heat consumption, and first in Europe by the amount of district heating customers.

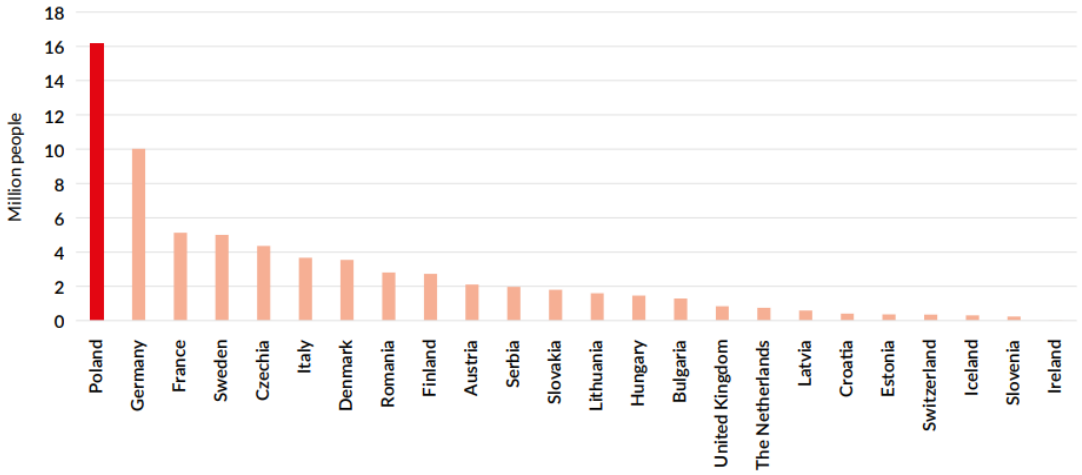


Figure 15. Population using district heating in Europe in selected European countries in 2015 (Macuk 2019).

About 40% of Poland’s domestic heating comes from district heating, as shown in figure 16.

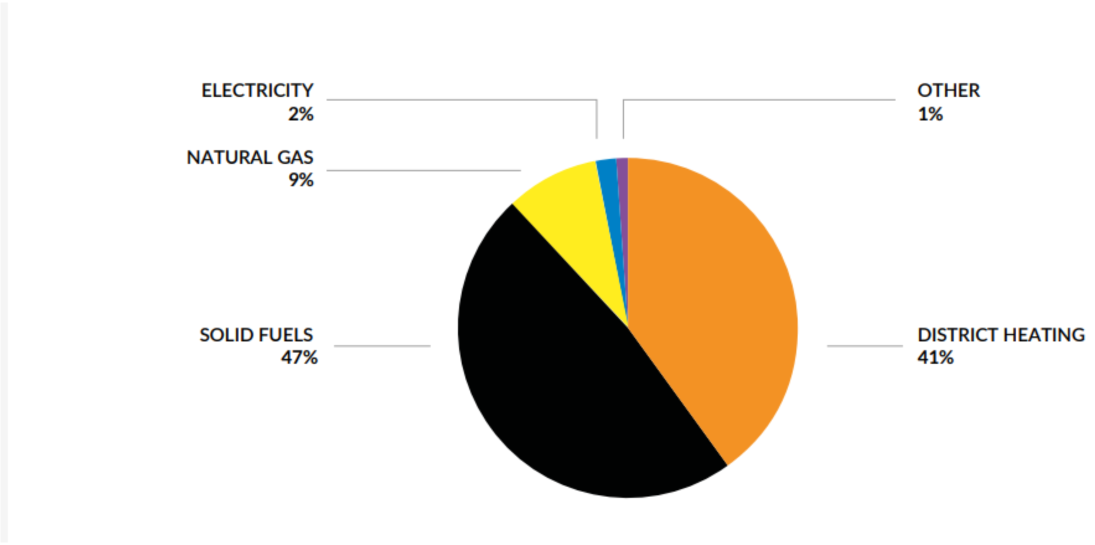


Figure 16. Heating by energy carrier in Poland, 2015 (Macuk 2019).

Despite being the country with one of the highest district heat consumptions, the district heating fuel mix consists mostly of fossil fuels.

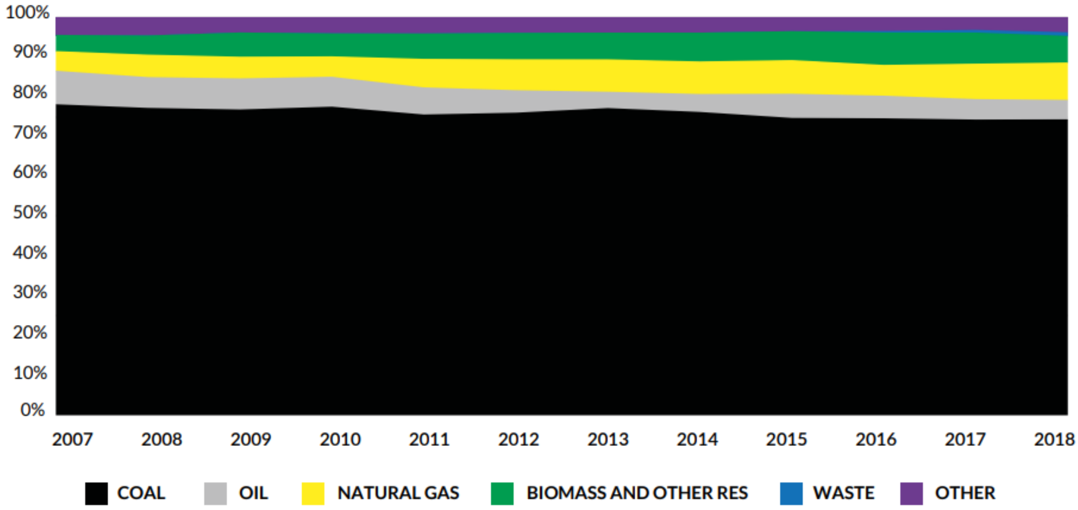


Figure 17. Heating fuels by type (Macuk 2019).

Almost 90% of fuel used to generate district heat in Poland is fossil fuel, as shown in the figure, since over the years no actions were performed to change the heating fuel mix. This large amount of not carbon neutral energy sources used for district heating, as well as the one of the largest consumptions of energy in Europe, potentially makes Poland district heating market a very promising and most free markets in Europe for nuclear heat sources to occupy, as a replacement to fossil fuels.

4.5 Denmark

District heating provides approximately 65% of all Danish households in the total heat supply. The demand for fossil fuels has been decreasing in the past decades, the figure below shows the shares of residential heating type.

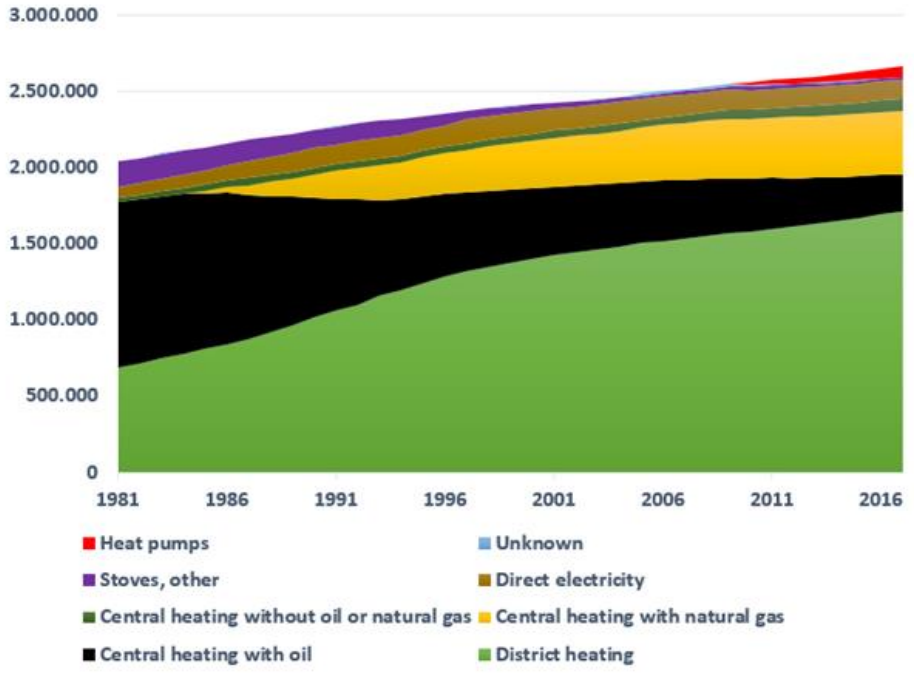


Figure 18. Shares of residential heating by type (Danish Energy Agency 2016).

The district heating sector is large, and heat is the third largest source of energy in total consumption. The graph below shows that district heating production between 1990 and 2016 has moved from being primarily fossil fuel based to being clearly dominated by renewable energy.

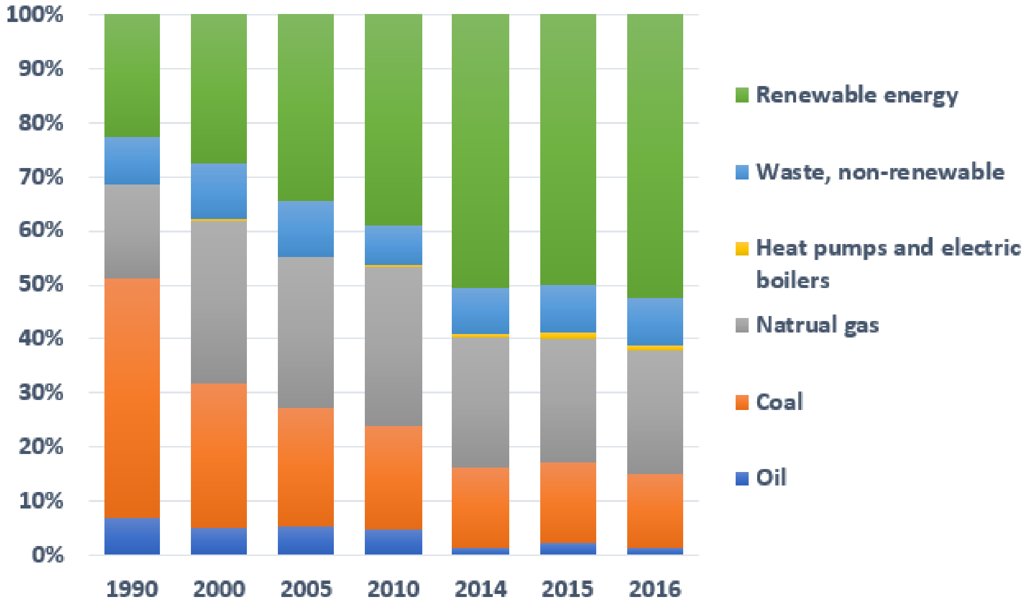


Figure 19. District heating production by fuel source (Danish Energy Agency 2016).

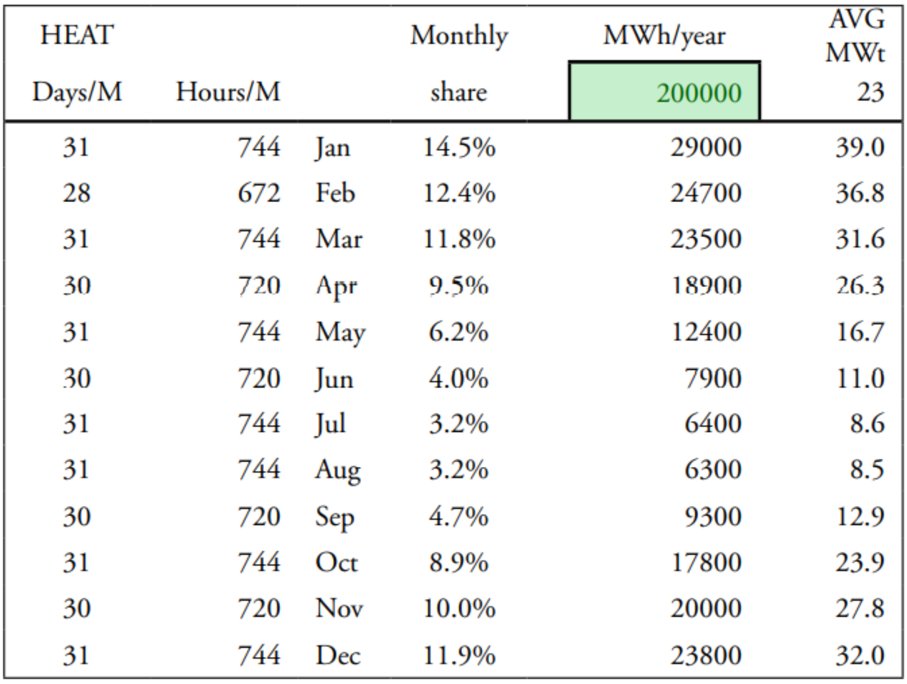
It can be seen from the figure that the share of fossil fuels has been gradually decreasing over the past decades, however, almost 40% of district heat production still comes from fossil fuels. Considering Danish environmental target of decarbonization of energy, Danish district heating can be one of the potential markets for nuclear district heating power plants.

5 Economic optimization of production

In this chapter a review of the modelling carried out in «Nuclear District Heating in Finland» report (Partanen 2019) is presented to assess two different cases of nuclear district heating – heat only reactors and Combined Heat and Power production (CHP), and the similar modelling is also performed for Denmark, which has much lesser heating demand difference over the yearly seasons, than that of Finland.

The simple demand and supply modelling was done, to give a view on different sizes of district heating networks and how the reactors could fit with the network demand. The modelling is carried out for Finnish example of the district heating networks. In Finland, with a greatly varying monthly demand, data was taken from nine random Finnish district heating networks, and the following table was filled with monthly share.

Table 4. Monthly average MWt demand calculations for each month (Partanen 2019).



HEAT			Monthly	MWh/year	AVG MWt
Days/M	Hours/M		share	200000	23
31	744	Jan	14.5%	29000	39.0
28	672	Feb	12.4%	24700	36.8
31	744	Mar	11.8%	23500	31.6
30	720	Apr	9.5%	18900	26.3
31	744	May	6.2%	12400	16.7
30	720	Jun	4.0%	7900	11.0
31	744	Jul	3.2%	6400	8.6
31	744	Aug	3.2%	6300	8.5
30	720	Sep	4.7%	9300	12.9
31	744	Oct	8.9%	17800	23.9
30	720	Nov	10.0%	20000	27.8
31	744	Dec	11.9%	23800	32.0

The following assumptions are made in the modelling:

- If possible, reactors are run at maximum capacity before the demand maximum is reached.
- Maintenance and refueling processes take one month for one reactor.
- Production from the nuclear reactor cannot exceed the demand. The reactor is run at lower capacity when it does exceed it.

With these assumptions, the following modelling is performed.

5.1 Finland District Heating Networks

In this section multiple networks of different sizes are considered with two cases of dedicated district heating reactors and CHP (combined heat and power) reactors.

5.1.1 Dedicated district heating reactors

Reactors of different capacities producing heat for district heating networks with different heat demand, starting with a very small hypothetical 24 MW(t) «FinReactor».

200 GWh DH Networks

In Finland there are approximately 20 district heat networks between 150 and 350 GWh energy demand over the while year with a total demand of 4.3 TWh. A hypothetical 24 MW(t) reactor running at around 85% load factor would produce 180 GWh of energy annually.

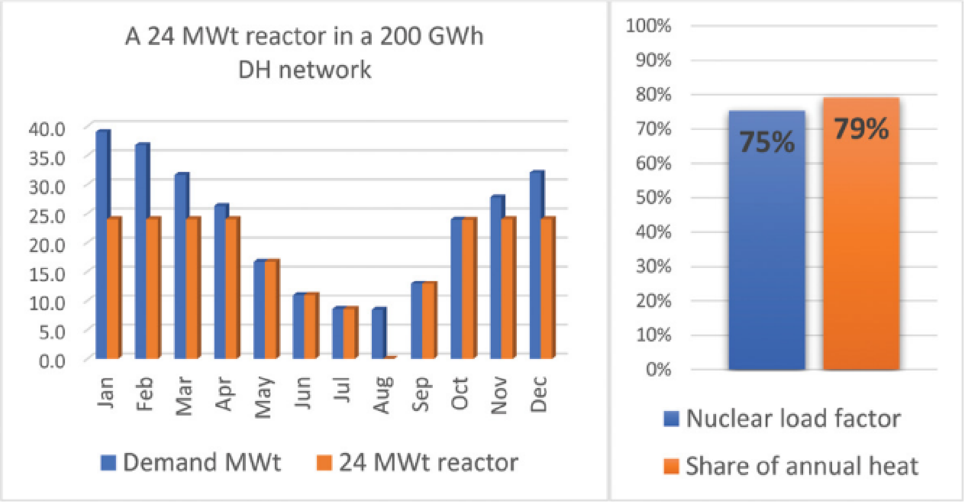


Figure 20. A 24 MWt reactor in a 200 GWh DH network, load factor and share of annual heat (Partanen 2019).

For a 200 GWh network, the reactor would run at a slightly suboptimal load factor of 75% but producing almost 80% of the energy demand. The colder months would require additional heat sources and August was chosen here for annual maintenance.

500 GWh DH Networks

In Finland there are around 10 district heat networks with yearly demand varying from 350 to 700 GWh, which can fit from one to two «FinReactors». In this case 500 MWh network is considered as an average with two 24 MW(t) hypothetical reactors.

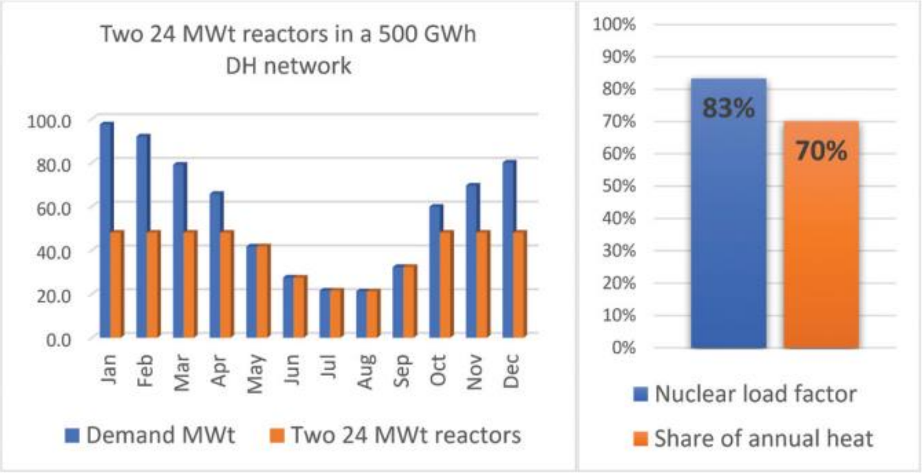


Figure 21. Two 24 MWt reactor in a 500 GWh DH network, load factor and share of annual heat (Partanen 2019).

Two 24 MW(t) reactors provide a good load factor of 83% with their maintenance done in two months with lowest demand – July and August, producing 70% of total heat demand.

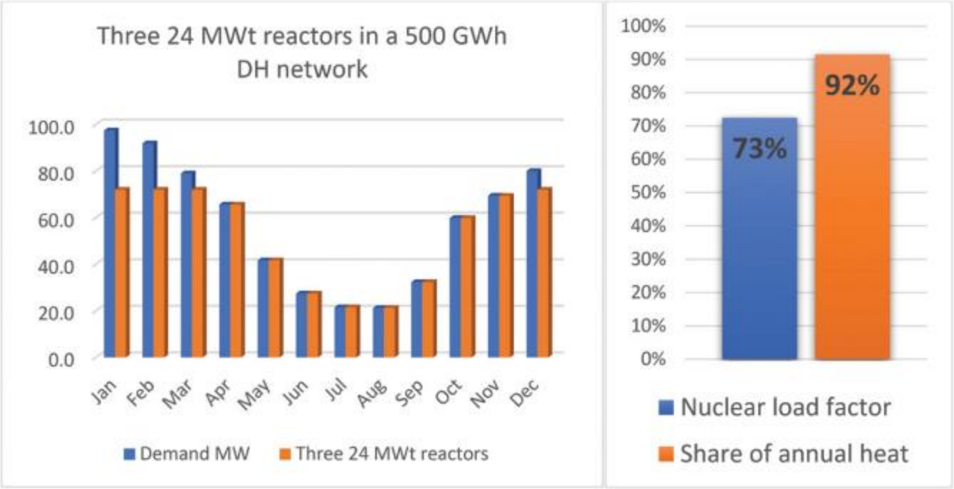


Figure 22. Three 24 MWt reactor in a 500 GWh DH network, load factor and share of annual heat (Partanen 2019).

Three 24 MW(t) reactors situation may be considered an extreme case, with reduced load factor, but producing 92% of annual demand.

1500 GWh DH Networks

There are five DH Networks with an annual demand between 1 and 2 TWh with population between 100 and 200 thousand people. In this case, different reactor configurations are considered.

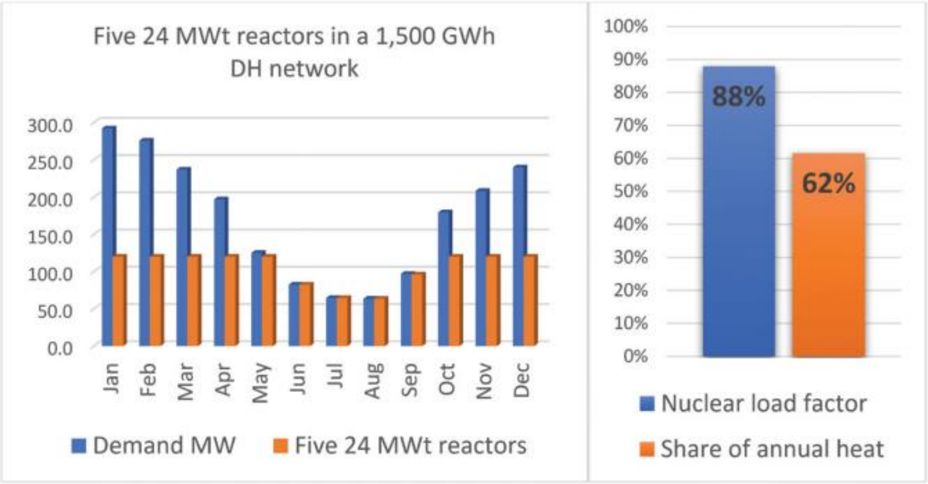


Figure 23. Five 24 MWt reactor in a 1500 GWh DH network, load factor and share of annual heat (Partanen 2019).

The first configuration is five 24 MW(t) reactors, which would operate at a good load factor of 88%, providing 62% of demand with maintenance of two reactors in June and July respectively, two in August at the same time and one in September.

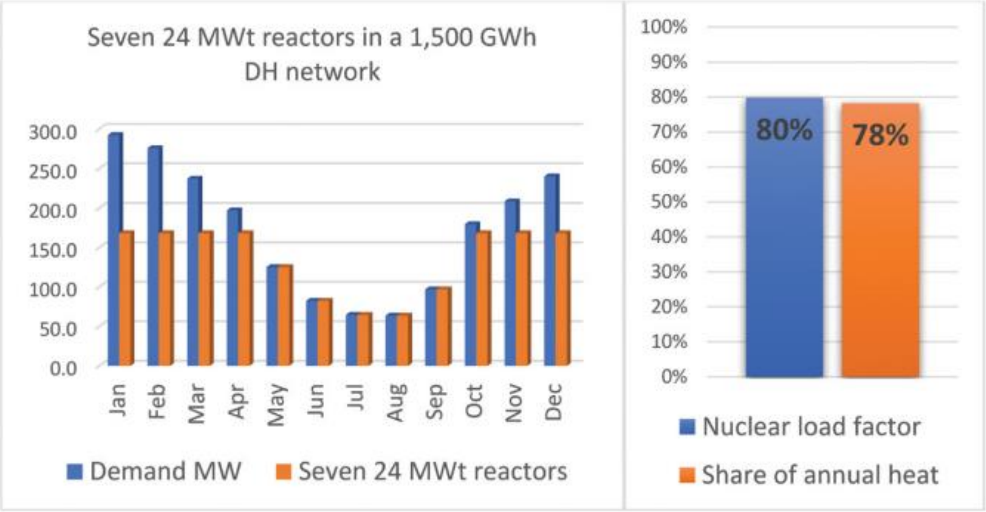


Figure 24. Seven 24 MWt reactor in a 1500 GWh DH network, load factor and share of annual heat (Partanen 2019).

Adding two more 24 MW(t) reactors greatly increases the share of annual demand, while keeping the reasonable load factor. The maintenance for the reactors is distributed in the following moths: two reactors respectively in July and August and one in each of the following months: May, June and September.

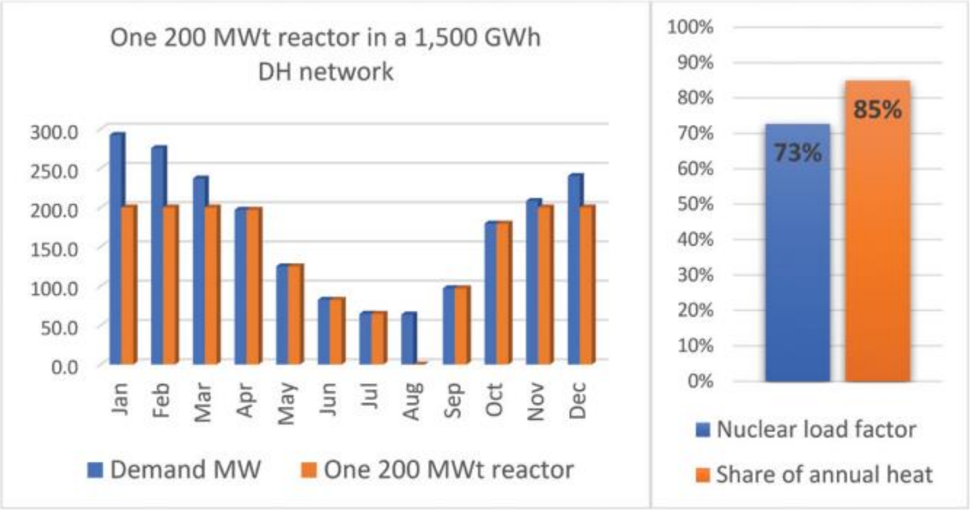


Figure 25. One 200 MWt reactor in a 1500 GWh DH network, load factor and share of annual heat (Partanen 2019).

A single 200 MW(t) reactor produces 85% of yearly demand, but with a cost of a low load factor of 73% with a maintenance in August or July. The downside of this configuration is having one single big source of energy, which can affect the security of energy supply.

2400 GWh DH Networks

In Finland there are only three district heating networks with annual demand of around 2400 GWh, specifically, Turku, Tampere and Espoo at around 2.4 TWh. As in the previous sections, different configurations are considered.

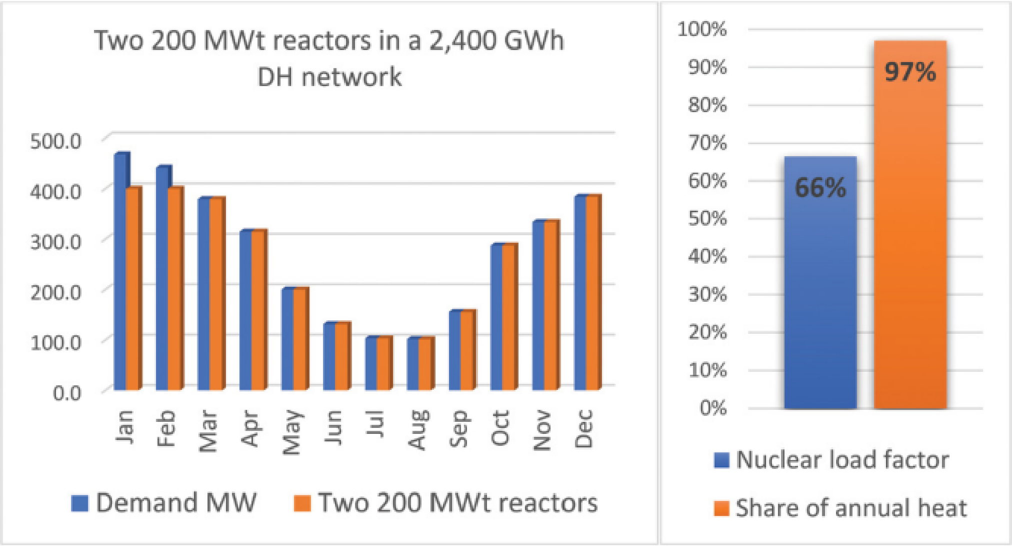


Figure 26. Two 200 MWt reactor in a 2400 GWh DH network, load factor and share of annual heat (Partanen 2019).

An extreme case configuration, providing 97%, which is almost all of the annual demand, but at a very low load factor of 66%. The economics of this configuration is questionable despite the added redundancy from having two reactors. The other application for the extra capacity should be considered, such as CHP, for example.

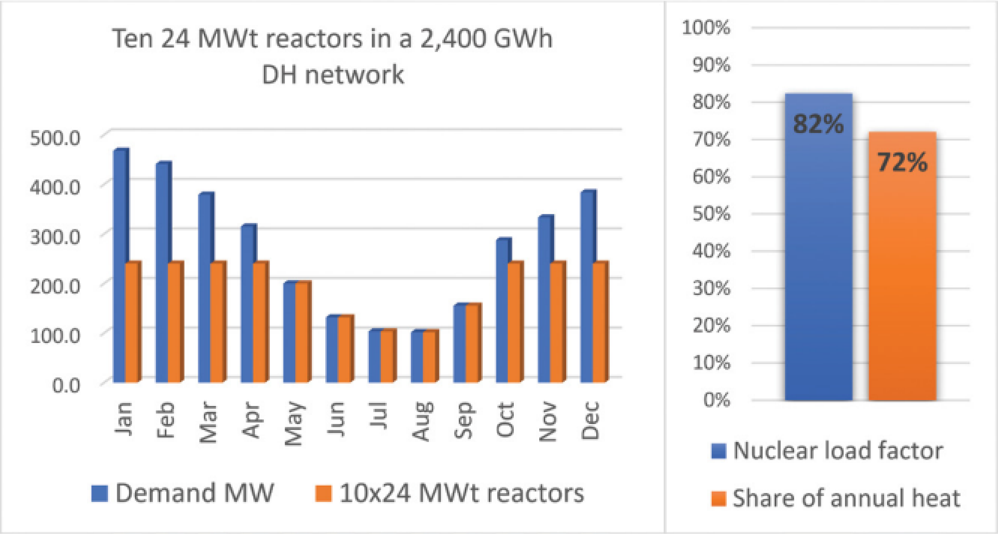


Figure 27. Ten 24 MWt reactor in a 2400 GWh DH network, load factor and share of annual heat (Partanen 2019).

Another questionable configuration with ten 24 MW(t) reactors, which provides good load factor of 82% and large share of annual demand of 72% but raises concerns of the cost of operating such a large amount of reactors, as well as adding the siting problem.

7000 GWh DH Network

Helsinki is the biggest district heating network in Finland with an annual demand of 7000 GWh. Multiple configurations are considered here as well.

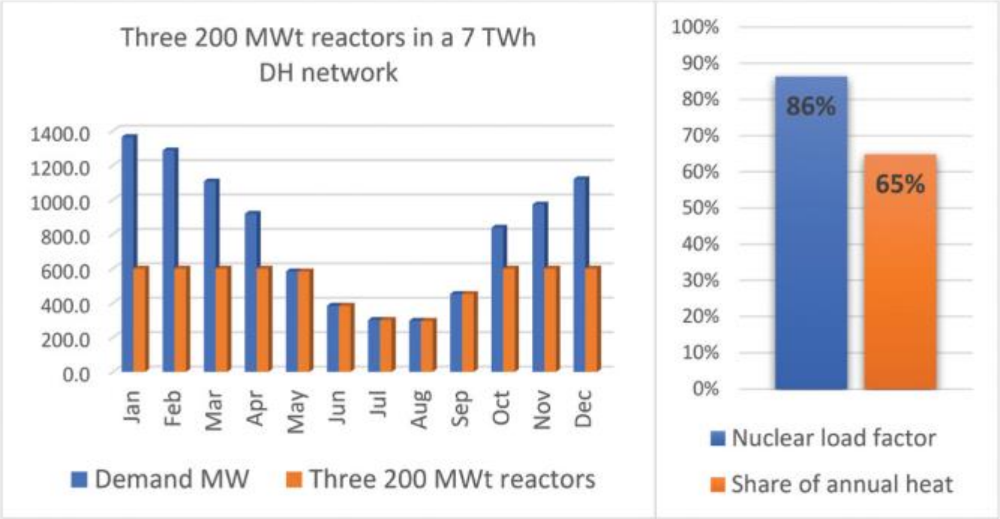


Figure 28. Three 200 MWt reactor in a 7000 GWh DH network, load factor and share of annual heat (Partanen 2019).

Three 200 MW(t) reactors, for example, SECURE or NHR-200-II which were presented earlier, would provide 86% load factor and rather low share of heat demand of 65%.

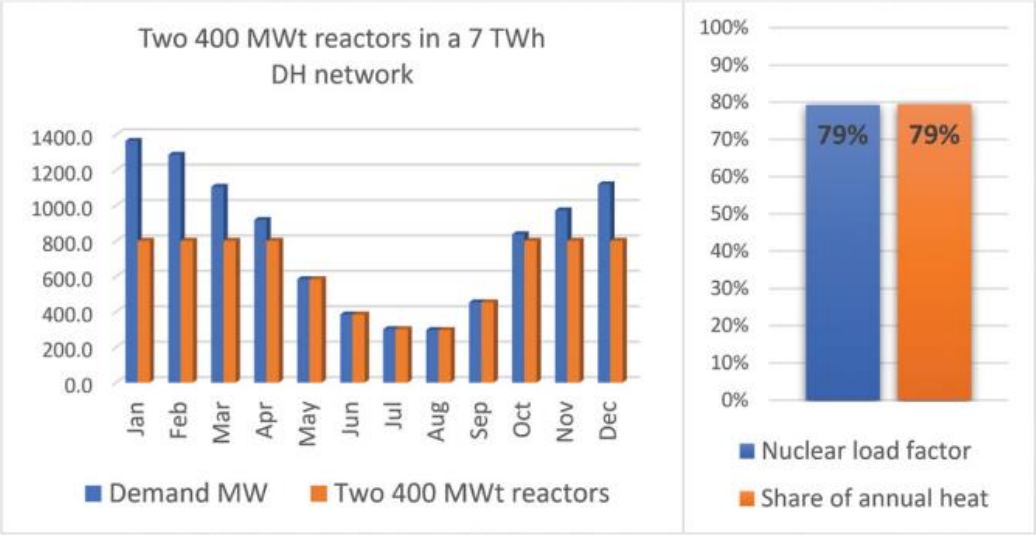


Figure 29. Two 400 MWt reactor in a 7000 GWh DH network, load factor and share of annual heat (Partanen 2019).

Another possible configuration are two 400 MW(t) reactors, such as Chinese DHR-400, which was previously discussed. This configuration is more preferrable compared to the previous, as it provides a reasonable load factor of almost 80%, as well as the share of annual heat of also almost 80%, also providing redundancy and requiring less siting and operation considerations.

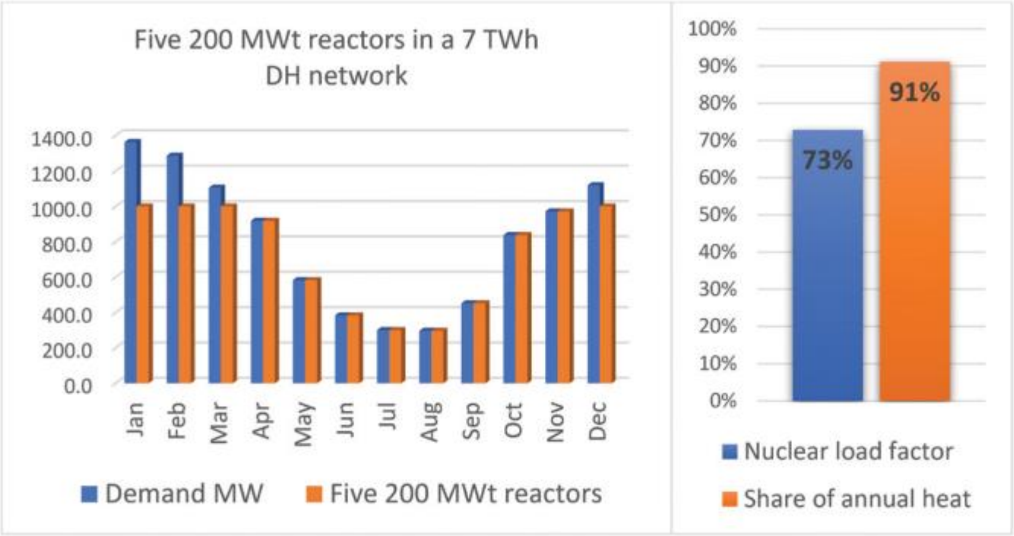


Figure 30. Five 200 MWt reactor in a 7000 GWh DH network, load factor and share of annual heat (Partanen 2019).

Five 200 MW(t) reactors can provide a large share of annual demand of 91% but running at rather low load factor of 73%. Even though five reactors allow for additional reliability of supply and redundancy, the problems of finding multiple siting areas and operation cost arise.

5.1.2 Combined Heat and Power

Combined Heat and Power (CHP) production is one of the most effective ways of utilizing nuclear power in district heating. Using a reactor in CHP would allow to meet the full demand for heat of the network and always run the plant at high capacity. Essentially, this can be done by changing the electricity and heat production ratios based on the demand.

Some assumptions and simplifications are made in the modelling in question:

- The steam for heating is taken from the turbine bypass for simplicity.
- The turbine must always be run at least on 25% of its total power.
- The turbine can be completely switch off to redirect all capacity into heating.
- The heat production can be completely stopped to direct all steam for electricity generation.

Since the assumptions and simplifications made greatly reduce efficiency of the process, the actual efficiency of the system can be higher.

2400 GWh DH Networks

Similar to the previous section, 2400 GWh district heat networks are considered, that is cities as Turku, Tampere and Espoo.

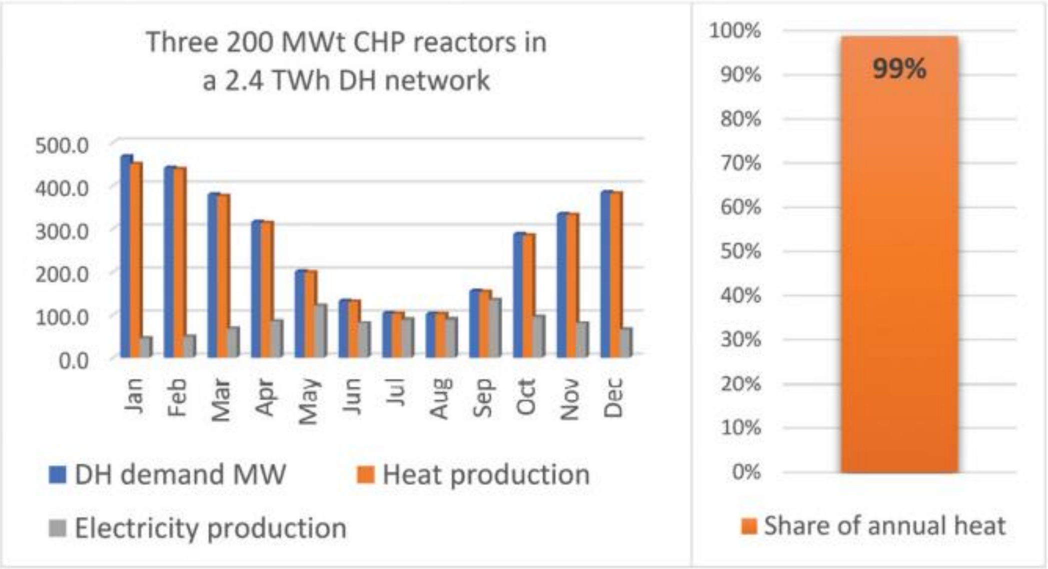


Figure 31. Three 200 MWt CHP reactors in a 2400 GWh DH network, share of annual heat (Partanen 2019).

Three 200 MWt CHP reactors can be used to provide all the annual heat demand, as well as additional 0.7 TWh of electricity.

7000 GWh DH Network

For a 7000 GWh district heating network, such as Helsinki, eight 200 MWt hours CHP reactors can be used.

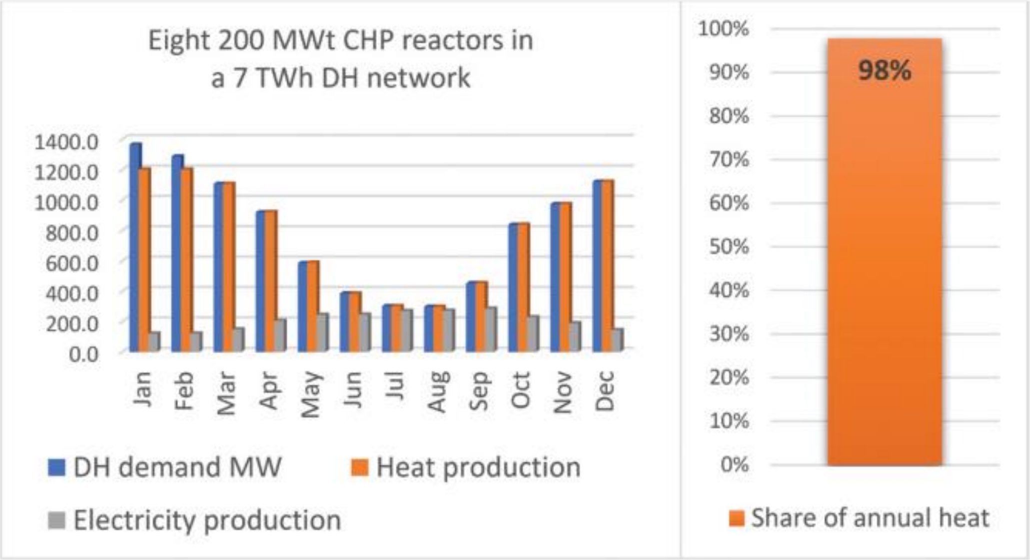


Figure 32. Eight 200 MWt CHP reactors in a 7000 GWh DH network, share of annual heat (Partanen 2019).

This configuration is enough to supply all heat demand for this network. Approximately 1.8 TWh of electricity is produced over a year as well. It is also worth mentioning that for demand spikes it is also possible to completely shut down the turbine to obtain additional heat capacity of 400 MW(t).

5.2 Denmark District Heating Networks

Modelling similar to the one reviewed was performed. The country in question is Denmark, as Denmark has a very developed district heating system, in which around 40% of heat generation comes from fossil fuels, which makes Denmark DH network a potential market for nuclear decarbonization.

Denmark’s population is comparable to Finland, but the average monthly temperature in Denmark doesn’t vary as much as in Finland, which makes the heat demand more uniform over the year. The modelling process is similar to the Finland case, with the initial data for demand distribution taken from the Danish Energy Agency. Only dedicated district heating reactors were considered here, in order to compare the load factor and heat share in a different climatic conditions with less temperature fluctuations over the year.

5.2.1 Dedicated district heating reactors

The networks sizes were chosen to be the same as the Finnish case for convenience of comparison.

200 GWh DH Network

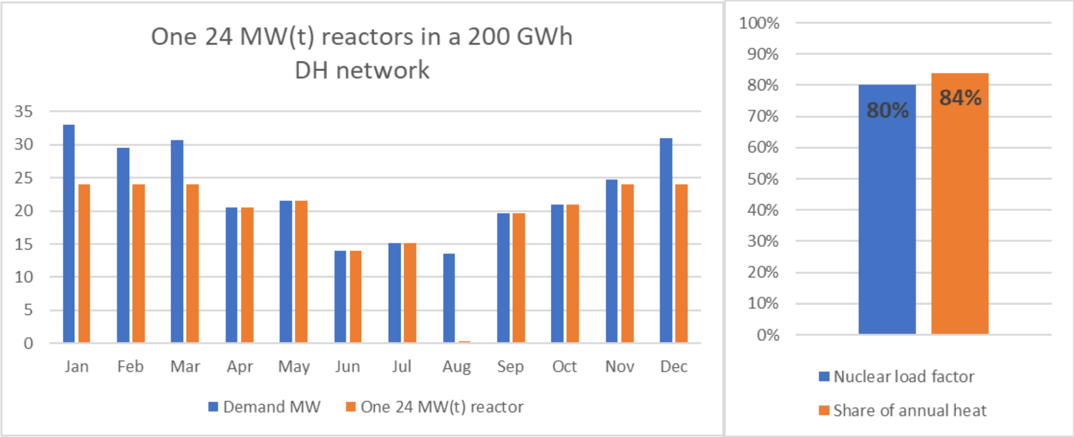


Figure 33. One 24 MWt reactor in a 200 GWh DH network, load factor and share of annual heat

One hypothetical 24 MW(t) reactor would be enough for 200 GWh DH network, providing 84% of heat demand with a relatively small load factor of 80%.

500 GWh DH Network

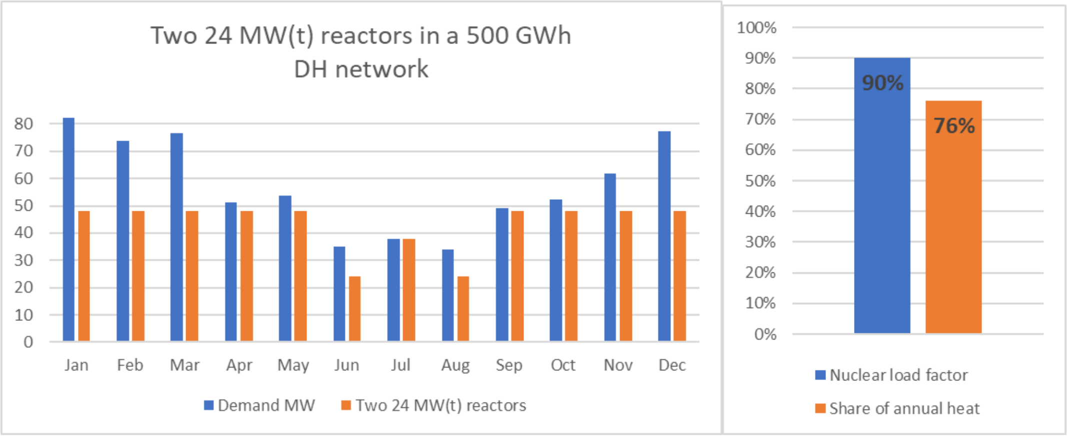


Figure 34. Two 24 MWt reactor in a 500 GWh DH network, load factor and share of annual heat

Two 24 MW(t) reactors would produce 76% of the annual demand at a good load factor of 90%, with maintenance in June and August.

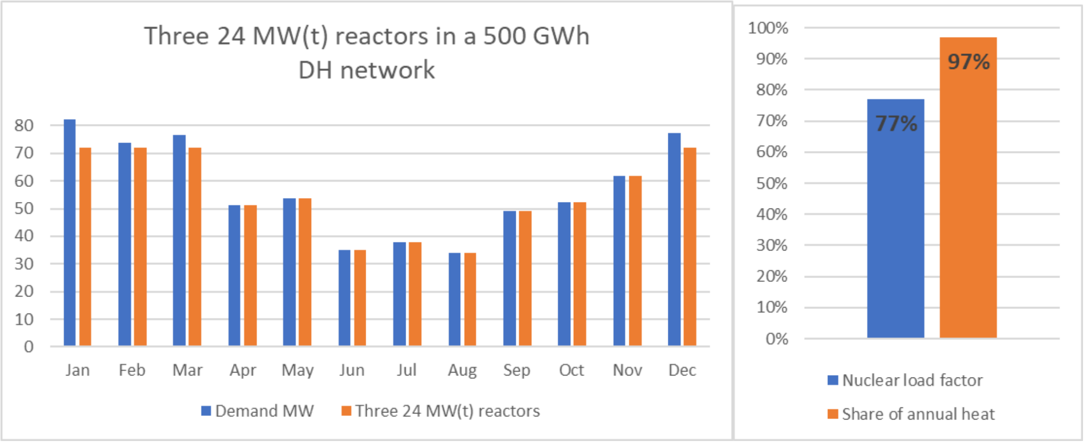


Figure 35. Three 24 MWt reactor in a 500 GWh DH network, load factor and share of annual heat

This is another extreme configuration, generating 94% of annual demand with a low load factor of 74%.

1500 GWh DH Networks

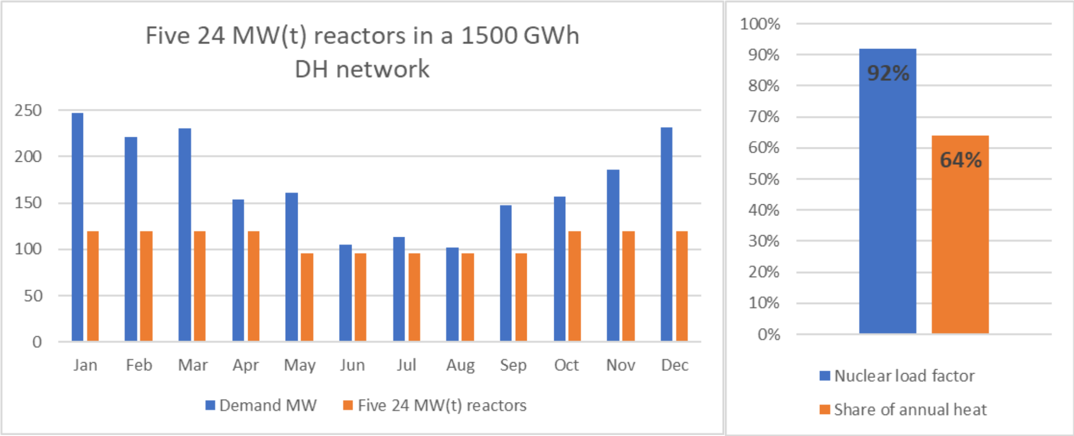


Figure 36. Five 24 MWt reactor in a 1500 GWh DH network, load factor and share of annual heat

Five 24 MW(t) reactors would produce 64% of annual heat demand at a very good load factor of 92%.

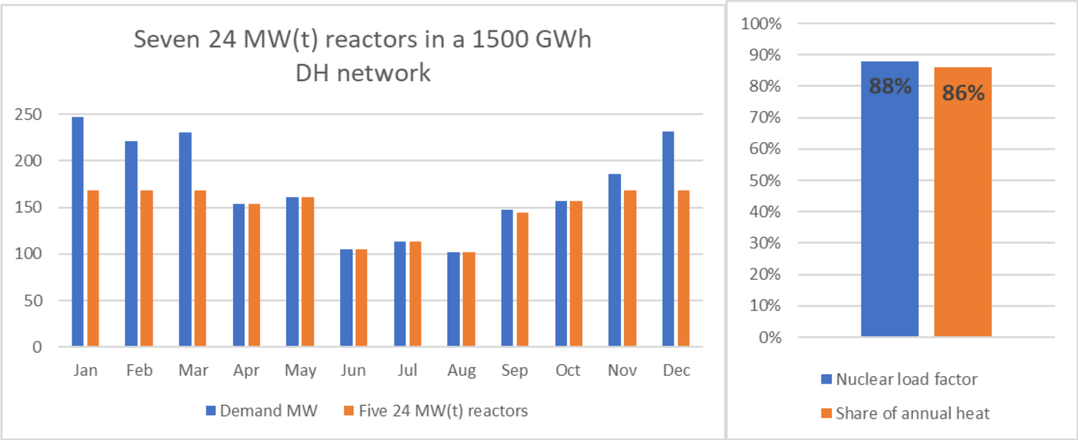


Figure 37. Seven 24 MWt reactor in a 1500 GWh DH network, load factor and share of annual heat

Seven 24 MW(t) reactors would produce 86% of annual demand at a good load factor of 88%

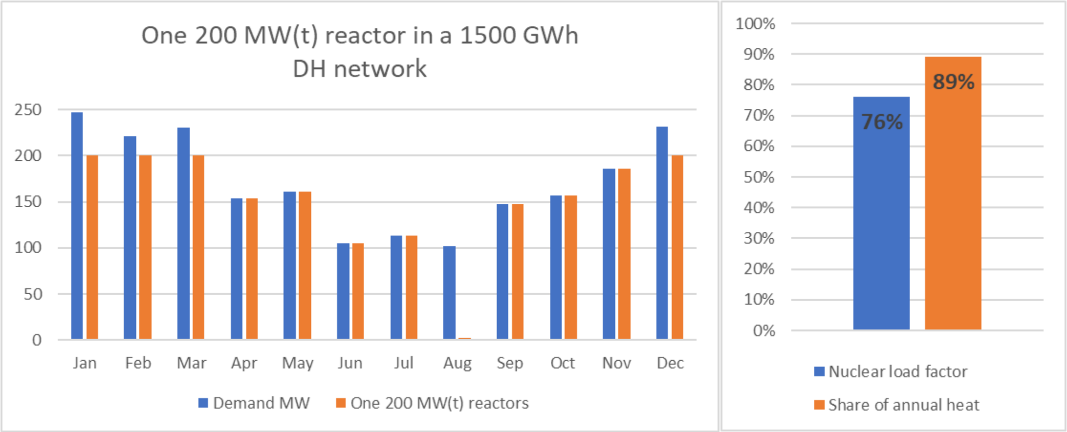


Figure 38. One 200 MWt reactor in a 1500 GWh DH network, load factor and share of annual heat

The case with a single 200 MW(t) reactor produces almost 90% of annual demand with a rather low load factor of 76%.

2400 GWh DH Network

In Denmark there are two cities with 2400 GWh DH network – Aarhus and Odense.

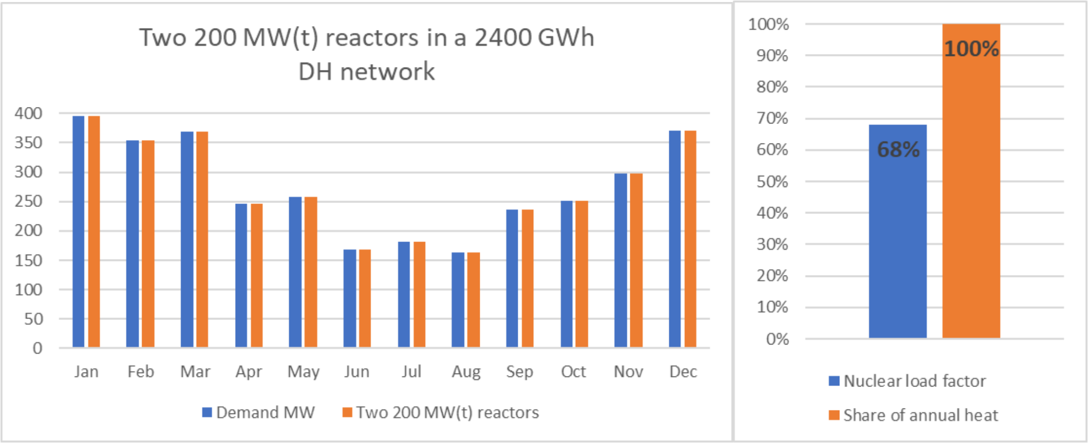


Figure 39. Two 200 MWt reactor in a 2400 GWh DH network, load factor and share of annual heat

This is a very extreme case, providing 100% of annual heat demand, but running at a very poor load factor of 68%.

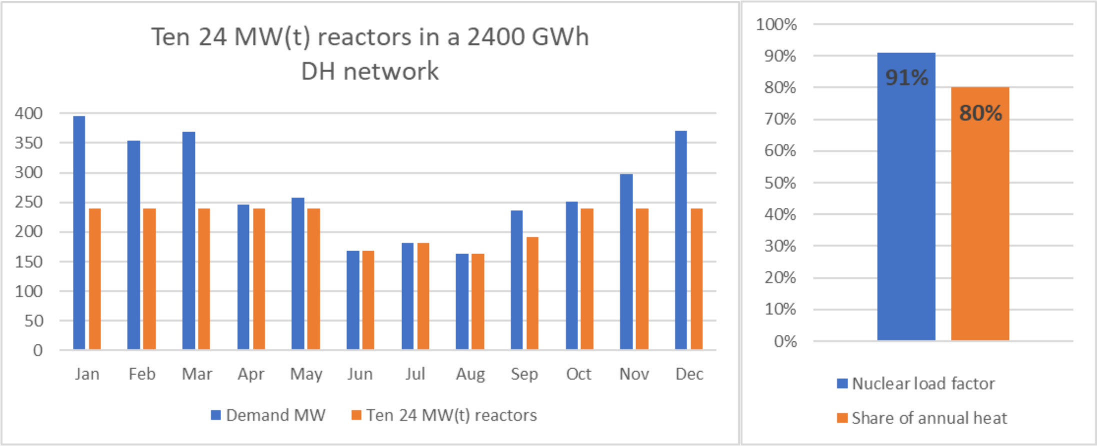


Figure 40. Ten 24 MWt reactor in a 2400 GWh DH network, load factor and share of annual heat

This case allows for 80% share of annual demand and a very good load factor of 91% with maintenance scheduled as three reactors in June, two in July, three in August and two in September.

7000 GWh DH Network

Copenhagen is the capital of Denmark with a population similar to Helsinki, which has the 7000 GWh district heating network.

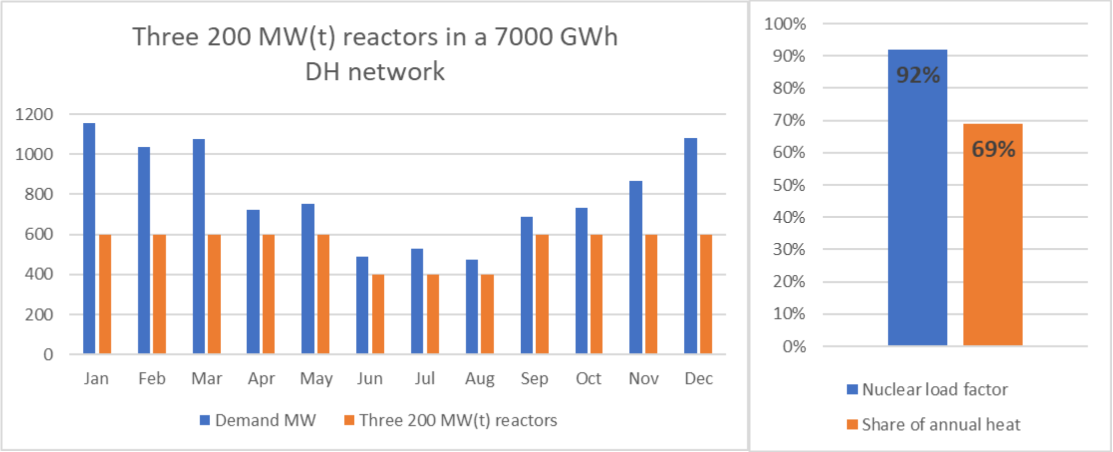


Figure 41. Three 200 MWt reactor in a 7000 GWh DH network, load factor and share of annual heat

Three 200 MW(t) reactors provide a great load factor of 92%, while producing almost 70% of annual heat demand. The maintenance scheduled for June, July, and August.

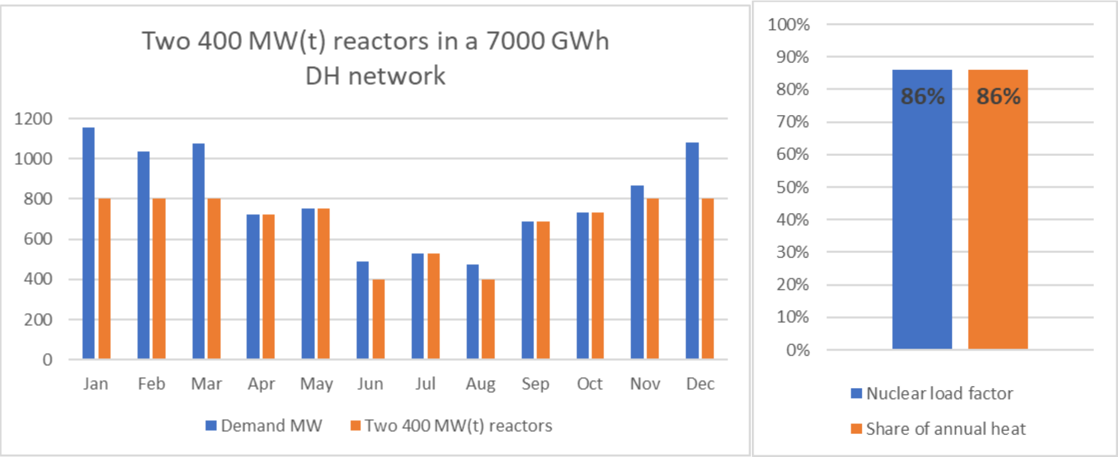


Figure 42. Two 400 MWt reactor in a 7000 GWh DH network, load factor and share of annual heat

Two 400 MW(t) reactors are a middle-ground case, providing a very large portion of the annual heat demand, while still operating at a relatively good load factor of 86%.

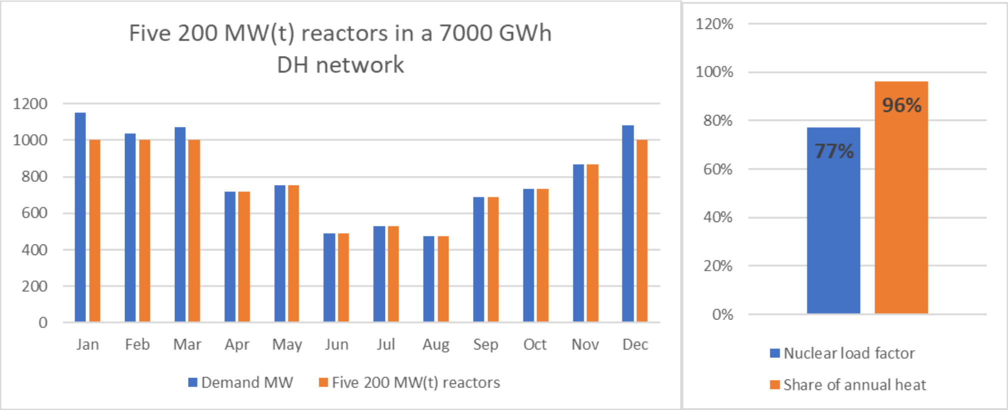


Figure 43. Five 200 MWt reactor in a 7000 GWh DH network, load factor and share of annual heat

Five 200 MW(t) reactors is an extreme case that provides almost all the annual demand but runs at a very low load factor of 77%.

5.3 Conclusion for the chapter

From the modelling reviewed in this chapter, it can be concluded that for heat-only reactors, there are two main configurations – producing around two thirds of the heat demand with a high load factor of approximately 85% or high heat production around 90% with a low load factor of around 70% which reduces the commercial viability.

Modeling done in this chapter allows us to conclude that a more even distribution of demand throughout the year allowed us to obtain a more favorable load factor and share of the annual head demand in all considered networks and reactor configurations. Using heat-only nuclear reactors in countries where yearly temperature doesn’t vary as much would increase the load factor with well-chosen capacity.

For the most cases, Combined Heat and Power reactors solve the issue of low load factor by producing electricity for time of the year when the heating capacity is greater than the demand for district heat. However, the electricity production, naturally, requires a turbine to be implemented, which can increase the capital cost of the plant construction, as well as the plant’s size, which might be crucial when choosing the site. More economical considerations, including cost and demand of electricity, should be made for an individual case to assess the practicability of using the CHP.

6 Considerations

As the issue of climate change is discussed more and more, the move towards district heating as a cleaner way of heating spaces is gaining popularity. However, the share of fossil fuels in energy production for district heating is still very high. The use of nuclear energy in district heating networks is one of the most promising solutions to the problem of heat decarbonization.

To date, the practice of using nuclear energy for district heating remains extremely limited. The most widespread is cogeneration of heat at large conventional nuclear power plants, but this energy is an extremely small part of the total heat produced for district heating. Despite this, the use of existing NPPs in nuclear heating is also important, as it sets an example of a really working nuclear heating system, which positively influences the mood and opinion of both potential investors and the public.

In addition to large conventional NPPs, many designs of dedicated district heating reactors have been developed, with the first of these dating back to the 1970s. As shown in the previous chapter, dedicated DH reactors can be very competitive in conditions where energy consumption does not vary much from month to month during the year, which makes it possible to obtain a good load factor. Even reactor designs developed many years ago have good economic potential, but they require design review and refinement to meet today's safety requirements.

One of the most popular and promising areas in the field of nuclear district heating is Small Modular Reactors. In recent years, there has been an increasing discussion of SMRs, new projects and designs are being created. Some of the projects, such as NuScale, are the closest to being built and commercially launched. Through modularity, design standardization, and improved inherent safety systems, SMRs can address several of the key challenges of using nuclear reactors in DH – system scalability, capital investment, ease of licensing with potential licensing recognized by Nuclear Agencies of multiple countries and location close to consumer.

In European countries, in recent decades, the scale of district heating networks has been gradually growing. District heat is especially widespread around the Baltics. Despite the general trend towards energy decarbonization, in many countries, fossil fuels are still the main energy sources for district heating production. In such countries, nuclear district heat could completely replace fossil fuels and start producing clean energy. Naturally, an analysis of the district heating market should be done based on the country's energy source share, for example, in Iceland, which has a highly developed district heating network, the largest part of the energy produced comes from geothermal sources, while Poland has most of the energy for district heating gets from coal.

For the successful application of nuclear energy in district heating, some changes to regulations and legislation should be made. In particular, the issue of licensing small reactors is currently very acute, since the process of licensing reactors is usually extremely long and expensive, which makes them unattractive to potential investors. It is also common practice that there is one license per nuclear power plant, which does not consider ëthe standardized nature of SMRs that can be produced off-site. Another concern is siting regulations. Since the regulations were written for large conventional reactors, they do not take into account the more advanced safety features of modern reactor designs, as well as the reduced power of reactors, which makes them equally safe even when located near the consumer, which is crucial when it comes to district heat production.

7 Conclusions

District Heating occupies a significant part of the energy consumed by mankind. Currently, many countries use fossil fuels to produce heat. Nuclear district heating is a promising direction for the decarbonization of produced heat. As of today, use of nuclear energy in district heating remains very limited. Most of the experience with nuclear district heating comes from large reactors with cogeneration, usually supplying heat to the populated area close to the NPP. The most promising direction for nuclear district heating are SMRs. Their implementation could allow for closer siting near larger populated areas, making nuclear district heat economically viable. Another promising concept are the reactors dedicated for district heat production. Such reactors are usually not classified as SMRs but can still be a viable solution for district heat production.

Current legislations and regulations for nuclear energy are a big concern for nuclear district heating. There are two main limiting factors. The first is the siting regulations since the heat transportation to consumers should not be carried out over long distances due to heat loss. The shorter the pipes, the more competitive nuclear district heating is. The solution to this problem may be to review existing legislation and regulation, allowing reactors to be located closer to populated areas. Changes in the design of reactors for nuclear district heating compared to large conventional plants should be considered, also taking into account the difference in safety approaches. The second point here is that nuclear regulators in most countries approach the issue of issuing a license for the construction of a nuclear facility on the principle of "one reactor - one license", which greatly complicates the process of building new NPPs, increasing both the cost and stretching the process in time. Legislation and regulations need to be changed to reflect the serial production of SMRs, which involve the production of standardized reactors produced in a single facility for delivery to the reactor site. This will reduce the cost and time needed to obtain a license for plant construction, allowing for a better competitiveness of nuclear energy in district heating.

The district heating market in Europe is quite large and for today almost a half of the current district heating is powered by fossil fuels. Nuclear District Heating can replace all the heat produces by fossil fuels. For district heating networks in countries with a demand for heat varying greatly over a year combined heat and power reactors could be a good solution, while in the countries with more uniform demand, dedicated heating reactors can be used with large load factor, and therefore, good economics.

At the moment, the most important barriers to nuclear district heating are legislation, regulations and public opinion. These obstacles are not engineering, or economics related, but rather political. Even though these changes that are still to be made is not a matter of one day, this is exactly what is worth striving for climate change mitigation.

References

Danish Energy Agency. Monthly Energy Statistics [Internet publication], [Referred 08.12.2022]. Available: https://ens.dk/en/our-services/statistics-data-key-figures-and-energy-maps/annual-and-monthly-statistics

Finnish Energy 2021. District heating in Finland 2021. [Internet publication] Energiateollisuus [Referred 05.12.2022]. Available: https://energia.fi/files/7488/District_heating_in_Finland_2021.pdf

Habibollah Sadeghi, Amir Ijaz, Rao Martand Singh 2022. Current status of heat pumps in Norway and analysis of their performance and payback time. Available: https://www.sciencedirect.com/science/article/pii/S2213138822008773

IEA 2020, World Energy Investment 2020, [Internet publication] IEA, Paris [Referred 02.12.2022]. Available: https://www.iea.org/reports/world-energy-investment-2020

IEA 2022a. Heating [Internet publication], IEA, Paris, [Referred 02.10.2022]. Available: https://www.iea.org/reports/heating

IEA 2022b. District Heating [Internet publication], IEA, Paris, [Referred 30.09.2022] Available: https://www.iea.org/reports/district-heating

IAEA 2000. Introduction of nuclear desalination. International atomic energy agency, Vienna. Available: https://www-pub.iaea.org/mtcd/publications/pdf/trs400_scr.pdf

IAEA 2017. Opportunities for cogeneration with nuclear energy, Vienna, IAEA nuclear energy series. Available: https://www-pub.iaea.org/MTCD/Publications/PDF/P1749_web.pdf

Ingard Shulga 2019. Atomic heating [Internet Publication]. [Referred 16.11.2022]. Available: https://atomicexpert.com/nuclear_heating

Leppänen, J. 2019. A Review of District Heating Reactor Technology. VTT Technical Research Centre of Finland. VTT Research Report No. VTT-R-06895-18. Available: https://cris.vtt.fi/en/publications/a-review-of-district-heating-reactor-technology

NuScale 2021. NuScale SMR Technology. [Internet publication] NuScale Power, LLC [Referred 27.11.2022]. Available: https://www.nuscalepower.com/-/media/nuscale/pdf/publications/nuscale-smr-technology-an-ideal-solution-for-coal-plant-replacement.pdf

Panasenkov A., Sychev V., Menzel K. 1984. Nuclear heating systems in the CMEA countries. Available: https://www.iaea.org/sites/default/files/26404792228_ru.pdf

Partanen 2019. Nuclear District Heating in Finland. [Internet publication], Helsinki, [Referred 05.11.2022]. Available: https://energia.fi/files/3740/Nuclear_district_heating_in_Finland_1-2_web.pdf

Peter Margen 1978. The use of nuclear energy for district heating. Progress in Nuclear Energy. Volume 2, Issue 1, pp. 1-28. Available: https://www.sciencedirect.com/science/article/abs/pii/0149197078900100

Power 2013. NuScale Puts Single-Minded Focus on Small Modular Reactor. [Internet publication] [Referred 27.11.2022]. Available: https://www.powermag.com/nuscale-puts-single-minded-focus-on-small-modular-reactor/?pagenum=2

Rafal Macuk. Heating in Poland 2019 edition. [Internet publication] Forum Energii 2019 [Referred 07.12.2022]. Available: https://forum-energii.eu/en/analizy/cieplownictwo-2019

Roman Polin 2020. Technical feasibility assessment of RUTA-70 nuclear pool-type reactor as a heat-only energy source for district heating systems in Finland. [Internet Publication] Lappeenranta [Referred 30.11.2022]. Available: https://lutpub.lut.fi/bitstream/handle/10024/161321/0225787_Roman_Polin_LUT_Masters_Thesis_2020.pdf?sequence=1

Rosatom 2016. RUTA. [Internet Publication] Rosenergoatom, [Referred 12.11.2022] https://www.ippe.ru/nuclear-power/small-power-npp/124-ruta-reactor

Rosatom 2019. Communications Department of Rosenergoatom Concern JSC [Internet publication], [Referred 11.12.2022]. Available: https://web.archive.org/web/20191227101553/https:/www.rosatom.ru/journalist/news/bilibinskaya-aes-poluchila-litsenziyu-rostekhnadzora-na-prodlenie-sroka-ekspluatatsii-energobloka-2/

Rosatom 2022. Communications Department of Rosenergoatom Concern JSC. [Internet publication], [Referred 16.11.2022]. Available: https://www.atomic-energy.ru/news/2022/09/09/128078

Sarkisov A.A 2011. Nuclear power plants of low power: a new direction in the development of energy, Moscow. Available: http://en.ibrae.ac.ru/docs/109/doklads_sq_wiht_cover.pdf

Statistics Norway 2022. District heating and district cooling. [Internet publication] SN [Referred 07.12.2022]. Available: https://www.ssb.no/en/energi-og-industri/energi/statistikk/fjernvarme-og-fjernkjoling

Swedish Energy Agency 2022. Energy in Sweden. [Internet publication] SEA [Referred 07.12.2022]. Available: https://www.energimyndigheten.se/en/facts-and-figures/statistics/

Westinghouse 2014. Westinghouse SMR & Nuclear Fuel Overview. [Internet publication], Rio de Janeiro, [Referred 17.11.2022]. Available: https://inis.iaea.org/collection/NCLCollectionStore/_Public/46/123/46123056.pdf