Nuclear District Heating in Finland

The Demand, Supply and Emissions Reduction Potential of Heating Finland with Small Nuclear Reactors

THINK ATOM

think deep decarbonization

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Executive Summary and key findings

Finnish district heating system and reactors suited for it

Finland has almost two hundred district heating (DH) networks of varying sizes, and they use over 35 TWhs of energy per year in total. **Almost half of this energy is currently provided with fossil fuels or peat**, while the rest is produced mainly through different bioenergy (~35 %) and waste-heat streams (~10%).

The total emissions from Finnish District Heating is around 5 Mtons / year, when counting bioenergy as zero in energy production (they are counted in Land Use, Land Use Change and Forestry sector).

The nine largest DH networks account for around 60 % (~21 TWh) of the total DH energy demand, and most of the fossil fuels use. These are good candidates for either SMRs (150 – 900 MW thermal) or micro-reactors (20 – 50 MW thermal) or combination of both.

The next thirty largest DH networks use over 25 % (~10 TWh) of the total DH energy demand. These could host one or two micro-reactors of 20 to 50 MWt capacity. The remaining 100+ very small DH networks use around 6 TWhs of energy in total and are too small to make sense even for micro-reactors.

Small nuclear reactors (SMRs – Small Modular Reactors) could help decarbonize local district heating networks in an affordable and efficient way. There are two main ways: by using simple and more affordable reactors that produce only heat for district heating, or by using reactors capable of combined heat and power (CHP).

Optimal maximum nuclear potential in district heating

In a Finnish district heating network, where monthly winter demand is five times higher than summer demand, we can produce roughly 60 percent of annual heat demand with (appropriately sized) heat-only nuclear reactor and still have a close to optimal capacity factor of ~85 percent or higher. We call this the **60/85 rule**.

Study looked at small reactors with thermal capacity between 24 and 900 MWt, and designs that could be used for heat only or combined heat and power production. **Around half of Finland's total DH energy demand could be met with small or tiny, heat-only nuclear reactors** that would operate at high load factors and provide affordable low-carbon energy. Ideally, as most of the fossil fuels are used in the larger district heating networks, this could mean that **SMRs could replace practically all fossil fuels burning, and hence cut total district heating emissions to zero**.

The levelized cost of heat (LCOH) of these reactors would likely be between 15 and 30 € / MWh. The operative costs (O&M + fuel) for nuclear heat are very affordable at 5 – 10 €/MWh. In total, this would save tens of millions of euros per year as saved emissions credits in the emissions trading system (ETS) and as lower cost of heating compared to most other low-carbon options.

This portion increases to around two thirds if we allow the heat reactors to run at slightly sub-optimal load factors (70 – 80 %). Running a reactor at 75 % load factor instead of 95 % load factor increases the levelized cost of heat by roughly 5 € / MWh. This would allow some of the biomass to go to more valuable uses in other sectors, such as chemical feedstocks of advanced biofuels for transportation.

With small reactors capable of combined heat and power, the larger cities could meet most of their district heating demand with nuclear reactors running at near-optimal load factor, producing both the heat and at least some of the electricity that the city uses.

Any long term (monthly or even seasonal scale) affordable heat storage solutions will increase the maximum amount of nuclear that can be optimally used. Integrating variable production from renewable energy sources will be much easier and cheaper if there is a source of low-carbon baseload production available.

A hypothetical, low-temperature heat-only "FinReactor" of 24 MWt capacity is used to model some of the smaller networks in the study. This could be designed and manufactured in Finland, and there is a potential domestic market for dozens of such reactors. In addition to producing heat at around 100 °C, it could also be used for district cooling or desalination of water, making it a potential export as well.

Tiivistelmä selvityksen avainlöydöistä

Suomalainen kaukolämpöjärjestelmä ja siihen soveltuvat reaktorit

Suomessa on lähes 200 erikokoista kaukolämpöjärjestelmää, jotka käyttävät yli 35 terawattituntia (TWh) energiaa vuosittain. **Lähes puolet tästä energiasta tuotetaan polttamalla fossiilisia polttoaineita tai turvetta**, ja loput tuotetaan pääosin (~35 %) bioenergialla ja hukkalämmöillä (~10%).

Kaukolämpöjärjestelmän kokonaispäästöt ovat noin 5 miljoonaa tonnia hiilidioksidia, kun bioenergia lasketaan nollapäästöiseksi (bioenergian päästöt kirjataan maankäyttösektorille).

Yhdeksän suurinta kaukolämpöverkkoa vastaavat noin 60 % (~21 TWh) kaukolämmön käytöstä, ja suurimmasta osasta fossiilisten polttoaineiden käyttöä. Nämä verkot sopivia ehdokkaita joko 150 – 900 MWt lämpöteholla toimiville pienreaktoreille (SMR) tai pienemmille 20 – 50 MWt mikroreaktoreille, tai näiden yhdistelmälle.

Kolmekymmentä seuraavaksi suurinta kaukolämpöjärjestelmää vastaavat yli neljänneksestä (~10 TWh) kaukolämmön kokonaiskulutusta. Näihin järjestelmiin soveltuisi yksi tai useampi 20 – 50 MWt mikroreaktori. Jäljelle jäävät reilu 100 pientä kaukolämpöverkkoa käyttävät yhteensä noin 6 TWh lämpöä, ja ovat pääsääntöisesti turhan pieniä jopa mikroreaktoreille.

Pienreaktoreilla (SMR't, sisältäen sekä pienet että mikroreaktorit) voisivat auttaa kaukolämpöjärjestelmän päästövähennyksissä kustannustehokkaasti. Tähän on pääsääntöisesti kaksi eri teknologista tietä: käyttäen yksinkertaisia ja edullisempia vain lämpöä tuottavia reaktoreita, tai käyttäen lämmön ja sähkön yhteistuotantoon (CHP) soveltuvia reaktoreita.

Optimaalinen maksimipotentiaali ydinkaukolämmölle

Suomalaisessa kaukolämpöjärjestelmässä kuukausittainen keskikulutus on viisinkertainen talvella kesään verrattuna. Noin 60 prosenttia vuotuisesta lämmöntarpeesta voidaan tuottaa pelkkää lämpöä tuottavilla sopivankokoisilla reaktoreilla siten, että ne ajavat lähes optimaalisella 85 % käyttökertoimella. Kutsumme tätä **60/85 säännöksi**.

Selvityksessä tarkastellaan 24 – 900 MWt kapasiteetin reaktoreita, sekä pelkkää lämpöä tuottavina että sähkön ja lämmön yhteistuotantoon kykenevinä. **Noin puolet Suomen kaukolämmön tarpeesta voitaisiin tuottaa pienillä, vain lämpöä tuottavilla reaktoreilla** siten, että niitä ajettaisiin verraten korkeilla käyttökertoimilla ja tuottaen verraten edullista vähähiilistä lämpöä. Koska suurin osa fossiilisista polttoaineista poltetaan isoimmissa kaukolämpöjärjestelmissä, tämä tarkoittaisi sitä, että **pienreaktoreilla voitaisiin korvata lähes kaikki fossiilisten polttaminen kaukolämmössä ja leikata siten kaukolämmöntuotannon päästöt nollaan**.

Lämmöntuotannon arvioitu kustannus (LCOH, Levelized Cost of Heat) pienreaktoreilla on karkeasti välillä 15 ja 30 euroa megawattitunnilta. Ydinvoiman käyttö- ja polttoainekustannukset ovat kokoluokkaa 5 – 10 € / MWh. Kaikkiaan, sekä muita vähähiilisiä pääsääntöisesti edullisemman kokonaiskustannuksen että päästökauppajärjestelmässä (ETS) säästettyjen päästöoikeusmaksujen myötä pienreaktorit säästäisivät kymmeniä miljoonia euroja vuosittain.

Pienreaktoreilla tuotetun lämmön osuus koko Suomen kaukolämmöstä voi nousta noin kahteen kolmannekseen, mikäli reaktoreita rakennetaan hieman enemmän, jolloin niiden käyttöaste putoaa optimaalisesta välille 70-80 %. Mikäli reaktoria ajetaan 75 % käyttöasteella 95 % käyttöasteen sijaan, on vaikutus lämmöntuotannon hintaan karkeasti 5 €/MWh. Tällöin osa biomassasta voitaisiin ohjata energiantuotannosta muille sektoreille, kuten kemianteollisuuden tai kehittyneiden biopolttoaineiden lähtöaineeksi.

Sähkön ja lämmön yhteistuotantoon kykenevillä reaktoreilla käytännössä kaikki isompien kaupunkien kaukolämmöstä

voitaisiin tuottaa pienreaktoreilla, jotka toimisivat lähellä optimaalista käyttöastetta. Tällöin ne tuottaisivat sekä kaupungin käyttämän lämmön että ainakin osan sen käyttämästä sähköstä.

Mikäli onnistumme kehittämään edullisia pitkäaikaisia (kuukausien tai vuodenaikojen mittakaava) energian varastointiteknologioita, myös pienydinvoiman käyttöedellytykset paranevat entisestään. Uusiutuvien ja vaihtelevatuottoisten energialähteiden integroiminen osaksi luotettavaa järjestelmää on huomattavasti helpompaa ja edullisempaa mikäli taustalla on pohjakuormaa tuottava luotettava energianlähde kuten ydinvoima.

Käytämme selvityksessä hypoteettista 24 MWt "FinReaktoria" mallintamaan pienempien kaupunkien kaukolämpöverkkoja. Tämäntyyppinen reaktori voitaisiin suunnitella ja valmistaa lähes kokonaisuudessaan Suomessa, jossa sille löytyisi useiden kymmenien reaktorien markkinapotentiaali. Noin 100 °C lämmön lisäksi sitä voidaan käyttää myös kaukojäähdytyksen tuottamiseen sekä meriveden suolanpoistoon, joten sille voi löytyä myös merkittävät vientimarkkinat.

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Introduction

According to the recent report by Intergovernmental Panel on Climate Change (IPCC 2018[1]), in the coming decades, almost all burning of fossil fuels (without carbon capture and storage, CCS) needs to stop. How urgently that needs to happen depend on the level of risk and overall warming we are prepared to have. Even the less urgent scenarios mean a clear step change for humanity's emissions, which have been persistently growing. Instead of growing, they should be falling at 5 to 10 % per year and go clearly negative sometime on the second half of this century.

So yes, we need to stop burning fossil fuels, and we need to do it much more efficiently than we have so far. And while sustainably produced biomass will play a role in energy production, even they need to be replaced where-ever possible to save that biomass for other uses that are more valuable or harder to replace with low-carbon, sustainable, non-fossil-based feedstocks. Such uses include materials for building construction, feedstocks for the chemical and paper industries and synthetic biofuels for those transportation needs we fail to electrify. To get carbon negative, we will need to reforest at massive scale and find ways to store carbon in soils and buildings at massive scale.

District heating networks are somewhat unique energy systems. They are fully or partly isolated (no "national grid" to fall back on, apart from electrification) and therefore need reliable and affordable sources of energy that are locally available. Fossil fuels have been the dominant energy source, as they are relatively easy to store and reliable to use. Burning fuels, on the other hand, is not compatible with our climate goals, and therefore we must look elsewhere for suitable heat sources. Nuclear energy ticks most of the boxes: it is reliable, low-carbon, can produce heat locally at relatively low cost, emits no particulate pollution and has proven to be one of our safest energy sources ever[2].

1 https://www.ipcc.ch/sr15/

2 See for example: Markandya, A., & Wilkinson, P. (2007). Electricity generation and health. The Lancet, 370(9591), 979–990. doi:10.1016/S0140-6736(07)61253-7, page 981.

Most major reports see a growing role for nuclear in our energy systems. In a carbon negative future, our use of nuclear energy will need to grow 2 to 6 times from current levels by 2050 (IPCC 2018[3]). To achieve this, we need to normalize how we see nuclear energy as a society. Given that it has been much safer than practically anything else out there, having a lot more nuclear would be a big improvement on public health and safety. This is in sharp contrast with public perception, which often worries about nuclear safety.

This study was made to answer this question: Could we use nuclear energy to decarbonize district heating? The answer is yes, and the most sensible way is to use radically smaller nuclear reactors than what we are used to. Nuclear district heating is not a new idea, either. As an example, the worlds currently oldest operational nuclear reactor, Beznau 1 in Switzerland, has also produced district heating to nearby population.

These small nuclear reactors (SMRs, or Small Modular Reactors) are being developed around the world and offer many interesting features. They could perhaps be sited nearer to population centres (and therefore, district heating networks) without compromising safety[4]. Indeed, this might be more of a regulatory question than a public health question; does the law and regulations allow us to site the reactors near population?

There are around 200 district heating networks in Finland alone. Most of them are small or very small, consuming less than 100 gigawatt hours of heat per year, and having capacities of a dozen megawatts, give or take. In this study we first present an overview of the networks, select around 40 biggest ones (with demand ranging from over 150 GWh to 7,000 GWh per year) for deeper analysis, and seek to match them with suitable nuclear reactors that are commercially available or are coming commercially available in the 2020s or early 2030s.

We also include a domestic option, a very small reactor that could be used to produce hot water for district heating. No electricity generation, no high-pressure steam, but a very simple and small

3 https://www.ipcc.ch/sr15/chapter/summary-for-policy-makers/

4 http://www.world-nuclear-news.org/Articles/US-regulators-agree-smaller-SMR-emergency-zones

reactor operating, in our example, at 24 megawatts thermal. Such a reactor could well be designed and (mass)manufactured in Finland by local companies and institutions. They could be fitted for the smaller DH networks as the main source of heat, or several of them could be used in larger networks to provide more distributed and flexible supply of heat.

After presenting the networks and potential reactors, we do some modelling to see what kind of reactors would fit in what size networks and how they would work; how much energy they could produce and how economical they would be to run (average load factor). In the examples, we only look at the potential of nuclear reactors in a broad sense, so in any given location, the local circumstances and existing infrastructure will be unique. We also include two cases from Poland, given that their district heating is mainly done by burning coal.

Next, we discuss the emissions reduction potential. Finnish DH networks use a wide variety of fuels from fossil to bioenergy and waste-heat. As bioenergy emissions are accounted for in the Land-use, land-use change and forestry -sector (LULUCF), they are counted as being zero-carbon in the energy sector, so we discuss how much of the available fuels might be saved for some other higher-value use if some or most of the baseload of the larger DH networks would be produced with nuclear.

Towards the end, we shortly discuss the possible business models and challenges for setting up multiple SMRs for district heating. Being a nuclear operator carries a heavy regulatory burden, so it would likely make sense to have one or several larger cooperatives or operators to handle the regulatory and operational work. We also present some cost estimates of producing district heating with nuclear.

Finally, we discuss the regulation, licencing, public acceptance and political themes around the subject. Can we have small reactors "in our backyards" and what it would mean?

Each chapter has a brief summary of the discussion and findings at the beginning.

It should be noted that this study is meant as a conversation starter. To give people and decision makers an overview of the possibilities of SMRs and the scale of the market in Finland and potentially elsewhere. It is in no way a scenario or a roadmap, but hopefully an inspiring outcome to push the SMR and district heating debate further in Finland and aboard.

I would like to thank Finnish Energy's Ympäristöpooli for funding this study. Thanks go also to the steering group for their valuable input, as well as all those experts, friends and colleagues who read and commented the drafts at various stages. All opinions, suggestions and, of course, mistakes, are the authors alone.

The District Heating Networks

In this chapter…

- We analyse the amount and demand structure of Finnish (with a glance to Europe as well) district heating systems, with the following key findings:
- There are several heat-only reactor designs coming up
- The total energy demand of DH in Finland is roughly 35 TWh per year and is divided to around 200 DH networks.
- Around half of their energy demand is met with fossil fuels and peat, while the other half is done with mainly bioenergy and waste heat streams.
- There is roughly 40 DH networks that could fit one or several tiny (20-50 MWt) or small (150 – 900 MWt) nuclear reactors.
- These networks use over 80 % of the total energy used in Finland's district heating, and account for most of the fossil fuels used for DH.
- In Europe, around 4,000 TWh is used annually for heating and hot water, but only around 10-15 % of households are on district heating.

Finland has almost 200 district heating networks, with a total demand of roughly 35 terawatt hours of heat annually[5]. Over 60 % of Finnish people live in houses that have district heating, and about 50 % of residential heating energy is provided by district heating. Two thirds of new houses join a local district heating system. The networks are mainly concentrated in towns and cities, and on areas with apartment buildings rather than single homes.

We will split the DH networks into four categories according to their annual demand, as seen on the table and graph below[6].

5 Note that these are pulled from a statistic by Finnish Energy as is, and the local situation might be more complicated. For example, some towns might have multiple smaller networks that are not connected, yet they are a single demand-figure in the data. On the other hand, some neighbouring networks might be connected to each other, leading to a "single" network that is larger than the single networks shown in the statistic.

6 In this study, we use municipality as the basic unit.

Size	Energy use GWh/a	Amount in Finland	Total energy use, TWh / year
Tiny	< 150 GWh	139	6
Small	150 – 1,000	31	10
Medium	1,000 – 2,000	5	7
Large	2,000+	4	14
TOTAL		179	~37

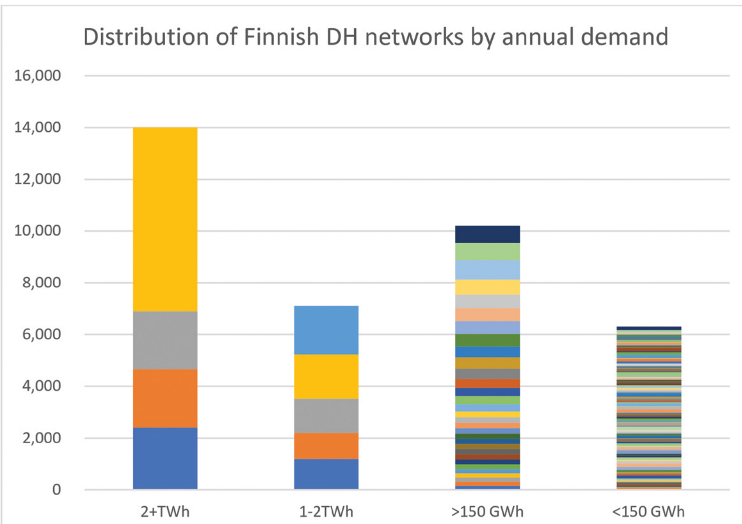


Figure 1 Finnish DH networks distributed into four categories by their annual heat demand.

The graph below shows the monthly demand profile of heat demand used in the study[7]. While any single network will deviate slightly from the next, the profile used here is the average monthly demand from nine random DH networks around Finland from the years 2015 and 2017, also averaged[8].

As we can see, the monthly average demand for heating varies five-fold between summer and winter. The momentary demand can vary as much as ten-fold.

7 Heat demand equals end use + losses throughout the study.

8 Data is from Finnish Energy.

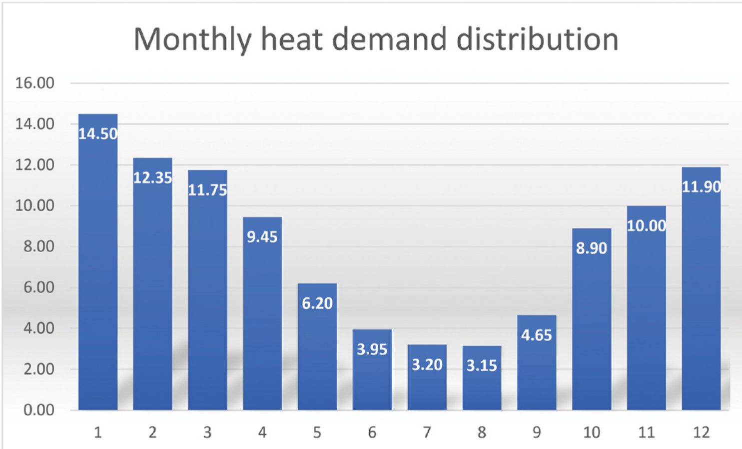


Figure 2 Monthly heat demand as percentage of total annual demand

District Heating energy sources

District heating is currently mainly done with burning fuels, both fossil and bio-based. There is also a limited, if growing, amount of large heat pumps and waste heat streams that are being used.

The share of bioenergy has been growing, especially in the smaller towns of the Finnish countryside, where biomass is more readily available from a local source. The share of natural gas has shrunken from over 20 percent a decade ago to just 10 percent today. With coal being banned in energy production by 2029 in Finland[9], it will likely push the share of bioenergy and natural gas up, as well as other sources. Coal is mainly used in bigger coastal cities.

To summarize, there is plenty of room for emissions free baseload energy sources in the Finnish district heating sector, be it in replacing fossil fuels and peat (almost half of current energy) or in allowing other, possibly more valuable uses to be found for biomass, especially in larger cities where enough biomass might not be locally available. Other options besides nuclear include various sources of waste-heat, heat pumps and deep geothermal heat, as well as turning electricity directly into heat.

9 In February 2019, the Parliament voted 170-14 to pass the law for banning coal in energy use by 1st May 2029.

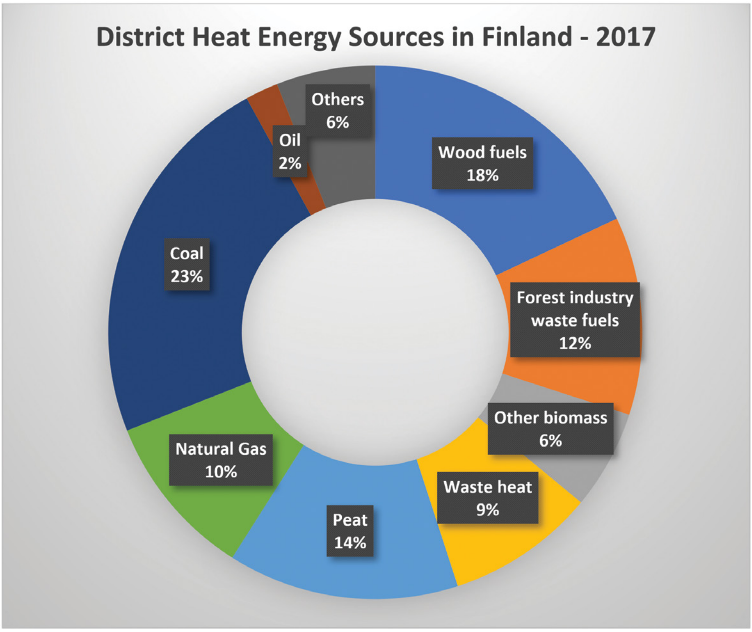


Figure 3 Fuels and energy sources used in DH networks in Finland. Data: Finnish Energy

European perspective

In Europe (EU28), heat accounts for roughly half of our final energy demand, and almost two thirds of that is space heating and hot water. This sums up to roughly 4,000 terawatt hours for space heating, hot water and other, non-industrial heat demand. District heating is less common in mainland Europe, with a share of around 10 – 15 % of homes.

There are some targets to increase this amount all the way to 50 % by 2050 to cut the emissions from heating[10]. In Europe, natural gas -based residential heating is common, as it is also used for cooking. Somewhat surprisingly, the warmer climate in central Europe does not directly translate to less heating per square meter of living space, as the insulation of buildings is much worse than it is in Finland and other Nordic countries. There are other factors playing a part as well. Households in countries like Croatia

10 https://heatroadmap.eu/sp_faq/how-well-become-100-sustainable/

and Luxemburg consume more heating per m^2 than Sweden and Finland[11].

If European homes are to stay warm without emissions, many of them will either need to move on to district heating or to electric heating with resistors or heat pumps – and decarbonize that electricity.

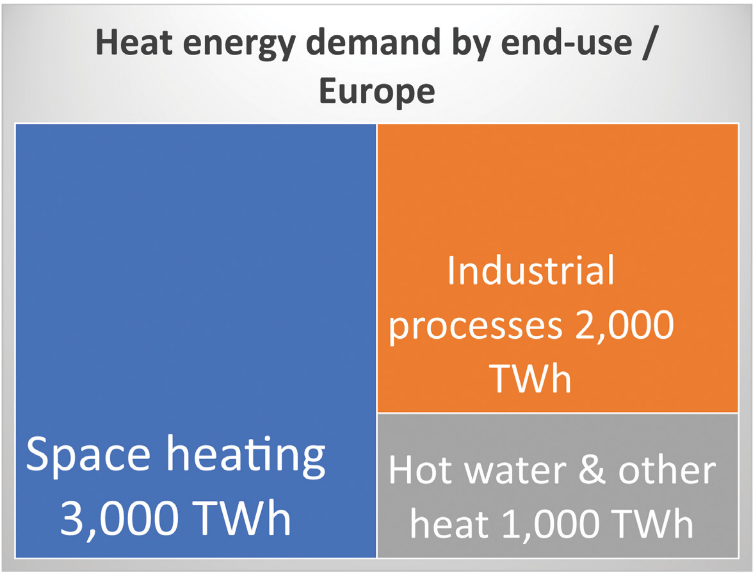


Figure 4 Heat demand in Europe

Some European countries have larger shares of district heating. These include the Nordic countries, as well as some Baltic and East-European nations. In this study, we also look at a case from Poland. The country has large share of district heating which relies mainly on coal and consumes more heating per m^2 than Finland. Poland also has a somewhat progressive policy when it comes to adding new nuclear to the country's energy mix, both for power and for industrial processes. All these factors make Poland one of the more interesting countries in Europe to look at from a nuclear district heating point of view.

11 See: http://www.odyssee-mure.eu/publications/efficiency-by-sector/households/heating-consumption-per-m2.html

Small Nuclear Reactors

In this chapter…

- We discuss the different small nuclear reactors being developed around the world, with the following key findings:
- There are several 200 to 400 MWt heat-only reactor designs becoming available likely in the 2020s that would offer potentially very affordable district heat. Also, the SECURE-reactor offered to Helsinki in the 1970s and 80s could be modernized to meet today's regulations and safety requirements.
- A tiny (24 MWt) heat-only reactor could be designed and built in Finland to meet the demand in the dozens of smaller networks and as part of larger networks.
- There are several SMRs that could do combined heat and power as well, either already available or becoming available in the 2020s timeframe.
- There are also several advanced (4th generation) reactor designs that are becoming available in the 2020s, which offer interesting features for combined heat and power production, such as higher temperatures and efficiencies and new, potentially simpler and more cost-effective ways of ensuring safety and flexibility in siting the reactors.

Small nuclear reactors are often referred to as SMRs. The letters stand for "Small Modular Reactor" or sometimes "Small or Medium Reactor." While current large reactors have power output between 1,000 and 1,700 MW, the SMRs usually have power output between 50 and 300 MW, although "Medium" sized reactors can be larger than that.

While being smaller in size and losing on the economics of scale compared to large reactors, the small size and lower capacity gives opportunity for other useful features, such as:

- Due to the lower capacity, many designs are designed to be passively safe[12] for extended periods of time, even indefinitely. This leads to less need for multiple active and redundant safety systems and/or the possibility of safely siting them near population centres.

12 Lower capacity makes it easier to rely on cooling based on laws of physics rather than electricity to power pumps for cooling water in case of emergency shutdown, for example.

- They can be sited underground or placed on barges or off-shore platforms for easy transportability and more siting options.
- They can be built in factories or shipyards instead of being constructed on-site, leading to potentially much higher worker-productivity and through that, lower costs.
- Initial investments are smaller and projects easier to manage, leading to shorter project-times and earlier revenues for investors.
- Due to smaller size, more units can be built on one site if needed.
- Some designs allow for the removal of the reactor module, to be taken away for refuelling or decommissioning elsewhere.
- Small capacity makes them suitable for more localized use-cases especially for heat, such as district heating, desalination, industrial process heat for industrial parks or power for isolated grids.
- Some designs are designed to have design-reusability, meaning that the same basic design can be built at locations with different environment and seismic activity.

The capacity of the nuclear reactors included in this study varies significantly. They are all “small” as far as nuclear reactors go, while some might even be categorized as tiny (micro-reactor). Many of the reactors are water-cooled, meaning that they operate in similar fashion to the mainstream nuclear reactors currently in use. Light water reactors are also the closest to being commercially deployable, both for technological and regulatory reasons.

There are dozens of SMRs being developed around the world, at least “on paper”. It is quite likely that many of them will never be commercially available. And overall, this is a good thing, as a few standard models that can be built over and over is a much more efficient way to build nuclear than hundreds of slightly different models being customized for each customer’s needs.

Right now, it is impossible to say with certainty which reactors will become widely available and used, and which will not. Therefore, the reactors presented (and not presented) here are chosen from a current, subjective point of view. There were a few criteria that affected the choices:

- We wanted a set of reactors with different sizes.
- We wanted reactors that are specifically for district heating, as well as reactors capable of combined heat and power.
- Light water technology is prominent due to it being familiar for the whole industry, from regulators to operators to the public, with some advanced reactor designs also briefly introduced.
- The reactor should be commercially available around 2030 at the latest.

Each design parameter, be it low or high temperature, water, molten salt or helium cooled, high pressure or low pressure or something else, brings both pros and cons to any application and usage scenario. It is therefore essential to define what one needs and what are the parameters and local conditions before one sets out to choose what kind of reactors to look more closely – or if it is nuclear reactor one needs in the first place.

We start by presenting the heat-only reactors, then the power reactors based on light-water technology, finishing with some non-water advanced reactors.

Heat Only -reactors

Reactors that are specifically made for producing low-temperatures for district heating, without the need for power generation and higher pressures, can be simpler in design and lower in cost while offering good safety features. There is no need for pressure vessels, or they can be relatively low-pressure (similar to a household espresso-machine), which reduces costs and makes safety potentially a much easier task to handle. Further, there is no need for turbine-island as there is no electricity production.

While in the last couple years there has been renewed interest in district heating reactors especially from China (with three domestic designs at various phases), they are not a new idea. SECURE, as presented below, was a DH reactor that was designed already in the 1970s in Sweden.

SECURE (Sweden)

"Having terrorists infiltrate the operations crew was one of the design basis for the reactor"

SECURE[13] is a 200 or 400 MWt reactor for district heating. It was originally designed in the 1970s by the Swedish company ASEA-ATOM, which tried to sell it for Helsinki district heating in the late 1970s and early 1980s. While it did very well in the economic comparisons (even without climate and emissions being a concern), it was not bought on political grounds. Since then, the project got cancelled as anti-nuclear sentiment rose. ASEA-ATOM has since been bought by Westinghouse.

In 2012, there was a review[14] on how "usable" the SECURE would be in the current situation and regulatory requirements. To summarize, while substantial modifications would be needed to modernize the design, for example on "Defence in Depth", they would not be enormous. It would be less work than designing a similar size reactor from scratch.

In 2018, there was a series of articles by YLE (Finnish public broadcasting Company) that also touched on SECURE[15].

DHR-400 (CNNC / China)

DHR-400 is a 400 MWt pool-type reactor that produces hot water around 90 °C (input water is 60 °C). Specifically designed for district heating production, the first reactor planned to be finished as early as 2021 or 2022 in China.

The estimated construction cost in China is around 200 million euros, which would mean a cost of just 500 euros per kWt. This would imply a very affordable cost per MWh of heat produced.

One downside is the somewhat low output temperature, especially when considering many Finnish DH networks that are designed to use temperatures up to 120 C in the winter time, when heating demand is greater. This means that the reactor output needs

13 Secure and Environmentally Clean Urban Reactor.

14 ATS Ydintekniikka -magazine, two-part article in issues 2 and 3 in 2012. In Finnish.

15 See here: https://yle.fi/uutiset/3-10065802 (in Finnish).

to be topped up or mixed with higher temperature heat sources in the cold winter months.

Many new DH networks are planned to operate at lower temperature to better utilise heat-pumps and many waste-heat sources. This also makes them better suited to use energy from these kinds of low temperature reactors.

NHR200-II (CGN / China)

NHR-200-II (Nuclear Heating Reactor[16]) is based on the NHR-5 which was commissioned already in 1989. NHR-200-II started as a heat-only reactor in the 1990s, but the temperature has been constantly increasing to provide more flexible uses. China General Nuclear Power Corporation (CGN) doing a feasibility study on the reactor. In 2018, CGN was approved by the National Energy Administration (NEA) to push forward the construction of China's first nuclear-powered heating project, and are now working on site selection and related tasks[17].

HAPPY200 (SPICRI / China)

The third Chinese national nuclear company also has their own district heating reactor in the plans. Happy is a 200MWt[18] reactor that produces 115 °C temperature for district heating with heat network pressure of 0.6MPa. A feasibility study is in progress, with construction of a HAPPY200 demonstration plant planned to be finished around 2022.

Microreactor – FinReactor

There are many "micro-reactors" being developed around the world, such as Westinghouse's eVinci[19], General Atomics, X-energy, NuScale and Oklo[20]. The main use for these is to offer power or CHP in remote communities, mining sites or islands that are not connected

16 http://tinyurl.com/yd5l6oza

17 http://tinyurl.com/ycgxpthu

18 http://tinyurl.com/ycmgufw2 (pdf)

19 http://www.westinghousenuclear.com/New-Plants/eVinci-Micro-Reactor

20 See Roadmap for Micro-Reactors (2018) here: http://tinyurl.com/y34ph8sc (pdf)

to national grids. These sites often rely on diesel generators with diesel being flown in, which makes the business case of offering micro-reactors with electricity production capability a more compelling one, even if they are rather expensive investments per kW. They are also often designed to have long operational lifetime without the need for refuelling.

In this study, we introduce a micro-reactor just for district heating. This, currently speculative, reactor is called “FinReactor”. The basic idea behind it is that it could be designed and manufactured in Finland. This could be an interesting argument in the national discussion as well as the acceptability of nuclear in society. With a higher number of direct stakeholders, companies, communities, jobs for people in addition to the possibility of providing clean affordable baseload heating, the case for public acceptance of nuclear could improve markedly. There might also be a large export market for these kinds of reactors, as they could also be used for district cooling and water desalination.

The “FinReactor” is presented as a potential way to decarbonize smaller networks of several hundred gigawatt-hours of annual consumption, or as baseload-capacity in multiple units in larger networks. These networks have heating demand of 20 to 50 MWt outside the warm summer months. We chose 24 MWt as the base capacity, although this number is somewhat arbitrary.

Given that they are such low capacity, it should be possible to design them to be very safe without relying on complex, active safety systems, but instead having passive safety features based on laws of physics. Simplicity can bring costs down, and if the reactor can be manufactured in series in a factory or a shipyard, costs can be lowered further, and quality control made more efficient.

There are a lot of challenges to realising this kind of project. Along with initial market and feasibility studies and finding potential stakeholders and customers, designing a reactor from scratch is a big undertaking requiring millions in investment and years of work, although there might be similar designs out there that could be used as a starting point. The technology nor the physics are not new, so it is a question of doing a safe and all-around cost-effective design.

This combination of passive safety and very low capacity could make siting the reactors near population more flexible. All of this, of course, depend on the design and regulation/regulator.

MWt	Name	When?	Status/notes
24	FinReactor	Unknown	Hypotethical - needs to be designed first. Prototype could be built in 2020s.
200	NHR200-II	2020s	Feasibility study and siting ongoing. Based on NHR-5 which was built in 1989.
200	HAPPY200	2022	Feasibility study underway in 2018.
200 or 400	SECURE	1980s / 2020s	Was available in 1980s, could be modified for todays use quite quickly.
400	DHR400	2022 ->	FOAK ready around 2022.

The table above presents the potential commercial availability of each reactor design. There is always uncertainty and even secrecy, and publicly available information is not often up-to-date, so these need to be taken with a grain of salt.

Light water power reactors

NuScale (US)

NuScale is a US-based company developing an integral Pressurized Water Reactor (IPWR), partly owned by the global engineering and construction company Fluor. Of the western SMRs, it is one that is furthest along the way to commercialization. In 2017, the US regulator NRC accepted the company's design certification application (DCA). In April 2018, the NRC had completed the first phase of its design certification review, which is by far the hardest and time-consuming phases. The first demonstration NuScale Power Module is planned to be constructed by 2024, with a commercial 12-reactor (720 MWe) plant following soon after, around 2026.

A single NuScale Power Module is a 200 MWth / 60MWe (gross) pressured water reactor. A complete power plant can consist of 12 of these reactor modules, but one can have less as well. This makes it well suited for gradual addition of capacity. Each reactor can be controlled independently for a very flexible system, especially for combined heat and power applications.

NuScale is making the case for the US regulator NRC that the plant would not need an emergency zone larger than the plant premises, which would greatly help with siting near population centres. They are also making the case that it would not need any active cooling (and backup for that cooling), which would lower the construction costs significantly.

Design operational lifetime for the reactors is 60 years.

SMART (South Korea)

SMART (System-integrated Modular Advanced ReacTor) is a South-Korean design that has 330 MW thermal and 100 MW electrical capacity. It was the first SMR to get a standard design approval (SDA) from a national nuclear regulator, the Korean Nuclear Safety and Security Commission, in 2012.

In principle the design is similar to NuScale, but without the "twelve-pack"-approach, as it is an integrated pressurized water reactor. It has a three-year refuelling cycle and a 60-year design-life. Currently, there are plans being developed to build first two reactors in Saudi-Arabia.

RITM-200(M) / KLT-40S (Russia)

KLT-40S is one of the SMRs that have already been built. The barge Akademik Lomonsonov had two of these reactors aboard as it was towed through the Baltic sea in 2018, and it was headed for Murmansk for fuel loading, with commissioning in 2019. KLT-40S is derived from KLT-40, which has a proven record of powering icebreakers. It is a 150 MWt reactor capable of producing 38.5 MWe or co-generate 35 MWe and up to 35 MWt for district heating/desalination.

The RITM-200, also already built, is a bit larger (175 MWth and 50 MWe) redesign from KLT40S and will likely replace the KLT-40S in the future. Two of them will power the LK-60 icebreakers, with the first one aimed to be commissioned in 2019. The RITM-200M model is meant for floating barges (Optimised Floating Power Units, or OFPUs). They will be towed back to base every 10 years for servicing, so no onboard used fuel storage is needed. Operational lifetime is 40 years with possible extension to 60 years. There are also plans for onshore versions of the RITM-200, with conceptual design finished in 201, more detailed design to be completed around 2020 with first construction stating around 2022, according to Nuclear Energy Insider[21].

CAREM (Argentina)

CAREM-25 is a small integral PWR being built in Argentina, due to start operation in 2019, although it has had problems with funding. It's a 100 MWt, 27 MWe reactor suitable for power, CHP and desalination and is being built as a research reactor. It is a prototype of a larger 100 MWe reactor meant for the export market.

BWRX-300

The largest reactor presented is the BWRX-300 from GE Hitachi. It has electrical output of 300 MW, and thermal output of around 900 MW. It is based on the ESBWR, a reactor that already has a licence from the US regulator NRC. This makes it possible to accelerate its licencing process significantly, with commercial availability envisaged for 2030.

The BWRX-300 has a remarkably low cost-target, around $2250 / kW, which would make it very competitive even with cheapest renewables (disregarding their unreliable production and its additional costs) and coal and natural gas (disregarding their externalized costs from emissions and particulate pollution).

The table below presents the potential commercial availability of each reactor design. There is always uncertainty and even secrecy, and publicly available information is not often up-to-date, so these need to be taken with a grain of salt.

21 Small Modular Reactors A Global Perspective (January 2019), Nuclear Energy Insider.

MWt/MWe	Name	When	Status/notes
150/38.5	KLT-40S	Now	Barge-reactor, first two start operations in 2019.
175/50	RITM200	Now	Icebreaker-power reactors already installed. Onshore version under consideration.
200/60	Nuscale	Mid-2020s	NRC review phase 1 completed in 2018.
~330/100	CAREM	Unknown	27 MWe prototype to start operations around 2020.
330/100	SMART	2020s?	General design approved. Plans to build first two in Saudi-Arabia.
900/300	BWRX-300	By 2030	Evolution from ESBWR which is already licenced by NRC in the US.

Advanced nuclear reactors

Although light water SMRs are technologically closest to being market ready, there are also some interesting advanced reactor technologies that bear mentioning here.

HTR-PM

HTR-PM is a gas-cooled, high-temperature pebble-bed reactor being currently built in China. The first plant with twin reactors, each at 250 MWt running a single 200 MW turbine, will likely come online in 2019. In January 2018 the first pressure vessel head was installed, and later in October, the first steam generator passed pressure tests. It is one of the first advanced reactors to come online and enter commercial markets. The design and the TRISO-fuel that it uses makes it meltdown-proof and hence a very safe design that could be deployed near population or other industry.

SEALER

SEALER is a fast, high temperature lead-cooled reactor design from the Swedish start-up LeadCold. It uses Uranium Nitride (UN) as fuel. The uranium used for the fuel is 11.8% enriched, and the nitrogen is 99.5% enriched in 15N.

Their 140 MWt/58 MWe reactor is currently (winter 2019) in the second phase of the UK government competition for SMRs, after being one of eight concepts to get R&D funding in the first phase. According to the company, the reactor can produce up to 77 MWt of 120 °C district heat and 40 MW of electricity when running in CHP.

The approximate radius of the emergency planning zone is estimated to be 600 meters, according to the company[22].

IMSR400

Integral Molten Salt Reactor, or IMSR[23], is one of the more promising of the many molten salt reactors being developed. IMSR400, a 400 MWt (190 MWe) high temperature reactor is developed by the Canadian company Terrestrial Energy. In the IMSR, the fuel is in a liquid (molten) form, mixed in a fluoride salt that acts as the heat transfer medium, with graphite as the moderator. The design has some interesting features that can help it come commercially available sooner. One of these is the integration of primary components into a replaceable core. The core has seven-year operational lifetime, which lessens the demand for the materials inside it, making it more economical to manufacture. The power plant itself has (at least) two docks for the replaceable cores, so production can go on uninterrupted, as when one core is shut down and left to cool off, another can start operating beside it.

Terrestrial Energy plan to have a commercial reactor available in the 2020s. The target cost for electricity is $50 / MWh.

ARC-100

ARC-100[24], is a sodium cooled fast reactor from Advancer Reactor Concepts LLC in cooperation with GE Hitachi. It is based on the EBR-II (Experimental Breeder Reactor) that ran in the U.S. successfully for 30 years. The factory-made, 100 MWe / 260 MWt ARC-100 has some interesting attributes and properties that sets it

22 Most details were obtained through personal communication with the reactor designer.

23 https://www.terrestrialenergy.com/technology/

24 https://www.arcnuclear.com/arc-100-reactor

apart. For example, it will have 20-year refuelling cycle (meaning fixed fuel costs for that period), and it can also use spent fuel from other (light water) reactors as its fuel. According to ARC, the reactor uses uranium fuel enriched to less than 20 %, and also breeds new fuel in-situ as it operates.

It is said to be passively safe and self-regulating and operates at atmospheric pressures with core temperature of 510 °C. The target cost for electricity is $50 / MWh.

Availability

When will these reactors be available? That is a legitimate question. Some of them are available practically today, and many will become available during the next 5 to 15 years. There are around 50 SMR designs being researched and developed at various stages around the world, according to IAEA[25]. But as a society, we need to ask ourselves, are we ready to buy and build them? And if not, what and how long will it take for us to get ready? We need to start the public discussion, the legislative and regulatory discussion and preparation, the feasibility and siting studies and the signing of "Memorandums of Understanding" with reactor vendors years before we get to the point of actually starting to build an SMR. So if Finland wants to be a climate leader and ready for SMRs even by 2030, it is high time we started taking all these other necessary steps.

There is uncertainty on the availability of any given new technology due to many factors. Developing and licencing, let alone building a first-of-a-kind reactor costs hundreds of millions, even billions of euros or dollars. The reactor developer needs to secure that funding from somewhere, and the more there is public interest, political acceptance, potential customers, Memorandums-of-Understanding and general interest in their future product, the more readily financing will be available.

When discussing availability, we also need to define what do we mean by it. There is a finished design licenced somewhere? First-Of-A-Kind (FOAK) is built somewhere? FOAK has been running

25 IAEA 2018, http://tinyurl.com/y6xn52r2

and tested for a few years? Many reactors commercially built and operational for a number of years already?

In the end, this is a decision of should we Finns be among the forerunners of climate mitigation or wait for others to make a path for us to follow. In the public discussion and political speeches, it's clear that Finland wants to be among the forerunners in climate mitigation. As a rich and technologically able western country, we have the ability to be there, so maybe it is time to put our money where our mouth is, also when it comes to nuclear technologies. Finland is, overall, one of the best countries to do nuclear power in. This is something that many political parties and youth-organizations have already written in their party-platforms, promoting nuclear, SMRs and even 4th generation "advanced reactors" to mitigate climate change efficiently.

Modelling

In this chapter…

- We combine the suitable DH networks of 200+ GWh of annual demand with potential reactors of 24 MWt to 900 MWt capacity, with the following key findings:
- Heat-only reactors could produce around 60 % of a suitable sized DH network energy demand while running at near optimal load factor of ~85 %.
- There would be space for 5-8 200 MWt heat only reactors in the five largest Finnish cities with around 2,000 GWh or more of annual heat demand. Helsinki could also fit larger reactors, or several smaller ones.
- There would also be room for around 50 smaller 24 MWt reactors in the medium and smaller cities with annual demand between 200 and 2,000 GWh.
- Reactors capable of combined heat and power (CHP) would increase the potential maximum share of nuclear heat significantly, as would running heat-only reactors at lower, but still reasonable load factors of 70+ %. Heat-only reactors could also be used to make district cooling in the summer.
- A single Finn living in these cities uses, as a rough average, around 10 MWh of heat annually.
- Poland has significant market for district heating reactors as well as CHP reactors, with large cities that have substantial sized DH networks in them (mainly coal-fired).
- For more details, see also the summary at the end of this chapter.

The simple monthly demand/supply modelling done here is meant to give an overall view on the sizes of networks and reactors and how they could (or could not) fit together. The different combinations of reactors and DH networks is almost infinite, so we only look at some select cases, hoping to give the overall picture and find some rough rules of thumb.

In Finland, the monthly demand of heat varies dramatically around the year. The study uses average 2015 and 2017 monthly demand data from nine random Finnish DH networks[26]. This demand per month is expressed as %-value of total annual demand (Monthly share in table below). Total annual demand (MWh/year) is fed into the excel-model as desired. The total monthly demand derived from these is then divided by the number of hours in each month to get the average demand in megawatts (AVG MWt) for each month. This is then compared with the thermal capacity of a chosen reactor or combination of reactors, with maintenance breaks hand-coded in, taking place during the most convenient months (months with the least demand).

HEAT Days/M	Hours/M		Monthly share	MWh/year 200000	AVG MWt 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

Table: Calculating the monthly average MWt demand for each month.

A reactor should work at as high a load factor as possible for the energy to be as low-cost as possible. Generally, the more affordable district heating reactors should work at "full capacity" at least around 5,500 to 6000 hours per year, meaning a load factor of roughly 65 % to 70 %, minimum. Ideally, the load factor would be at or over 85 %, with ~93 % being the maximum after mandatory maintenance breaks.

26 Data is from Finnish Energy.

General assumptions made:

- When available, nuclear is always run at maximum capacity or until demand is met (no other energy sources are included, as those vary greatly on location, cost and availability and we are mainly interested in the feasible maximum share that nuclear reactors could provide on their own).
- Maintenance and refuelling take one calendar-month per reactor. Multiple reactors can have maintenance breaks simultaneously.
- In the graphs, the production from nuclear does not exceed demand even when there would be spare capacity. It is assumed that the nuclear reactor is run at lower capacity during those times, which shows in the load factor number.

The graphs and models are not meant to tell cities and their utilities how much nuclear energy and what kind of reactors they should use for district heating. That is their business-choice and depends on many other things as well. The point is to show what is the optimal or near-optimal maximum amount of nuclear that could fit in any given DH network, while maintaining reasonable load factors for the reactors, and what kind of reactors could be used to achieve that. These graphs are more of a thought experiment, not a direct policy recommendation.

Storage

In this study, we assume that daily and weekly demand fluctuations can be handled with storage and demand-side flexibility technologies already in the market or entering the market. The demand in cold winter days can be double the monthly average, so this is something that certainly needs to be handled but is out of the scope of this study. A stable source of baseload energy makes it much easier to hand demand variations, as then one does not need to worry about supply variations as well, which is the case with intermittent energy sources such as wind and solar.

The possibility of affordable long-term, even seasonal, heat storage would make any system run more smoothly, and would fit a nuclear-system perfectly. One of the few seasonal storage options is geological storage, even though large-scale water storage schemes, such as caves, can also play a part. With a geo-storage one heats the bedrock deep (perhaps several kilometres) underground with extra energy during the summer months when energy demand is lower and recovers the stored heat in the high-demand winter months. Ideally this should be a terawatt hour -scale storage, as the losses to the surrounding rock get smaller with added size of storage, compared to the amount of energy stored.

One can use any energy source to do this, but preferably it should be a low-carbon one. Electricity from solar PV panels or windmills are one option, especially if there is high supply during low demand and the market price for electricity goes very low. With a nuclear reactor, one can store the generated heat directly – whether one operates a heat-only reactor or a CHP capable reactor.

Heat only reactors

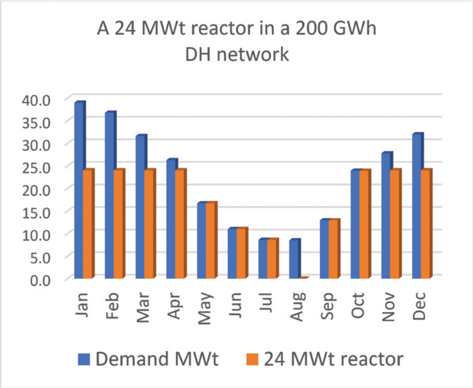
We start with a simple analysis of having different reactors producing only heat for DH networks of different sizes, starting from small ones and getting larger. After that we discuss some options for providing district cooling (with spare heat capacity in the summer) and combined heat and power for added flexibility. We also include a couple Polish cities as case-studies from mainland Europe.

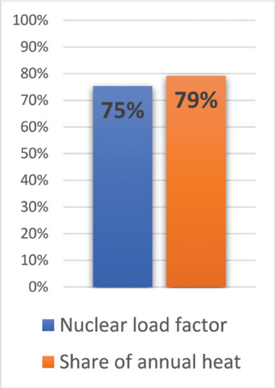
200 GWh DH networks

There are around 20 DH networks in Finland between roughly 150 and 350 GWh of annual energy demand, with a total demand of 4.3 TWh. These towns usually have between 15,000 and 35,000 inhabitants. We start with a very small 24 MWt reactor (the hypotethical "FinReactor" presented earlier) running in small DH networks. Running at around 85 % load factor (or 7,500 full load hours), a single 24 MWt reactor produces around 180 GWhs of energy annually.

Of these networks, around half are over 200 GWh and half are between 150 and 200 GWh annual demand. Especially the ones at or above 200 GWh demand could host this kind of energy source. This would make a market for ~10 reactors, which would produce around 1.8 TWh of clean heat annually (around 40 % of the total heat demand of these smallish networks). Running at slightly suboptimal load factors to include the <200 GWh networks, this market size would double to 20 reactors.

One 24 MWt reactor in a 200 GWh annual demand DH network



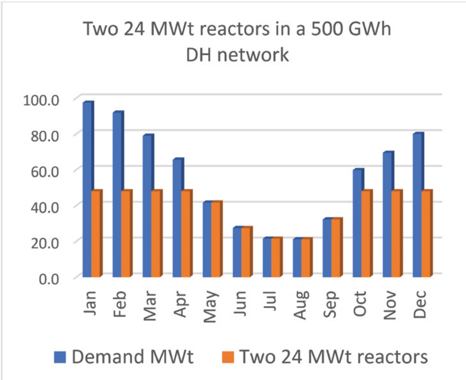


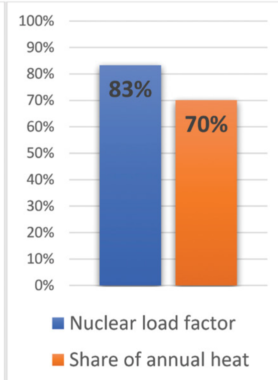
The reactor would operate at 75 % load factor in a 200 GWh network, which is a bit on the low side. On the other hand, it would produce almost 80 % of the total energy demand, and as a heat only reactor, the cost for energy could be tolerable even if the reactor would not run at optimal load factor. The colder months from November to April would require other heat sources as well, and July or August would be ideal months for annual maintenance (in the graph August was chosen). Small DH networks often have only one major source of heat with spare capacity to back it up, so a situation where a big share of the heat comes from a single source is not new.

500 GWh DH networks

There is around a dozen DH networks in Finland between 350 and 750 GWh of annual demand, with a total demand of around 6 TWh. These municipalities usually have between 45,000 and 75,000 inhabitants. Each could fit one (smaller ones) or two (500+ GWh networks) FinReactors, with a total market for 15 to 18 reactors, producing around 3 TWh (half of total demand) of clean heat annually.

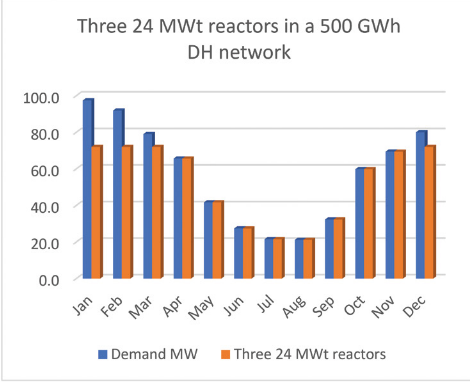
Two 24 MWt reactors in a 500 GWh annual demand DH network

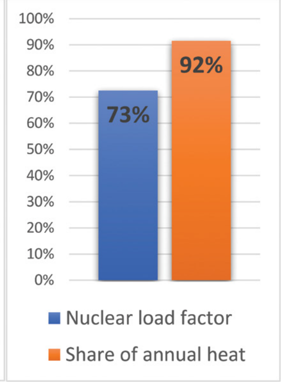




The two 24 MWt reactors would run at reasonable 83 % load factor, as their annual maintenance periods can be timed optimally for July and August, the months with the lowest demand. The reactors would produce around 70 percent of the total annual heat demand. Two reactors would also improve redundancy, as if one would shut down for some reason, the other could go on producing heat.

Three 24 MWt reactors in a 500 GWh annual demand DH network





Three 24 MWt reactors (total capacity of 72 MWt) represents a somewhat extreme case. They would increase the amount of de-

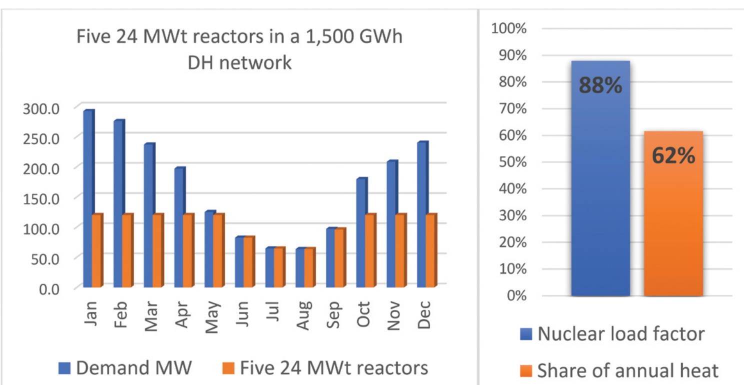
mand met by clean nuclear heat to 92 %, while having a load factor of 73 %. The reactors would have annual maintenance breaks from June to August.

1,500 GWh DH networks

Finland has five DH networks that have a demand between 1 and 2 terawatt hours per year. These are Kuopio (1.0 TWh), Jyväskylä (1.2 TWh), Lahti (1.3 TWh), Oulu (1.7 TWh) and Vantaa (1.9 TWh). These have populations roughly between 100,000 and 200,000. We will look at configurations of five and seven 24 MWt reactors and a single 200 MWt district heating reactor, such as SECURE, HAPPY, NHR200-II or a single NuScale Power Module. Two slightly smaller options are the Russian KLT-40S and RITM200.

Together, these DH networks use around 7.1 TWh of energy annually. It would take roughly 22 “FinReactors” of 24 MWt capacity to produce ~4 TWh, a bit over half, of the total energy demand (while they would operate at reasonably high load factor).

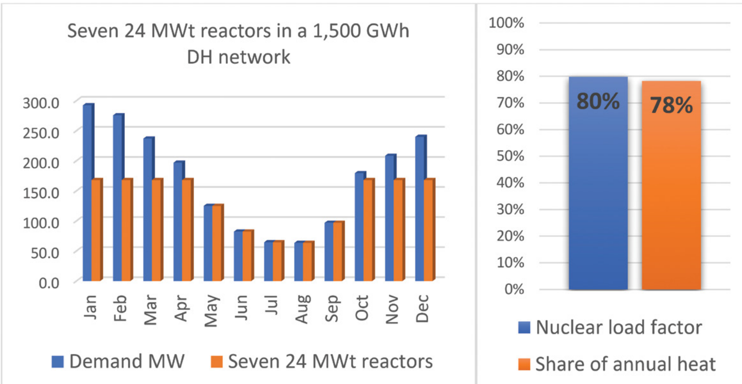
Five 24 MWt reactors in a 1,500 GWh annual demand DH network



Five 24 MWt reactors would operate at almost optimal 88 % load factor, while producing over 60 % of the energy demand. Five reactors would offer a good amount of redundancy as well, but they should probably be sited in more than one location. Maintenance

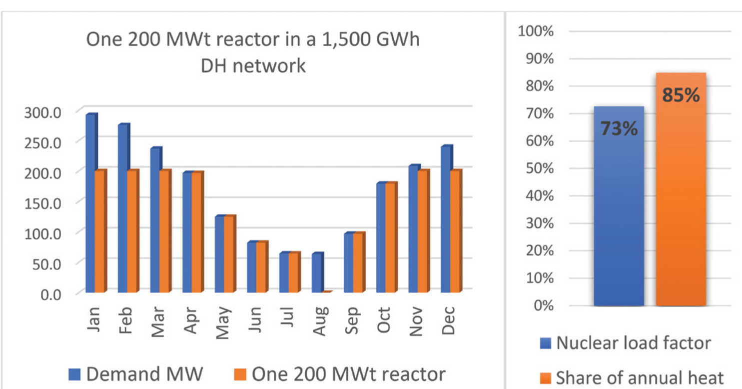
here is scheduled as follows: one reactor in June and July, two in August, one in September.

Seven 24 MWt reactors in a 1,500 GWh annual demand DH network



Adding two more 24 MWt FinReactors, the share of heat demand produced by nuclear increases to around 78 % while the capacity factor drops to a still reasonable 80 %. The annual maintenance for the reactors is scheduled as follows: two in July and August and one in May, June and September.

A 200 MWt reactor in a 1,500 GWh annual demand DH network



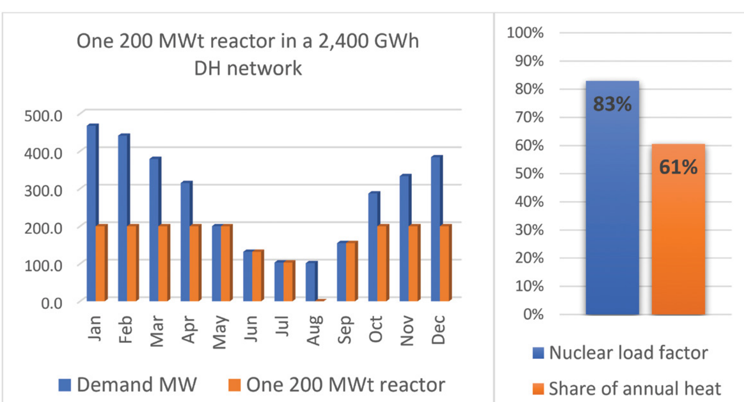
A single 200 MWt reactor would provide 85 % of the annual heat demand but would work at a somewhat low 73 % load factor, with scheduled maintenance in July or August. It would also be a rather big single source of energy, when considering security of supply. A single heat-only reactor would likely have lower O&M costs so that could mitigate the low load factor.

2,400 GWh DH networks

There are three DH networks in Finland that use around 2,4 TWh of heat annually: Turku and Tampere at around 2.3 TWh and Espoo at 2.4 TWh. Their population varies roughly between 180,000 and 280,000 inhabitants. We will look at several different configurations on how the energy demand of these networks could be met by low-carbon nuclear energy.

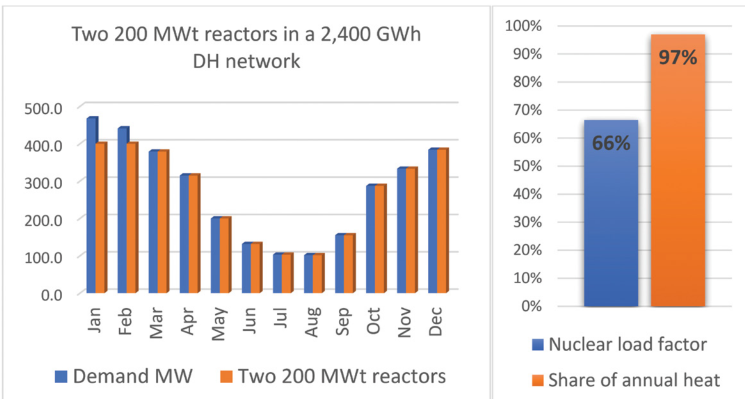
These networks are large enough to accommodate one or two 200 MWt reactors. Each could also have ten or so 24 MWt reactors which would still operate at decent 80+ % load factors, making for a potential market-size of roughly thirty FinReactors, or three to six larger 200 MWt reactors. Thirty FinReactors would produce ~70 percent (over 5 TWh) of the annual 7 TWh heat demand that these three cities have combined.

A 200 MWt reactor in a 2,400 GWh annual demand DH network



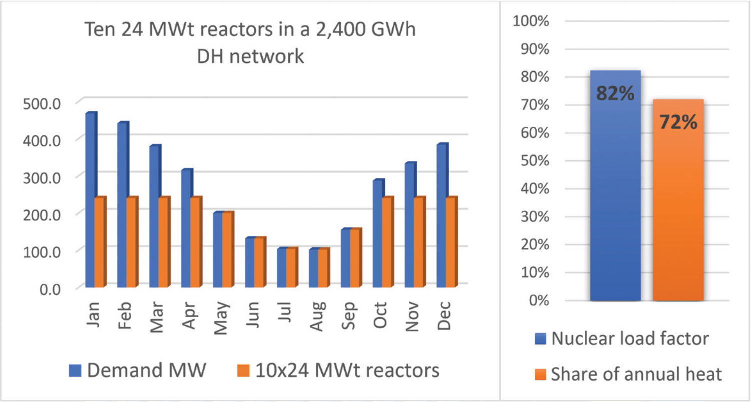
One 200 MWt reactor would operate at a load factor of around 83 % and provide 61 % of the energy demand. The monthly (average) peak demand in January and February would be a bit over double the reactor's capacity, at around 450 MW.

Two 200 MW reactors in a 2,400 GWh annual demand DH network



As a somewhat extreme example, having two 200 MWt heat-only reactors in a 2.4 TWh demand networks takes the nuclear load factor to a rather low 66 %, although it does produce almost all, 97 %, of the energy demand. Having two reactors means added redundancy, and some cost savings could be achieved by having either one of the reactors down for the five summer months from May to September (including the annual maintenance). Still, the economics might look questionable unless other use for the extra capacity – district cooling or CHP – would be found, and both of these would often mean additional investments as well, either to cooling infrastructure or to reactors capable of doing power as well as heat.

Ten 24 MWt reactors in a 2,400 GWh annual demand DH network



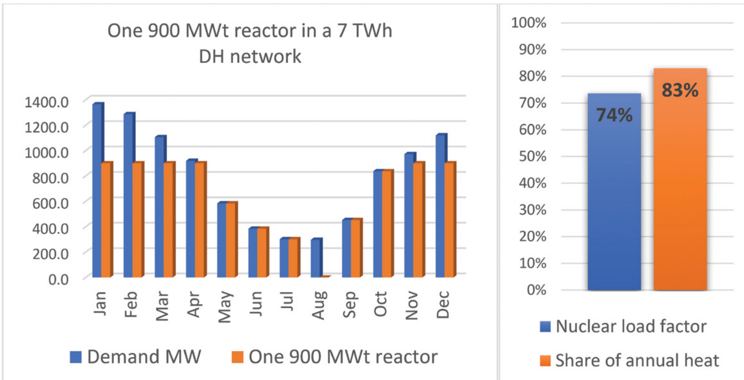
As another somewhat extreme example, here are ten 24 MWt reactors in a 2.4 TWh network. This setup allows to have both a decent load factor of 82 % and a high share of 72 % clean nuclear in the district heating mix. A similar setup could be achieved with one 200 MWt reactor coupled with two 24 MWt reactors, or five FinReactors that would be double the size of the 24 MWt reactor, at around 50 MWt. Some of the concerns are the relative cost of operating multiple reactors – can several of them be operated by a single crew, for example? They would also need to be placed in multiple locations, adding to the siting problem.

Later we inspect how this setup would offer capacity for district cooling as well.

A 7 TWh DH network

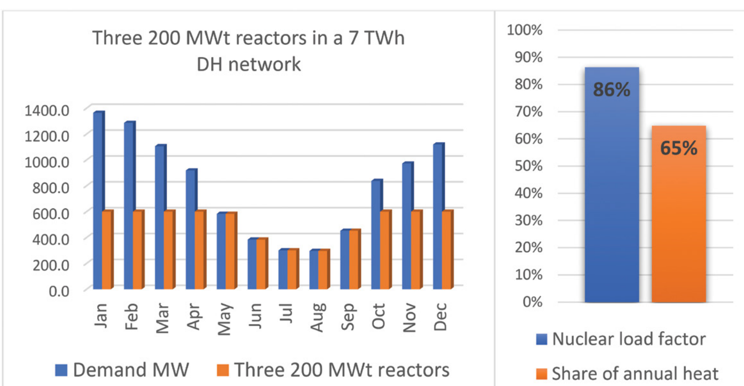
Helsinki has by far the biggest single district heating network in Finland at slightly over 7 TWh of annual demand and around 650,000 inhabitants. The average annual use of a single inhabitant is around 10 MWh of heat. If combined with the nearby Espoo and Vantaa networks (and some smaller towns nearby), the metropolitan area has a total demand of over 11 TWh. We start by inspecting what it looks like if we place one 900 MWt thermal reactor in the DH network to produce heat only (the BWRX-300 by GE Hitachi).

One 900 MWt reactor in 7 TWh annual demand DH network



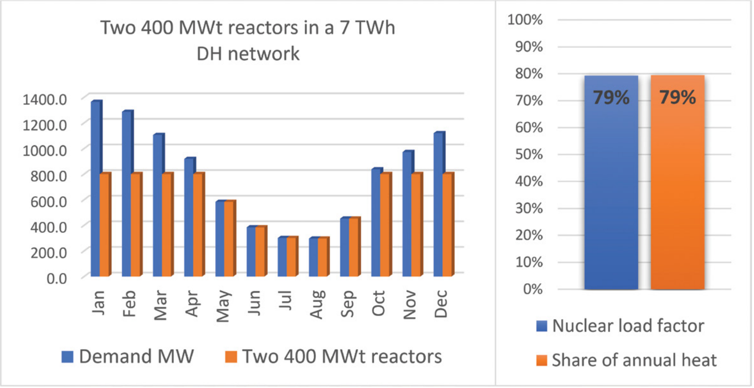
As we can see, the single 900 MWt reactor would run at a suboptimal 74 % load factor, but it would supply 83 % of the total heat demand. The BWRX-300, the only reactor of this size presented in this study, is suitable for electricity production as well (at 300 MWe), so it would make more sense to run it at combined heat and power. With CHP, there might be room for a second unit as well.

Three 200 MWt reactors in 7 TWh annual demand DH network



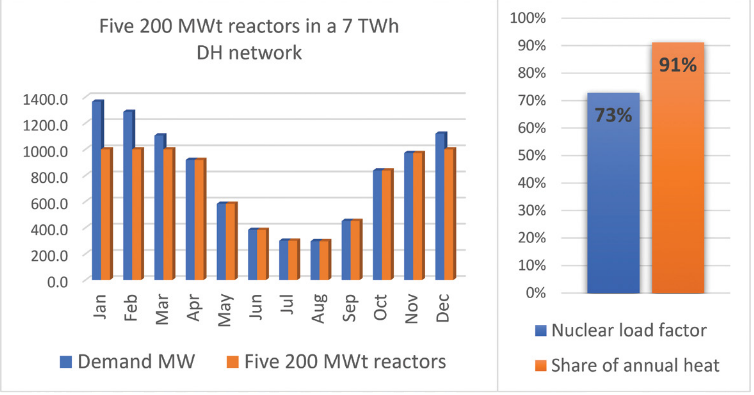
Three 200 MWt district heating reactors, such as SECURE, HAPPY or NHR200-II, would be able to operate at a rather optimal load factor of 86 % and produce two thirds of the annual heat demand.

Two 400 MWt reactors in 7 TWh annual demand DH network



Two 400 MWt DH reactors, like the DHR400 from China, manage to run at almost 80 % capacity factor and produce almost 80 % of the energy demand, while adding redundancy compared to the case with a single larger reactor. A similar, even more flexible setup could be achieved with four 200 MWt reactors.

Five 200 MWt reactors in 7 TWh annual demand DH network



As an extreme case, five 200 MWt heating reactors running in 7 TWh network manage to produce over 90 % of the required heat, while running at 73 % load factor. This configuration would allow for (require) several different sites for the reactors. While this would add to reliability and redundancy of the whole energy system, it would also bring the trouble of finding multiple potential sites. There would be ample extra capacity for district cooling in the summer-peak in this configuration as well. Maintenance of the reactors would be done from May to September.

District Cooling with Nuclear Heat

In the summer, heating demand is very low, mainly just for warm water use. Given that there is very little savings to be had from shutting nuclear reactors down or lowering their production, it might be feasible to use the extra heat capacity to run absorption chillers[27] to provide district cooling.

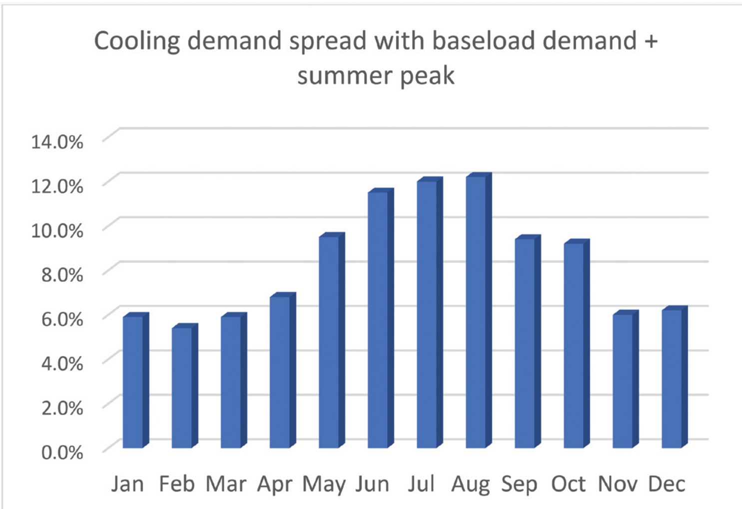
The technology is nothing new, as such chillers have been commonly used for example in trailers (gas-fired fridges), as well as in larger applications such as for district cooling. They require a heat source of around 90 °C and use that to generate cooling. The efficiency (roughly 1:1) is not as good as with heat pumps, but on the other hand, if there is "free" heat available, the lower efficiency might not matter that much, as long as the additional investment costs are reasonable and there is demand.

District cooling is currently done in several cities in Finland, including Helsinki, Espoo, Turku, Lahti, Pori and Tampere. Air conditioning / cooling demand is estimated to keep on growing both in Finland and in Europe both due to rising living standards and the warming climate, so district cooling has a growing market potential. The total cooling demand in Finland was roughly 1,4 TWh in 2014 and can grow to 1.7 TWhs by 203028, where district cooling can grow its share to around 25 % by 2030. The same numbers for EU (EU27) are 330 TWh in 2014 and 500 TWh by 2030, with around one percent share for district cooling currently.

27 Also called absorption heat pumps.

28 VTT 2015, https://energia.fi/files/399/Rakennusten_jaahdytysmarkkinat_18-12-2015.pdf (Summary also in English, report in Finnish)

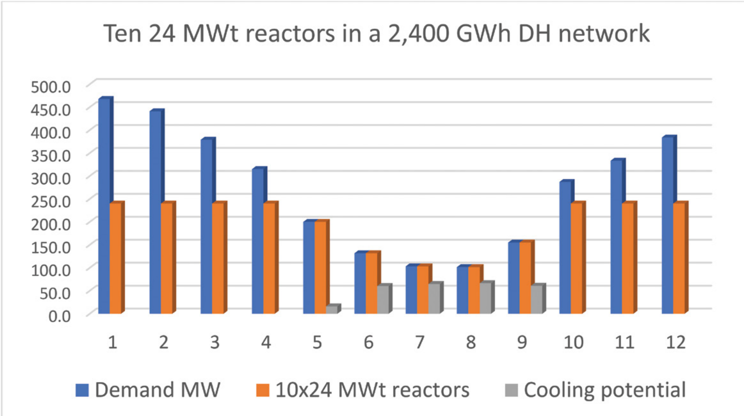
Total district cooling sold in Finland was around 220 GWh in 2017, with a total capacity of around 300 MW[29]. In Helsinki, 141 GWh of cooling was used in 2017, and the capacity stood at a bit less than 220 MW in late 2018. The growth in Helsinki has averaged at slightly under 20 MW per year and is estimated to grow further in the future, at least up to 350 MW.



District cooling is sold around the year, and is used at sites like data-centres, while summer-time (May to October) has a peak in demand as residential buildings are also cooled. This peak can be handled by the otherwise un-used nuclear heat capacity, which will increase the load factor of the reactor by a couple percentage points, depending on the situation. The above graph of the monthly demand variation of cooling is for illustrative purposes (not exact data).

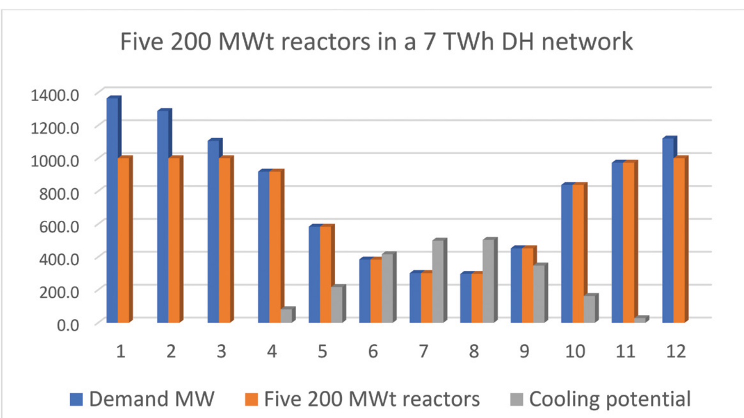
29 Finnish Energy association energy statistics 2018.

District cooling – medium-sized city



The graph above shows the extra-capacity available for cooling in a setup of ten 24 MWt reactors in a DH network the size of 2.4 TWh of annual demand (Turku, Tampere, Espoo). Below is the case of having five 200 MWt reactors heating (and cooling) Helsinki.

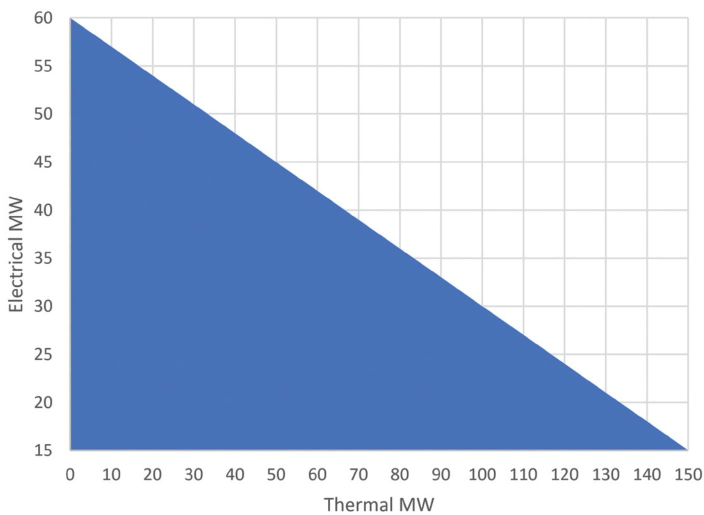
District cooling – Helsinki



Combined heat and power

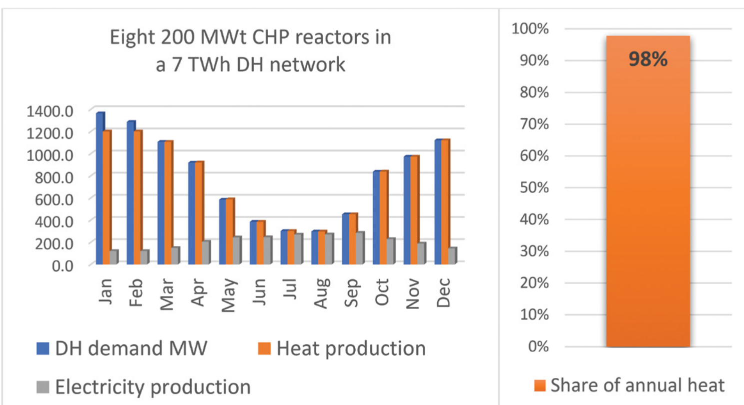
Combined heat and power (CHP) production is a potential game-changer for nuclear decarbonization, and even more so with higher temperature reactors which improve the total efficiency. Using suitable nuclear reactors in CHP allows the plants to both run at high capacities and to produce almost all the heat demanded by the local district heating network. In practice, this is done by varying the amount of electricity and heat production to follow the demand. A plant's ability to vary the production between electricity and heat depends greatly on the chosen technical solutions, as does the overall efficiency at which this is achieved.

To keep the examples here simple and conservative, this study assumes that the heat (steam) for district heating is taken from a turbine bypass, even though it is the least effective way to do CHP. This means that part of the steam is diverted before it goes to the turbine to produce electricity, and is directed to another condenser instead, which then produces district heat. This is a simple solution, and from total efficiency point of view, it is also the worst, as the waste energy coming from the turbine is all lost. We also assume that the turbine must run at least 25 % of its power level. See the graph below for an example how taking steam for district heating affects the electricity production. With a light-water reactor such as the 200 MWt NuScale, this means **the maximum heat production is 150 MWt, with additional 15 MW of electricity produced as well**, to keep the turbine running.



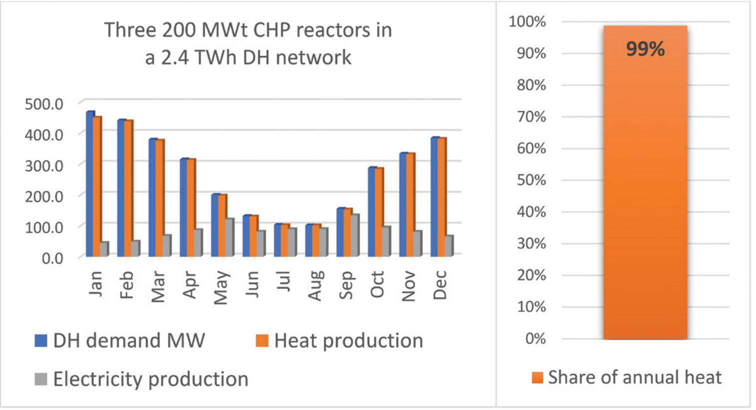
The turbine can also be switched off completely to allow for all the reactor's capacity go to heating. Depending on the turbine this "stopping and starting" might cause some wear and tear in the long term, especially for larger turbines. In the graphs below, this is not done. Minimum heat production is 0 MW, when all the steam is directed to the turbine for electricity production. Like stated above, this is the least effective way of doing combined heat and power, so in reality the total efficiencies can be higher – meaning that more electricity can be produced while producing similar amount of district heat.

Eight 200 MWt CHP reactors in a 7 TWh annual demand DH network



The graph above has eight 200 MWt reactors running CHP. They could produce almost all the heat needed even without turning any of the turbines off, meaning that there is actually additional heat capacity available (400 MWt total) in case demand spikes or other situations – although then the corresponding electricity production would be lost. The power generators run between 25 % and 75 % of their maximum capacity (15 MWe to 45 MWe each, with 60 MWe as max). Around 1.8 TWh of electricity is produced annually on top of the almost 7 TWh of heat.

Three 200 MWt CHP reactors in a 2.4 TWh annual demand DH network



To produce all of the heat demand of a 2.4 TWh annual demand city such as Turku, Tampere or Espoo, three 200MWt CHP reactors could be used. In addition to the heat, they would produce 0.7 TWh of electricity as well.

Load Following with SMRs

While this study assumes that short-term load-following and storages are handled by other means, we still discuss it briefly in relation to SMRs, as load following capability could be a valuable feature in the future of more intermittent energy production clashing with ever-higher dependency on reliable energy delivery in society.

Normal light-water reactors can lower their power level to around 40 or 50 % of maximum capacity by using control rods, although this depends on many things such as the age of the fuel in the reactor. Practically all modern reactors have the capability to decrease and increase their power output quite rapidly, up to a point. The reason this is not often done is that there is rarely any economic incentive to do so, as it doesn't reduce the O&M costs (and might actually increase them slightly). In Europe, it has also been a licencing issue, as reactors have been licenced to operate either as baseload or load-following (like in France and Germany).

In some designs, such as NuScale's reactor, they can also use turbine bypass for relatively fast load following (this same turbine bypass can also be used for getting the required energy for district heating as we did in the previous chapter). See images below for examples of two kinds of load-following capabilities NuScale reactors have[30]. If there are suitable heat storages (or demand) available, the heat lost due to load following could still be captured and used for district heating later, depending on the technical details how the plant is built.

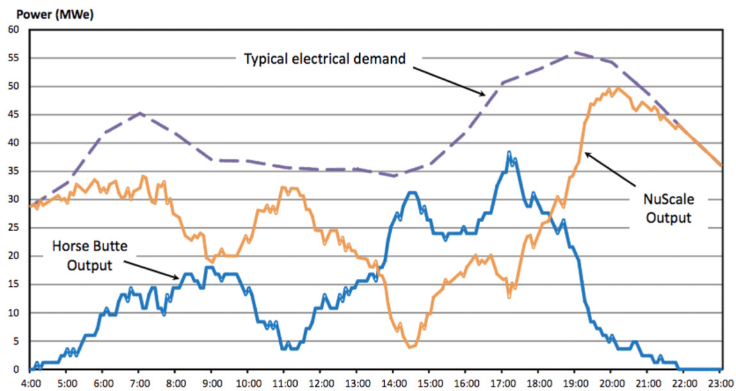


Figure 5 NuScale load following Horse Butte wind farm and daily demand variation

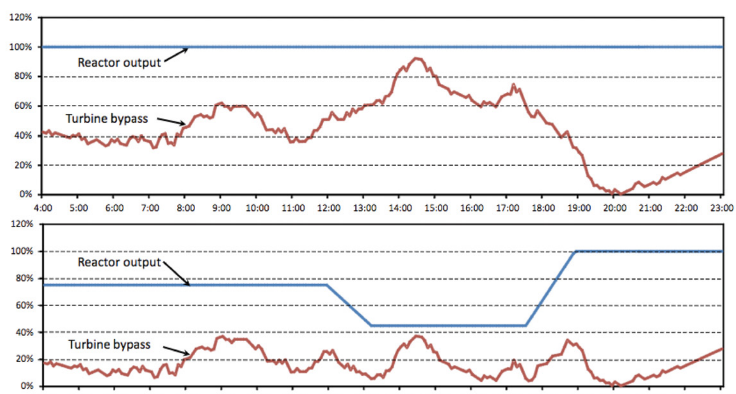


Figure 6 Two load following options for NuScale. Above is turbine bypass only. Below is turbine bypass and reactor power manoeuvring in combination.

30 D. T. Ingersoll, C. Colbert, Z. Houghton, R. Snuggerud, J. W. Gaston and M. Empey, "Can Nuclear Energy and Renewables be Friends?" Proceedings of the 2015 International Congress on Advances in Nuclear Power Plants (ICAPP 2014), Nice, France, May 2-6, 2015. http://tinyurl.com/yaws7mcc

Warsaw, Poland – 14 TWh demand in 2040

As a European case, we take a look at the Polish capital Warsaw and its surrounding metropolitan area. Warsaw currently has heat demand at around 7 TWh per year, which is projected to almost double to around 14 TWh by 2040[31]. The heat today is produced from four mostly coal fired powerplants[32]:

- Siekierki (2078 MWt / 622 MWe, CHP. Built in the 60s and 70s, modernized in the 2000s)
- Żerań (1580 MWt / 386 MWe, CHP. Opened in 1954, modernized in 1997-2001)
- Kawęczyn (512 MWt, heat only, operational since 1983)
- Wola (465 MWt, heat only. Seasonal use, burns mainly heavy fuel oil, opened in 1973)

The total thermal capacity is over 4.4 gigawatts.

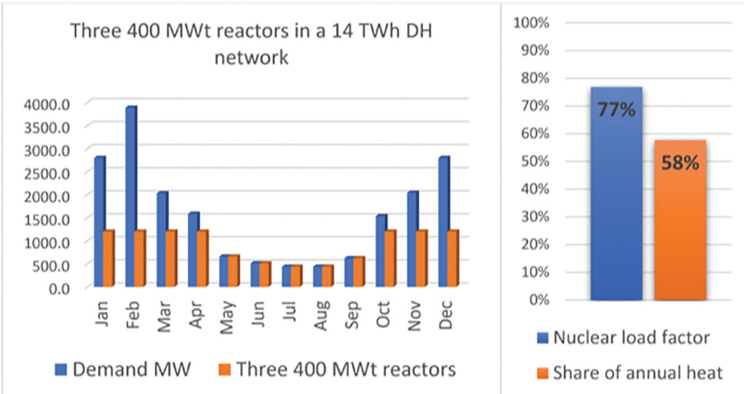
We do the basic modelling with 14 TWh annual demand. It should be noted that in Poland's case, nuclear energy would replace coal burning almost exclusively, with comparable effects on emissions as well as air quality. Somewhat surprisingly, the difference between high winter and low summer demand is even more pronounced than in Finland. There is a high peak in February that is up to nine times higher than the summer months[33].

31 Based on Deep Decarbonization of Urban Areas – Warsaw Metropolitan Area by Climate-KIC (2018), original source: Założenia do planu zaopatrzenia w ciepło, energię elektryczną i paliwa gazowe dla m.st. Warszawy Projekt z dn. 01.07.2018

32 Details of the plants can be found at PGNiG TERMIKA website: http://www.termika.pgnig.pl/en/zaklady

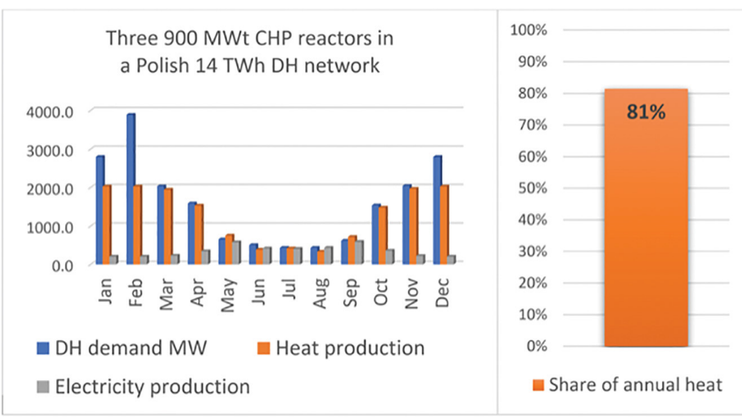
33 The approximate data for the demand is from Fortum.

Three 400 MWt reactors in a 14 TWh DH network



Since the demand differences between months are higher, the demand for baseload heat is lower and longer than in Finland. Three 400 MWt reactors, such as the DHR-400 from China, would operate at 77 % load factor while providing 58 % of the annual heat.

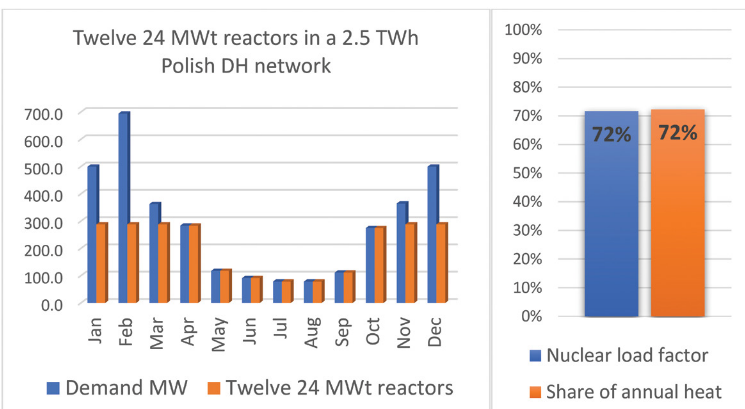
Three 900 MWt CHP reactors in a 14 TWh DH network

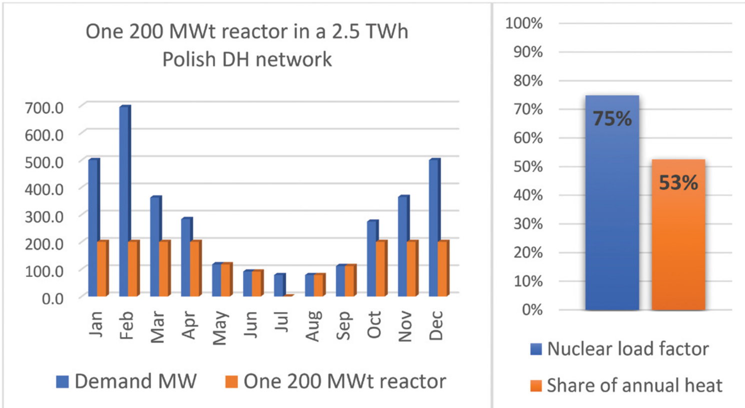


Having CHP-capable reactors would make a lot of sense for Poland, as not only heat, but also electricity is done mainly with coal. In addition, the flexibility of CHP would increase the load factors for the nuclear power stations, allowing also for a larger part of the heating demand to be met without combusting fuels, therefore bringing emissions and costs down, as well as lowering particulate pollution levels and the health hazards they pose. In the example above, we have three 900 MWt reactors (such as the BWRX-300) running in CHP. The assumptions on how the CHP is technically done are the same conservative ones as used previously: turbine by-pass for the steam.

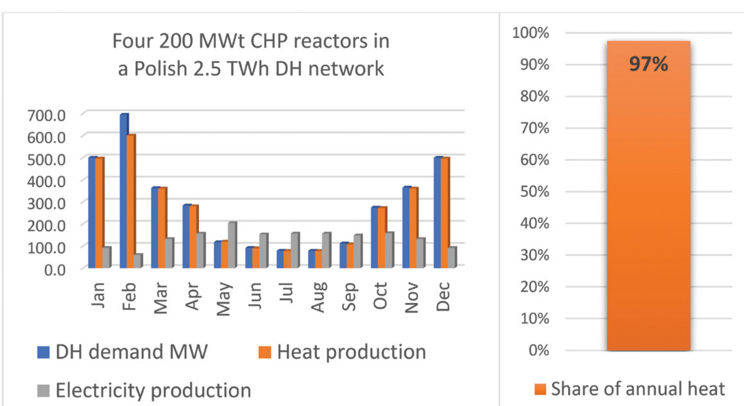
Poland – Medium sized cities with 2-3 TWh of demand

Poland also has a number of smaller cities than Warsaw that are still of substantial size. These include cities like Krakov, Wrocław, Poznan, Gdańsk, Białystok and Lublin, that each have 300 000 to 800 000 inhabitants and district heating networks of varying sizes. We use 2.5 terawatt hours as the representative annual demand to get a perspective on these cities and their monthly heating demand and how it could be met with heat-only or CHP nuclear reactors.





Here are two examples for a mid-sized Polish DH network. The examples have the nuclear units running at 72 % (for a set of twelve 24 MWt FinReactors) and 75 % (one 200 MWt reactor) load factors. Having more smaller units increases the share of clean heat and redundancy, while it also increases O&M costs per heat produced as there are more people needed to operate more reactors and sites. The example with one 200 MWt reactor has a similar load factor but produces almost 20 percentage points less of the annual demand, which will increase the costs and emissions of producing the rest of the demand. A single reactor is also less redundant, requiring more backup.



With CHP enabled (using the same parameters as we did previously), a set of four 200 MWt reactors (such as the NuScale) would produce practically all the heating demand, and 1.2 TWh of electricity.

Poland also has a program looking into high-temperature reactors (such as the Chinese HTR-PM) to supply industrial process heat. These kinds of reactors would likely offer some very interesting opportunities of co- or tri-generation of industrial process heat, electricity and district heating, and even hydrogen.

Summary

We chose a variety of different DH network sizes and reactors to see how the reactors could fit into different DH networks. Here are some conclusions and findings.

For heat only reactors, a reactor or a set of reactors can produce about two thirds (~65 %) of the needed energy while running at a reasonably high load factor of around 85 %. Inversely, if 90 % of the heat is produced with nuclear heat reactors, they will run at around 70 % load factor (slightly over 6,000 hours / year). The percentages vary slightly according to how many reactors and what size are used as well as the local demand profile, so these are only rough "rules of thumb."

Producing district cooling with absorption chillers for summer-time peaks (May to September) with the extra heat capacity can increase the nuclear load factor by a couple percentage points, depending on the demand for district cooling. In countries with less seasonal variation in heating demand and greater demand for cooling, this increase of nuclear load factor can be larger.

The more (smaller) reactors, the more distributed, flexible and redundant the system is, but the more expensive also the energy produced, due to economies of scale. In larger networks, there is a guideline that no more than one third of the needed capacity comes from one source, to add redundancy and resilience.

A very small heating reactor of 20 to 50 MW thermal capacity would offer a very interesting way to decarbonize baseload heat production in small-to-mid sized networks with annual demand of 150 GWh or more. This would require safe and affordable designs that could be placed near population (as per regulations) and the public acceptance and legislation to allow that. These hypothetical "Fin-Reactors" could be manufactured in a factory or suitable shipyard, driving down their costs with repetition and added productivity.

In DH networks of 150 – 2,000 GWh of annual demand, there is potential market for roughly 50 reactors of 24 MWt capacity. They would operate at reasonably high load factors of 80 – 90 percent, allowing for low-cost baseload heat, and produce roughly half of the total demand of 17 TWh that these networks have. The forthcoming commercial reactors of 200 MWt and higher capacities are somewhat large for DH networks of this size, unless one operates them as CHP plant.

For the three 2,000-3,000 GWh DH networks in Finland, a 200 MWt district heating reactor could be a good fit and could even be complimented with a couple small FinReactors. Alternatively, they would have room for up to ten FinReactors each.

Helsinki, at seven terawatt hours of annual heat demand, could host anywhere between one to four 200 MWt reactors, or one or two 400 MWt reactors, or a combination of these. Four 200 MWt reactors would operate at roughly 80 % load factor and produce ~80 % of the annual heat demand in Helsinki.

Helsinki could also have reactors capable of CHP production, as it now has with fossil fuel plants. Eight 200 MWt CHP reactors (such as NuScale's) could produce all the heat while also producing around two terawatt hours of electricity.

All in all, small and very small nuclear reactors could be used to produce between 50 and 70 percent of Finnish district heating even with heat-only reactors operating at tolerable to high load factors between 70 to 90 percent.

Adding combined heat and power allows much more flexibility and increases the potential techno-economic share of nuclear significantly, given that there is a market and reasonable price for the electricity as well. This is, of course, a required precondition for any investment, including renewable energy.

Any affordable large-scale energy storage would increase the load factors of the reactors and therefore potentially decrease the costs of nuclear energy and the cost of providing a reliable energy service to the people and businesses.

Emissions Reduction Potential

In this chapter…

- We inspect what is the emissions reductions potential of nuclear district heating, with the following key findings:
- Average and total DH emissions vary significantly depending how biomass is treated.
- With bio counted as zero-carbon, the average DH emissions are around 140 gCO_2/kWh, and roughly 5 million tons in total.
- Almost all these emissions could be eliminated with heat-only SMRs running at high load factors.
- In addition to that, with lower load factors or CHP capable reactors, millions of cubic metres of biomass such as forestry residues could also be left for other uses, such as feedstock for biofuels or the chemical industry.
- Tens or even hundreds of millions of euros would be saved annually from the emissions trading system (ETS) with emission prices between 20 to 50 euros per ton.
- Poland uses coal for district heating, so in there, the emissions reductions potential for nuclear DH would be even greater, and it could greatly improve local air quality as well.

Calculating the emissions reductions potential from district heating is not a simple task. First, district heating is often made with power plants running in combined heat and power (CHP) mode. So the emissions from the fuel needs to be distributed between electricity and heating in a dynamic situation.

Second, in a power plant nearly all of the primary energy in the fuel can be utilized as useful heat, but only about a third of it can be made to electricity. Yet the absolute amount of emissions is the same, as same amount of fuel gets burned. With combined heat and power, we can use nearly all of the energy as both electricity and heat. The relative amount of heat and power produced varies depending on the plant and the fuel used but is usually between 1:1 and 3:1 (heat in relation to power produced).

Third, different kinds of biomass (industry waste-steams, logging residue, saw-dust, roundwood, crop residues, energy crops and so forth) have different kinds of typical emissions, and their actual climate forcing depends also on the time-scale used to calculate how fast their emissions are sequestered back into the living biosphere, by the time they would decompose into CO_2 even if left unburned, and their other potential uses (opportunity cost).

Further, when we harvest crops or log forests, they will grow back even if we do not burn the residues immediately but choose to do something else with them (which could lead to net-negative emissions). So while forest management (thinnings etc) often increases the amount of large roundwood production and carbon sequestration in a forest, we can do this management even if we would not use most of the residue – even though in many cases it might be a reasonable use for it and an incentive to do this forest management in the first place[34].

And lastly, all bioenergy is currently calculated as zero-carbon when used for heat and electricity production inside the European Emissions Trading System (ETS). Instead, they are accounted for in Land Use, Land Use Change and Forestry -sector, known as LULUCF. So whatever emissions/climate forcing bioenergy do have, they come on top of those within ETS.

The LULUCF -sector has its own targets of reducing emissions and storing carbon in the land and forests, but it is somewhat problematic that, by increasing our use of bioenergy, we are in a way moving our energy emissions to another account, the LULUCF -sector. On the other hand, if they are mainly residues and waste-streams from other forestry and forest management practices, they are accounted there whether we burn them or not.

34 This doesn't mean other incentives don't exist.

"While there indeed is ample potential for biomass waste to replace the fossil fuel inputs to the chemical sector, this implies the condition that no, or a little part only, of these streams will be used for other energy production and production of transport fuels.[35]"

Emissions from bioenergy are a complex subject, as they can be seen both as zero, as comparable to coal, and everything between these two depending on the quality, potential other uses and timescale observed. The situation in energy-use is made more complicated as they are accounted for in the Land-Use, Land-use-Change and Forestry -sector (LULUCF).

What is undeniable is that the sustainably (be it economically or environmentally sustainable) available amount of available biomass is limited. We are already causing loss of biodiversity and the shrinking of species population in many places at massive scale, and that is mainly due to agriculture and forestry – the growing and appropriation of biomass for human use.

Therefore, we need to think carefully what we use the harvested biomass for. What is it replacing? How long will the product last and hold the carbon content? What is the value we get from that product to society? Can biomass be used to replace fossil fuels in sectors that have little or no other substitutes?

For example, liquid fuels for transportation are mainly derived from crude oil. There, advanced biofuels might be one of the few solutions to replace crude oil. Scales matter as well: replacing for example 10 TWhs of bioenergy in DH production with other energy sources would enable us to produce around 5 TWh of liquid fuels from it, as well as 2-3 TWhs of district heat[36]. The total demand for liquid fuels is around 60 TWh in Finland, so we need all the potential substitutes we can find even if electric transportation would grow substantially. The plastics-industry uses mainly oil and natural gas as feedstock, with biomass offering one of the few alternatives, both as material and as raw material for chemical processes. Same goes for pharmaceutical industry, clothing industry and many others. Even without massive energy use, there is more than enough alternative demand for biomass, and many times it also offers higher value.

This defends the position that biomass should preferably be used outside the heat and power sector, but it also needs to be men-

35 Decarbonizing Energy Intensive Industries: The Final Frontier (2016), https://www.ies.be/node/3698

36 See: VTT develops a new sustainable way to turn forestry waste into transport fuels and chemicals (2019), http://tinyurl.com/y8m68q2p

tioned that there might be limited amount of greater value uses for biomass at any given locale, at least in the short term. On the other hand, these uses will not materialize if most of the potential feedstocks are directed to combustion in the energy sector, especially if this is done with subsidies, renewable-energy production targets or other means.

Still further, the situation will change, perhaps dramatically, on which fuels will be used ten or more years from now compared to today.

Emissions in numbers

So, it is a complex situation to say the least. For reference, here are three different examples on how bioenergy and their climate forcing[37] can be seen:

1. ZERO. Zero carbon emissions in the energy sector as is currently agreed.
2. IPCC. Based on IPCC median estimate of emissions for bioenergy, 230 gCO_2/kWh of electricity, which equals to around 75 gCO_2/kWh for heating[38].
3. FULL, as in how much CO_2 is released from the combustion process when we burn biomass (the specific emissions of biomass: 390 gCO_2/kWh of heat[39]).

The Finnish district heating has average emissions of ~140 gCO_2/kWh[40], which is calculated as bioenergy having ZERO emissions as they are accounted for in the LULUCF sector. Around 36 % of Finnish district heat is made with bioenergy (in 2017). If we use 75 gCO_2 (IPCC) and 390 gCO_2 (FULL) as alternative values, the average emissions for district heat are roughly 165 and 280 gCO_2/kWh of heat, respectively[41].

37 Climate forcing is used to compare different sources of emissions, and with bioenergy, it includes the fact that with time the carbon will be sequestered back.

38 IPCC, in another document, recommends nations to use zero as the basis for counting bioenergy emissions.

39 See more info on Specific Carbon Dioxide Emissions of Various Fuels: https://www.volker-quaschning.de/datserv/CO2-spez/index_e.php

40 he exact number changes from one year to the next. In 2017 it was 139 grams and in 2018 it was 150 grams. Data according to Finnish Energy.

41 Getting exact numbers is both unnecessary for the scope of this study as well as very complex.

	CO_2/kWh	Total DH energy	Total Emissions
ZERO	140 gCO_2/kWh	~36 TWh	5 Mtons CO_2
IPCC	165 g CO_2/kWh	~36 TWh	6 Mtons CO_2
FULL	280 g CO_2/kWh	~36 TWh	10 Mtons CO_2

As seen on the table above, currently the Finnish district heating system has total emissions of 5 million tons of CO_2 per year. If measured at the "end of the smokestack", this roughly doubles to 10 million tons of CO_2 per year. Using the IPCC median estimate for bioenergy, the total emissions are 6 million tons of CO_2.

A nuclear reactor does not produce direct emissions, and indirect emissions are so small that they do not make a big difference – IPCC states that in electricity production, nuclear has median emissions of 12 gCO_2/kWh, which would translate to around 4 gCO_2/kWh when heat is produced.

When inspecting a single case, one must find out what is the "marginal fuel" that gets replaced. If there is an ageing coal plant producing baseload, then that is likely to be replaced, but adding new clean capacity might also affect how much other energy sources are used. Given that currently almost half of the heat is produced by burning either fossil fuels or peat, both of which face the rising costs of emissions credits in the ETS (and a complete ban in the case of coal).

In the face of all this complexity and just to give a broad picture, this study uses three values to base the emissions savings calculations on.

1. Average approximate emissions today at **~140 gCO_2/kWh**.
2. A mix of natural gas, coal and peat (replaced at the margin) at **250 gCO_2/kWh**[42].
3. A mix of forest industry residues and side-products in **cubic meters**[43], averaging at 1 MWh / m3. Note that this is not comparable to "solid cubic meters of wood", which is around double the energy density.

For the Polish cases we use coal as the fuel to be replaced, averaging at **350 gCO_2/kWh**.

42 Natural gas has 200 grams, while coal and peat have around 350 gCO_2 / kWh.

43 This mostly means "loose" material, as in a pile and not compressed. Energy content varies greatly depending on humidity as well, and wood pellets have several times the energy content of bark of chips, as does black liquor.

In emissions trading credits, these translate to following costs per MWh, at 20 euros per ton and 50 euros per ton of CO_2.

1. At average 140 gCO_2/kWh, emissions credits would cost:
    a. **2.8 €/MWh** at 20 euros per ton of CO_2
    b. **7 €/MWh** at 50 euros per ton of CO_2,

2. At mix of gas, coal and peat at 250 gCO_2/kWh emissions credits would cost:
    a. **5 €/MWh** at 20 euros per ton of CO_2
    b. **12.5 €/MWh** at 50 euros per ton of CO_2

In the Polish case, with coal emissions of 350 gCO_2/kWh, replacing coal, there costs would be **7 €/MWh and 17.5 €/MWh** with emissions credit prices used above.

All in all, the following numbers need to be taken with grain of salt. **The local fuel mix is never the national average, and if a reactor will get built, it will never replace the average mix**, but more likely a specific power plant or plants. Therefore, these are just examples to give the reader an idea of the magnitudes involved.

Small networks

The thirty or so smaller DH networks with 150 – 1,000 GWh of demand use a total of around 10 TWh of heat annually, of which perhaps 60 % (6 TWh) could be produced with FinReactors. At the current average emissions of Finnish district heating (139 gCO_2/kWh), their total emissions are roughly 1,4 million tons CO_2. If they would use exclusively forest residues averaging at 1 MWh / m^3, they would use around ten million cubic meters.

In the table below, we see the how many million tons of emissions would be saved if 60 percent of energy would be nuclear, with two different assumptions on what average fuels emissions would be replaced.

Total heat produced: 10 TWh Nuclear heat produced: 6 TWh	Saved CO_2 (first two rows) or forest residue (bottom row)	Saved euros in ETS (millions/year)	
		at 20 €/ton CO_2	at 50 €/ton CO_2
CO_2 saved at 140 gCO_2/kWh	0.84 Mton CO_2	16.8	42
CO_2 saved at 250 gCO_2/kWh	1.5 Mton CO_2	30.0	75
Forest residue saved (Mm^3)	6 Mm^3		

Medium and large networks

Finland has five medium-sized DH networks that use between one and two terawatt hours of heat annually. They could each host 4 to 8 FinReactors or perhaps a single 200 MWt DH reactor and could produce between 65 to 85 percent of their heat demand with these reactors running at relatively high load factor of 75 to 90 %.

A single DH network with 1,5 TWh of demand could, therefore, produce around 1.1 TWh of heat with nuclear (+/- 0.2 TWh). Altogether, the five networks have a combined demand of 7 TWh, of which around 5 TWh could be produced with district heating reactors.

In the table below, we see the how many million tons of emissions would be saved if around 70 percent of energy would be nuclear, with two different assumptions on what average fuels emissions would be replaced.

The three larger, 2 – 3 TWh annual demand networks also add up to around 7 TWh, and Helsinki has similar demand by itself, so the table below applies in principle for each of these cases as well. As they are larger networks, they can accommodate a larger variety of reactors and their combinations, as well as reactors capable of combined heat and power (CHP). This makes it possible to have a higher portion of the energy produced with nuclear.

Total heat produced: 7 TWh Nuclear heat produced: 5 TWh	Saved CO_2 (first two rows) or forest residue (bottom row)	Saved euros in ETS (millions/year)	
		at 20 €/ton	at 50 €/ton CO_2
CO_2 saved at 140 gCO_2/kWh	0.7 Mton CO_2	14.0	35
CO_2 saved at 250 gCO_2/kWh	1.25 Mton CO_2	25.0	62.5
Forest residue saved (Mm^3)	5 Mm^3		

At the table below, we have all the medium and large DH networks combined.

Total heat produced: 21 TWh Nuclear heat produced: 15 TWh	Saved CO_2 (first two rows) or forest residue (bottom row)	Saved euros in ETS (millions/year)	
		at 20 €/ton	at 50 €/ton CO_2
CO_2 saved at 140 gCO_2/kWh	2.1 Mton CO_2	42.0	105
CO_2 saved at 250 gCO_2/kWh	3.75 Mton CO_2	75.0	187.5
Forest residue saved (Mm^3)	15 Mm^3		

To give some scale, one Finn emits around 10 tons per year[44], as our annual emissions are around 55 million tons CO_2. Hence, one million tons is emitted by a total of 100,000 Finns annually. A lot of those emissions come from different industries. For example, SSAB is the single biggest source of emissions in Finland, emits around 4 Mtons CO_2 annually. Outokumpu Stainless emits around 0.7 Mtons, Stora Enso around 1 Mton and Helen and Neste just under 3 Mtons. The eight biggest single emitters in Finland emit a total of around 15 Mtons. This is roughly the same as the total emissions from transportation in Finland combined.

44 Roughly around third of that is stored in Finnish forests due to their net-growth, so this number excludes land use and forestry sector.

Finland total Summary

As we found out in the Modelling -chapter, the maximum optimal of district heat that could be provided with small nuclear reactors is around 60 percent of total (+/- 10 percent depending on assumptions like load factor and CHP availability). With the current fuel mix and disregarding the local differences and circumstances, **this would be enough to replace practically all the fossil fuels and peat in the mix**, as they represent almost half of the fuels used today. However, this is just a macro-view of the situation, looking at the numbers. Further, such nuclear project would potentially help save a couple million tons of biomass for other uses on top of replacing the fossil fuels and peat.

Given that the other half of the energy in Finland's DH system is bioenergy or waste heat that are counted as zero emissions, it is safe to say that **small nuclear reactors could be used to erase almost all the emissions, five million tons of CO_2, that are currently produced annually in Finnish district heating**. At emission prices of 20 or 50 euros per ton, **this would translate to savings of 100 to 250 million euros per year** on the ETS alone.

Roadmap for nuclear decarbonization

To get to zero-carbon district heating in roughly 20 years (by 2040), the emissions would need to decrease by 5 percentage points per year, on average (if linear). If we assume bioenergy and waste-heat are zero carbon in this sense, we need to replace around half of the total energy used in district heating, roughly 15 TWh per year (around 2 GWt of capacity). At five percent per year, this would mean around 750 GWh of annual clean production built and replacing fossil fuels each year. This would leave the current bioenergy, waste heat and other sources roughly at their current levels.

Since this is a study on the potential for nuclear, we discuss what it would mean to do this with small nuclear reactors. To get ~750 GWh of annual production added each year, we need around 100 MWt of added capacity per year. Four FinReactors each year, or a 200 MWt DH reactor every two years, or a 400 MWt DHR-400 every four years – on average. Given that it will likely take many years (maybe a decade) before we can start construction in earnest, this build-rate would need to be roughly double, 200 MWt per year. Is this feasible?

Let's compare it to another Finnish nuclear project. Olkiluoto 3 has faced many difficulties and delays and will take around 15 years to go from start to finish. It has a thermal capacity of 4,500 MWt, so the average construction speed is around 300 MWt per year. From this perspective, the nuclear district heat project is totally doable, but of course we need to have multiple smaller projects going on at the same time.

To have 15 TWh of nuclear heating capacity online in the Finnish context, we would need to build something roughly like this:

- Five to eight 200 MWt reactors (depending if they are heat only or CHP – for a total capacity of roughly 1 to 1.5 GWt).
- Between 20 and 40 FinReactors at 24 MWt (for a total capacity of roughly 0.5 to 1 GWt).

We would need to design (or obtain an already made design[45] and modify it as needed) the FinReactor, have it licenced, and the necessary permissions given and signed, and get a manufacturing line or shipyard ready to start building them at a speed of 3 to 5 per year by around 2030. By then we would need to have the full supply chain in place and site preparations well under work on at least several sites. Before this, we will need to modify our nuclear legislation to better enable permitting, licencing, siting and manufacturing SMRs. There is a lot to do.

The graph below shows a potential roadmap for the scenario above, where around 2,000 MWt of nuclear capacity is brought online by 2040. It has total of seven 200 MWt reactors and 25 FinReactors of 24 MWt.

45 See for example https://en.wikipedia.org/wiki/SLOWPOKE_reactor

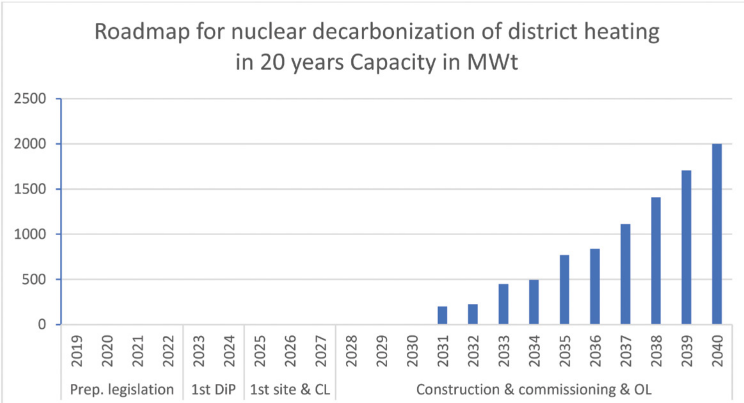


Figure 7 Potential roadmap to decarbonize district heating in Filnand by 2040 with small nuclear reactors.

Regarding the bigger SMRs, many of the suitable designs are becoming available likely during the 2020s, and some in the early 2020s. Having a customer (or customers) ready to buy (several of) them would enable faster progress in many cases, as the existence of willing customers is bound to increase funding opportunities for finishing the design and building pilot programs faster.

At a cost of 1,500 €/kWt, which is rather conservative (high[46]) on the heat-only reactors, adding 100 MWt per year would have a total cost of 150 million euros per year. For twenty years, the total "overnight" cost would be around 3 billion euros.

Polish emission savings

In Poland, it is safe to assume that any added nuclear capacity will likely replace coal, which has specific emissions of around 350 gCO_2/kWh of heat produced. Each terawatt hour of heat done with nuclear instead of coal will mean that 350 thousand tons of CO_2 are not emitted. **A 400 MWt SMR would produce around 3 TWh of heat per year[47] and hence save around one million tons of CO_2 emissions per year**, and at emissions prices of 20

46 The Chinese DHR400 is estimated to cost around 500 euros per kilowatt in China, so this average cost is three times higher.

47 Running 7,500 hours per year, or at 85 % load factor.

and 50 euros, it would also save 20 to 50 million euros per year, respectively.

Warsaw uses over 25 TWh of heat annually, and there are at least half a dozen smaller networks in other cities using 1 – 3 TWh of district heat. The overall potential for emissions savings with heat and CHP SMRs a in just these networks is in the order of ten to twenty million tons per year. Meanwhile, direct and indirect health costs from air pollution would drop significantly as well, and tens, even hundreds of millions of euros would be saved by the Polish people through the emissions trading system as less emission rights would be needed.

Business models and opportunities

In this chapter…

- We inspect what are the potential business models as well as opportunities for nuclear district heating, with the following key findings:
- There are options such as "Heat-Mankala[48]" co-operative, where smaller utilities could benefit from nuclear heat without the heavy regulatory burden of being a nuclear operator.
- It would likely make sense to limit the amount of different reactors designs used to cut costs through building the same designs multiple times.
- Nuclear heat can be very cost-effective. The estimated levelized cost of heat (LCOH) is between 15 and 30 €/MWh, depending on assumptions and average load factors. It would likely lower the average cost of producing district heating, while also removing emissions.

Being a nuclear operator carries a heavy burden of bureaucracy, short and long-term responsibilities and other overheads. It is an intergenerational endeavour, which requires credible and large organizations of people to run it. It would make no sense for a small local energy company to become a nuclear operator.

There are other options, however, briefly summarised here.

Heat as a service / heat purchasing agreement

One option is for the local company to make a long-term contract for purchasing heat at a certain price for a certain time from a larger operator who will construct and operate the small reactors, taking care of the responsibilities that nuclear operators have. With a longer term purchasing agreement, they have the certainty of a customer and can control their risk that way. Larger firms also have more financial muscle and often more favourable position to ne-

48 See more information on Mankala cost-price model here: https://www.pohjolanvoima.fi/filebank/24471-The_Mankala_cost-price_model.pdf

gotiate for financing. They can enjoy the benefits of scale in their construction and operations, as they can offer to build and operate multiple sites with the same crews being used and rotated.

The downside is that the local company enters a long-term contract and can become somewhat dependent on a single supplier, which can be seen as risks. The upside is that the local company will need to do much less capital investment themselves.

Mankala co-operative

A more involved option for heat/power purchasing agreements is to have a cooperative of smaller and larger companies can pool their resources to build and operate bigger infrastructure. Mankala-co-operative is one such model used in Finland for energy companies.

It is an energy company that is owned by other companies, and its purpose is to sell its produce to its owners **at cost**. It is often used in large endeavours in Finland. TVO, PVO and Fennovoima are all Mankala-companies, selling electricity to their owners at cost, in proportion to their share of the company. A steel mill might own 200 MW's, a local utility somewhere might own 50 MW, and so forth. None of these companies need to take the burden of being a nuclear operator, yet they still get to enjoy the benefits of clean reliable energy at an affordable price.

In principle, there should be nothing preventing from having a "heat-cooperative" that is similar to current Mankala-companies. It would be owned by local district heating providers, and would build and operate local district heating reactors, selling their produce to the local heat utilities at cost.

Multiple units, single design

There is ample proof[49] from around the world that having a single design being built repeatedly by the same project management, supply chain and workers is the most effective way to cut construction costs of large nuclear projects. There is no reason to believe this would not be the case for small reactors as well.

49 See for example the recent Nuclear Cost Drivers study: http://tinyurl.com/y65bnex6

If there was to be something like the heat Mankala discussed above, it would likely be a good idea to concentrate on building as few different designs as possible, construct them with same project management teams, working in series and having same supply chains and subcontractors for multiple projects. There should also be information exchange between teams, to share best practices and inform others of potential bad practices and mistakes.

There are some setbacks to single designs as well. If a serious security problem is found on the design after they have been built, the regulator might say that they all need to be shut down until the issue is remedied. There are ways to mitigate this problem, but it needs to be recognized.

The cost of nuclear heat

We must decarbonize our society and economy as fast and thoroughly as possible. On the surface, it might seem that therefore we should do everything we can right now or at least as soon as possible. But given that the real world has limits on how fast things can be done while still having the society – people and businesses – go by their day-to-day lives relatively undisturbed (or at least as undisturbed as possible), this is not the case. We should do a lot but given that we have very limited resources compared to the size of the challenge, we need to plan carefully what we do and prioritize. Simply doing "everything" or something that is right in front of you is not going to take us there. Sometimes doing what seems sensible at the moment might take us in the right direction, but on a path that won't take us all the way.

One way to look at this is to look at the total costs of any given climate mitigation effort. So here are some estimates and comparisons on the costs of district heat production with small nuclear reactors. One needs to take these numbers as rough estimates and read the assumptions made carefully, as there are not enough real-world experiences specifically for nuclear district heat production to get firm numbers. Some studies[50] have been made to look at

50 See Energy Options Network's study "What Will Advanced Nuclear Power Plants Cost?" (2017) http://tinyurl.com/y36px3gc (pdf)

the costs estimated by the different reactor vendors as well as the overall rigor of those estimates. The vendors' LCOE estimates vary between $36 and $90 per MWh (electricity), and are roughly in line with the levelized cost of heat estimates presented in this study, which range between 15 and 30 €/MWh.

Operations, maintenance and fuel costs

When you get it constructed, running a nuclear power plant is remarkably cheap. From big nuclear power stations that have their capital costs amortized, we know that the cost of electricity from them hovers around 20 euros / MWh. As they produce electricity at around 35 % efficiency, the cost of steam (heat) is around 7 euros / MWh. Smaller plants might have higher costs due to more operators per energy unit produced, but on the other hand, they might not, as there are designs that were meant to work without any onsite crew, like SECURE. This is much cheaper than the fuel costs for coal, natural gas or bioenergy.

Indeed, there was a cost comparison done regarding SECURE and other district heating options back in the early 1980s when the topic of building a reactor was on the table, and even without any considerations for climate change, SECURE was the lowest cost option.

Capital investment costs

A large share of nuclear costs come from the capital investment, or the construction of the power plant. There is a saying that there are two things that matter for the nuclear costs: The capital cost and the cost of capital.

The capital cost of any given plant is hard to tell before it is built, but there are estimates.

- DHR-400 district heating reactor is estimated to cost around €200 million in China, or 500 € / kWt.
- NuScale Power Module, 12-pack of 200 MWt reactors totalling 2400 MWt (720 MWe) has a First-of-a-Kind cost estimate of around $3 billion (~2.6 B€). The estimated cost per kWe is $4,200, or about 1,250 € / kWt.
- IMSR400, a high-temperature molten salt reactor has a cost estimate of

around €800 million, or 2,000 € / kWt.

- BWRX-300 has an estimated cost of around 2,000 € / kWe, or around 700 € / kWt[51].

Capital costs can be "overnight costs" or costs that also include the cost of capital (such as interest on loans during construction). The interest rate depends a lot on the situation, perceived risks and the owner(s) of the project, as well as the amount of their own capital they are investing in the project and their available collateral.

Further, the differences in those prices are large, and in some sense, they are not directly comparable. The Chinese cost could easily double when brought to western market. The DHR-400 also produces hot water at 90 °C, while the IMSR400 produces steam at 650 °C. NuScale and the BWRX-300 both produce steam at around 300 °C, while the cost for a single NuScale power module is likely to be comparably higher than the cost per reactor on a set of twelve in a single power plant.

Levelized cost of heat

When capital costs and cost of capital and O&M costs are put together, we get what is called levelized cost of heat per MWh (LCOH). There are numerous assumptions that needs to be done when calculating LCOH, the interest/discount rates and the assumed lifetime of the facility among the largest ones.

Each utility and reactor vendor will do their own calculations on slightly different assumptions, so we won't attempt to do them here. Instead, we refer to some calculations done and published by others.

DHR-400 is estimated to have a cost around 15 to 20 euros per MWh of heat[52] (in China).

NuScale has a target LCOE of $65 / MWh of electricity for its first customer[53]. It does include support from government and some tax credits, but it is also first of a kind project. This cost of electricity is very near to 20 € / MWh of heat.

51 $2,250 / kW, https://analysis.nuclearenergyinsider.com/ge-hitachi-chases-gas-plant-displacement-new-300-mw-reactor

52 See: http://www.bjreview.com/Nation/201712/t20171229_800113368.html

53 https://www.powermag.com/nuscale-boosts-smr-capacity-making-it-cost-competitive-with-other-technologies/

Terrestrial Energy estimates the LCOE of their IMSR to be around $50 / MWh[54], and their cost for heat to be around 20 €/MWh (supplied at over 600 °C, which means that electricity can be done at much higher total efficiency compared to light-water reactors). There is also a study comparing IMSR costs to PWR costs that comes to similar conclusion[55].

Given that power reactors have heat costs around 20 €/MWh, the simpler district heating reactors with lower capital costs should have lower capital costs as well – they can be simpler designs and they lack all the equipment needed for power production, such as the turbine generator.

LCOE cost estimates often assume that the plant will be amortized in 10 to 20 years, after which the capital costs and interest payments drop very low, and only O&M and fuel costs remain. On the other hand, Mankala-companies aim to sell energy to their owners as cheaply as possible from day 1, which means that they pay back theirs loans in much longer timeframes, maybe in 30 years. This lowers the initial LCOE cost but means a slightly higher cost in the longer term as loans are paid back more slowly.

With all this said, we might have a range of **LCOH costs between 15 and 30 euros / MWh**, with 30 euros as a conservative estimate for reactors running at significantly lower load factors. With combustion-based energy, the fuels (gas, biomass…) alone cost more than the LCOE cost of nuclear heat. In their 2017 study on having a single NuScale reactor in a DH network the size of Espoo (~2.4 TWh), VTT estimated that nuclear would decrease the average cost of producing district heat by more than a third[56].

If the reactors are used at lower capacity factors, LCOH will increase, as there is little cost savings to be had. Calculating this effect is out of the scope of this study, but some rough estimates can be made. If there are only fixed costs (no savings to be had by running at lower capacity), and the cost at 95 % load factor is 20 € /

54 https://www.terrestrialenergy.com/technology/competitive/

55 Samalova, L., et al., (2017), Comparative economic analysis of the Integral Molten Salt Reactor and an advanced PWR using the G4-ECONS methodology, Annals of Nuclear Energy, https://doi.org/10.1016/j.anucene.2016.09.001

56 Tulkki, V. & al, (2017), https://www.vtt.fi/inf/julkaisut/muut/2017/OA-District-heat-with-Small.pdf

MWh, then the cost at 75 % load factor would be roughly 25 € / MWh. For low-carbon reliable baseload energy source, this cost is still quite competitive.

Politics, regulation and legislation

In this chapter…

- We discuss the political, regulatory and licencing hurdles of SMR district heating, with the following key findings:
- In principle, it is possible to have SMR built and operated in Finland, but there are many (needless) hurdles to it.
- To make SMRs a more realistic option for district heating, some changes in the Finnish nuclear legislation and regulation should be made. These include: licencing a design or multiple reactors in one go instead of the "one licence per reactor" system we have now.
- The 5km emergency-zone is based on STUK (Finland's nuclear regulator) regulation, and in principle could be reduced from the current zone, which was made for large reactors, without compromising safety. This modification can be done by STUK, so no change in the legislation is needed.
- Finland needs to get moving now if it is to benefit from SMRs when they come more widely available, as this is much sooner than people often think (in the 2020s instead of after 2030), and making the necessary changes in legislation, applying for permissions and inspecting the siting questions will take years.

Nuclear energy is political by its nature and building nuclear requires an extensive public and political discussion. In Finland, constructing a new nuclear power plant (apart from small research reactors) also requires a Decision-in-Principle (DiP) from the parliament.

With climate change mitigation needs setting the frame and pace for energy sector decarbonization, the question of political will to build nuclear also becomes a question of political will to decarbonize our energy systems. According to the Paris climate accord (2015) and the subsequent IPCC report on how and why to stop warming at 1.5 or 2 °C (2018) we will need globally somewhere in the neighbourhood of two to six times more nuclear energy by 2050, and even that requires many heroic efforts elsewhere as well, and might put our planets biodiversity at serious risk due to expanding use of biomass.

To accomplish this, we (as a society) not only need to give permission to build nuclear, we need to actively encourage and make it more feasible to build nuclear, both to decarbonize energy use in and outside the electricity sector but also to get low-carbon load-following capabilities to the electricity grid in order to help integrate more variable electricity output in it. As one of the rich and technologically capable nations, Finland should be a forerunner in researching, developing and constructing new types of clean technologies, and there is no reason why this should not include nuclear. Indeed, there are many reasons why Finland is one of the best places to do this.

A Licence to Decarbonize

If we want to decarbonize our energy use with SMRs, first we need to allow it. In many countries, Finland included, the licencing process has been developed for large reactors. Each reactor needs a separate licence, and the process is both heavy, time-consuming and expensive. This process is not suited for SMRs and needs to be re-thought.

The head of Finnish regulator STUK, Petteri Tiippana, offers some potential improvements and changes in an interview for YLE (Public Broadcasting Company in Finland)[57]. He agrees that the current "one reactor, one licence" licencing process is too heavy for factory-manufactured SMRs, and that we could "licence multiple SMRs at one go". He also states that "if it is simple to show the safety of the SMR, which is the aim of the vendors designing these reactors, the licencing can also be done faster and in a more straightforward way." Of course, none of this would be done in a way that would compromise nuclear safety.

A faster and simpler licencing process for multiple reactors at a time is precisely what would help us to decarbonize our energy supply more efficiently. Thinking bigger, this needs to be done internationally, allowing for reactors to get an internationally or

57 Article is in Finnish here: https://yle.fi/uutiset/3-9857325. The translations are the authors

regionally[58] valid general licence that the local regulators can agree with, at least partly. This would allow the reactor vendors to manufacture reactors with the same standard design for multiple markets, which would both cut costs and potentially improve safety as well. Any kind of legislative or regulatory change needs political will and work to happen.

The Chicken, the Egg and the Regulatory Uncertainty -problem

Most experts see that we need new kinds of regulation and legislation to enable the use of SMRs more readily, but few know what that legislation and regulation would look like. So first we would probably need to study things like "how does the placement of small reactors in underground locations affect emergency zone requirements and other environmental impacts", or "how to do an effective safety analysis for smaller and/or non-water reactors". Questions like "what about operating the reactors with a remote connection" and "what are (and are not) the requirements and parameters for using SMRs for heat-only or CHP production" need also analysis and studying.

The truth is, there is little appetite for anyone to start the licencing progress for an SMR unless the regulatory environment is clear, stable and more favourable for SMRs than it is today. On the other hand, there is less incentive for the policy-makers and regulator to renew their texts and regulations unless there is someone with a clear need and a case. We need a case to more clearly see what is needed for regulation, and we need regulation to be clear to get a case in the first place.

One of the biggest obstacles is the emergency zone and how it is defined. Currently the legislation implies that nuclear reactors are always built in remote rural locations. It should be clearly stated that both the size and the inherent features of the reactor should be used as a basis when defining the size of the emergency zone instead of applying "one number fits all"-method. It needs to be site- and

58 Not necessarily geographically – there is no reason why countries and their regulators can't agree with one another on reactors licencing across the world.

reactor specific, and it needs to be based on evidence – otherwise it is too easy for the regulator to just say that the zone is the same as for large reactors (which would be the easy default option). There are also matters like recognizing that a certain accident or root-cause scenario is impossible due to the reactor design and laws of physics, and can this be used to simplify and decrease the needed safety systems?

And for this evaluation to be made thoroughly, as well as the reviewing and rewriting of their regulations with the perspective of making SMR district heating feasible, the regulator needs resources – money and personnel – from somewhere. Demanding things without giving the resources to accomplish those changes is not constructive.

The premise where the regulator has an incentive to demand ever higher nuclear safety ("just to be on the safe side") needs to change as well. There is a point, for example, where further added nuclear safety makes a project unfeasible. This will then lead to some other energy source being used – which can then cause hundreds or even thousands of times more risk and harm for the public than the nuclear project would have caused. It is not clear at all that added nuclear safety, when it adds costs and uncertainty to projects, adds to overall safety of the population.

From the perspective of the safety and health of the public, this "alternative cost" should be considered more carefully when writing new or analysing current regulations. None of the current actors, STUK itself nor the nuclear energy utilities, are in a particularly good place to do this kind of wider analysis or questioning the implications of current regulation and legislation. STUK because it is problematic for them to question their own regulations, and nuclear utilities because it is in their best interest not to oppose or question the regulator, with whom they need a good working relationship, too much. It might be that we need an independent third party, which in turn would need the knowhow and resources, to tackle this topic of increasing the overall safety of our energy sector by pushing for more sensible and cost-effective regulations in the nuclear energy space. To be clear, this is not calling for less nuclear safety, but it is calling for more overall public safety.

What is happening abroad?

The UK Government has been taking concrete steps to enable getting SMRs into the market and help achieve their potential. Richard Harrington, the Government Minister for Business, Energy and Industrial Strategy, announced new policies in a Speech to the Nuclear Industries Association Conference on 7 December 2017[59].

First, better and earlier access to Regulators. Government has announced up to £7million for UK regulators to build the capability and capacity needed to assess and licence small reactor designs. This funding will also provide support for pre-licensing engagement between vendors and regulators.

Second, turn new developer's ideas into detailed designs. To help deliver this, over the next three years Government will be providing up to £44m ($56m) in R&D funding to support development of Generation IV advanced reactors.

Third, create the right market conditions to enable developers to bring new reactors to market. A crucial element is the need to demonstrate commercial viability – in particular, the ability of new designs and delivery mechanisms to attract investment and generate cost-competitive electricity.

In the UK Governments 2017 Clean Growth Strategy[60], they also confirmed £460million ($604m) of funding to support work in areas including future nuclear fuels, new nuclear manufacturing techniques, recycling and reprocessing, and advanced reactor design.

In December 2017, the Government announced a package of up to £44m ($56m) for R&D funding (£4m in phase 1 and, subject to government approval, up to £40m for phase 2, for 'advanced' modular reactors, and bids were invited for Phase 1 feasibility studies[61].

In June 2018, the UK government announced its "Industrial Strategy – Nuclear Sector Deal.[62]" It includes an ambitious £200m

59 https://www.gov.uk/government/speeches/nuclear-industry-association-nia-annual-conference-2017

60 https://www.gov.uk/government/publications/clean-growth-strategy

61 https://www.gov.uk/government/publications/nuclear-sector-deal/nuclear-sector-deal#fn:10

62 https://www.gov.uk/government/publications/nuclear-sector-deal

($262M) funding deal with the nuclear sector that could lead to a new generation of small modular reactors (SMRs) to be built at existing licensed nuclear sites.

Canada has also stated its willingness to have SMRs on the market. Canadian Nuclear Laboratories (CNL) started carrying out siting studies back in 2016. In 2017, a committee representing all three major political parties published a study, calling for the government to reaffirm its long-standing support for the nuclear sector, including the commercialization of SMRs. In 2018, Canada made a SMR strategy roadmap, which was published in late 2018[63].

In 2018, CNL received submissions four international and domestic small modular reactor (SMR) developers to build demonstration plants at a CNL-managed site. Also, New Brunswick committed to funding of CAD10 million (USD7.5 million) to help the New Brunswick Energy Solutions Corporation develop a nuclear research cluster in the province, and soon after, Advanced Reactor Concepts (ARC) and Moltex were announced as partners in the research cluster[64].

CNL also did a stakeholder study to find out what was needed of them regarding SMRs. Many emphasised **economic benefit, public acceptance, clean production of energy, safety, licensability, and reliability** as the requirements for a successful deployment of SMRs, as well as consistent, long-term political support. Canada is also interested in off-grid microreactors, as it has many remote communities and mining sites that rely on diesel-generators for their power needs.

Also in 2018, The United States, Canada, and Japan launched the Nuclear Innovation: Clean Energy (NICE) Future Initiative in Clean Energy Ministerial in Copenhagen, with more than dozen countries interested in joining[65]. In a nutshell, the purpose is to (rightfully) start acknowledging nuclear as a clean energy source – something that is often not done. Innovative nuclear systems will

63 https://smrroadmap.ca/

64 http://www.world-nuclear-news.org/NN-First-partner-announced-for-New-Brunswick-SMR-project-1007187.html

65 http://www.world-nuclear-news.org/V-Nuclear-Innovation-Clean-Energy-Future-22051801.html

play a critical role in world-wide decarbonisation, including use in many energy intensive applications such as:

- Desalination
- Industrial process heat
- Integrated nuclear-renewable systems
- Flexible electricity grids
- Hydrogen production
- Energy storage (thermal, electrical, or chemical).

Yes in my backyard? Siting SMRs

Heat, be it process heat for industry or district heating for buildings, is a local service, as heat is much harder to move long distances than electricity. This means that SMRs for district heating should be sited relatively near to population centres. Current large reactors have emergency- and evacuation zones around them, in case of an accident and radiation release. In Finland these are around 5 and 20 kilometres. Inside 5 km radius there should not be major population, schools, hospitals and so forth, and for the larger radius there needs to be evacuation plans made. But small reactors can be quite different in this respect. They have much smaller amount of fuel (radioactive material), they are lower capacity and can therefore be cooled down in an emergency easier, and they can be built underground as well, to name a few differences.

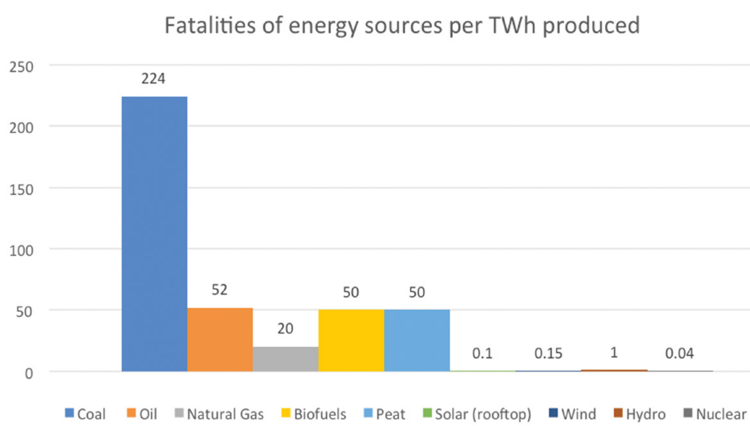


Figure 8 Fatalities of different energy source per TWh of energy produced.

Besides the fact that nuclear power has proven to be the safest energy source we know of, including the whole lifecycle[66], there remains two sides to siting SMRs near population. First is the regulatory/legislative side. Can the safety-zones be reduced in line with the inherently safer SMR designs? Currently, the emergency-zone of around 5 km around nuclear power plants is written mainly with large power stations in mind. This distance is based on STUK (the Finnish regulator) regulation, not law. **In principle, STUK could modify the emergency zone to be smaller if similar level of safety is achieved.** Indeed, as an independent regulator, STUK is the only one that can modify its regulations in this way[67].

Shrinking the emergency zone is a key feature for using SMRs for local heat production, and it is something that several designs aim to do. NuScale has stated that their Power Module only needs a safety zone that is the size of the plant premises, and the US regulator NRC has agreed that this is possible in principle, if the safety-case is proven. Many other SMR vendors are aiming to do the same.

The second side is public acceptance. What kind of solutions are people willing to accept "in their backyard" in the name of climate mitigation and staying warm? How can we bypass the decades of nuclear dread in people? Open discussion, with the introduction of the benefits – direct and indirect jobs, cleaner air, no constant truck traffic, more affordable heating, tax revenue etc – might be a better approach than trying harder and harder to convince people how nuclear is safe. We can learn from history that this makes most people only more afraid of nuclear, as it reminds them of risk and danger each time.

Small reactors also offer further flexibility in siting. They can be readily sited on barges or fixed offshore platforms, on (relatively small) islands, and/or dug underground. The SECURE presented earlier briefly was designed to be so safe that one could safely have it under a popular park in Helsinki.

66 See for example: Markandya, A., & Wilkinson, P. (2007). Electricity generation and health. The Lancet, 370(9591), 979–990. doi:10.1016/S0140-6736(07)61253-7, page 981

67 The emergency zone was previously (up to start of 2016) set by government decree but has since become a regulation set by STUK.

Overall, combustion-based energy production is much more harmful to people than any of the clean options, nuclear included. From this perspective, the main problems of SMRs are not related to actual safety or risks but more of factors like if they are allowed (legislation and regulation) or wanted (popular opinion of people living nearby a potential site). Ironically, if either of these becomes an insurmountable obstacle for SMRs, it is very likely that something more harmful, riskier and more expensive will take their place.

Going offshore

One real, but less discussed, option is to have reactors offshore, on barges or on fixed (towable) platforms. While this opens up a whole new can of worms when it comes to regulation, licencing, public discussion and many other aspects, it also offers an impressive list of potential benefits, some of which are discussed briefly below.

1. The whole power (or heat) plant can be assembled in modules in a shipyard and then towed to the site and fastened to the bottom if needed. This effectively moves the project from on-site construction (least productive way of making big things) to shipyard manufacturing (likely the most productive way of making big things). This can drop construction costs very significantly.

2. Less people live out there, so finding a place relatively near to a city might be easier. The offshore nuclear platform can be right by the shore or farther at sea.

3. There is abundance of cooling water available at sea, and the platform-powerplant can be designed to be very safe.

4. The platforms can be designed to hold standard reactors in different configurations and sizes, from small to medium sized reactors and from one to several per platform.

5. Heat can be transported for several kilometres without significant losses with highly insulated pipes.

Safeguards, Security and Waste

It is not in the scope of this report to discuss how small and potentially remotely located nuclear reactors would solve the requirements for adequate plant security and safeguards and how spent nuclear should or could be handled. It still bears mentioning that these matters need to be solved to prevent sabotage and theft of nuclear materials, to name a few. As vendors seek to have smaller exclusion zones and smaller staff operating the plants (which have smaller capacities and seek to keep their operations costs low per MWh produced), these matters only exacerbate, especially as there are increasing amounts of irresponsible and even malevolent people and organizations that seek to hinder any efforts to use nuclear energy to decarbonize energy systems.

Conclusions

SMRs offer great opportunities to decarbonize the district heating market in Finland and elsewhere, and to do it cost-effectively. In Finland, there are essentially two markets: half a dozen cities that could host one or several 200 to 400 MWt SMRs, either as heat-only or as CHP, and around 30-40 cities that could host smaller micro-reactors in the range of tens of megawatts of capacity. The hypothetical 24 MWt FinReactor was used in the case-studies as an example, and it was found usable in networks with around 200 GWh or more of annual demand.

Around half of current district heating is done with fossil fuels and peat, and almost all of this could be replaced with SMRs. First, this would mean that there would be no need to import bioenergy from elsewhere to replace fossil fuels. In addition, more of domestic biomass could be used for advanced biofuels, biochar, chemical industry feedstocks or other uses. Bioenergy would likely remain a key-source of energy in many smaller district heating networks with good local availability and for providing peak demand in winter months.

For Poland, emissions savings would be even higher, as there SMRs would replace baseload-coal almost exclusively, saving both in health costs due to air pollution as well as in emissions credits in the ETS. **A 400 MWt SMR would produce around 3 TWh of heat per year[68] and hence save around one million tons of CO_2 emissions per year, replacing coal in Poland.**

Regarding cost competitiveness, nuclear baseload heat will likely cost somewhere around 20 euros per MWh, which is comparatively low cost of low-carbon reliable heat. When running at lower load factors, the cost would increase, but with reasonable load factors, it should remain under 30 euros per MWh. In most cases, this would be a win-win: the district heating production costs would go down as well as the emissions. As a nation, we should think carefully if there would be better uses for that money saved, especially as it would be combined with lowering emissions.

68 Running 7,500 hours per year, or at 85 % load factor.

The biggest obstacles for SMRs are political, legislative and regulatory, and NIMBY (Not in my backyard). Not technical, economical or safety-related. The good news is that most of these can be mitigated actively at the political level. We need to allow this extremely promising technology to be used to it's full potential, and for faster and more efficient results, we should also encourage SMR-studies, R&D and pilot-projects to be undertaken. This is, after all, what leading on effective climate change mitigation means.

APPENDIX – Policy and action recommendations for Finland

Policy and legislation need to change to better enable small and advanced nuclear reactors to be used for effective decarbonization in Finland and elsewhere. Finland has a great opportunity to be one of the forerunners in setting a more allowing policy and regulation for new types of nuclear reactors and new types of uses for them. This needs to be kept in mind when thinking of policy: **how can we make it easier, faster, less risky and less expensive to use SMRs for decarbonization**. If we do not, we face the risk of far greater harm from climate change.

The economic and political risks regarding applying for Decision in Principle for a nuclear reactor need to be mitigated. Currently the process is too heavy for individual SMRs and induces unnecessary costs to decarbonizing our energy systems efficiently. This can be mitigated in many ways, but one of the most straightforward is for parties and individual politicians to openly state that they won't oppose (and/or will support) the use of SMRs for decarbonizing district heating as in the national interest of Finland doing its part in the climate mitigation efforts.

Permission for multiple reactors at once can, in theory, be applied even in today's legislation, but so far, they have not been successful when done. In theory, it is even possible to apply for multiple reactors in multiple sites. This would need to have one actor behind the applications, and likely multiple municipalities and municipal energy companies working together.

The regulation and licencing needs to be clear and stable regarding SMRs, otherwise there is little incentive for anyone to start the process of getting one. When preparing legislation, a potential operator of such a reactor should be an important part of the preparation process so that the right things are concentrated on and mitigated.

The emergency zone of 5 km, set by STUK regulation, is meant for large power plants. It needs to be modified so that SMRs can meet similar safety levels by other means, so that this zone can be shrunken accordingly. Many SMR designs aim to have this emergency zone to stop on the plant premises and still have similar safety level for the surrounding public. For district heating projects, this is a necessity.

For example, the subject of siting SMRs underground needs to be studied properly, as well as how to do overall safety analyses for SMRs and/or non-water reactors effectively, which all takes resources. Similarly, proving alternative ways to achieve a given level of safety needs to be feasible. For all of this, the regulator needs resources, as does the reactor vendors and/or nuclear operator.

Licencing reactors is now done for each reactor individually, and it is an expensive and lengthy process. This could be mitigated by **licencing the reactor design once** or by **allowing similar reactors to be licenced in series**. Of course, site-specific details need to be taken care of.

There is a case for looking at the overall and alternative risks posed by added and&/or heavy nuclear regulation. Nuclear has proven to be by far the safest way to produce energy, yet current legislation and regulations are so heavy that it is often easier and more feasible to build something else that doesn't suffer from similar regulation – leading to overall less public safety and lower public health. We might need a third party to mitigate this and to bring the wider public safety perspective to nuclear regulation as well. Not to call for less nuclear safety, but to call for more overall public safety.

Some designs allow for the reactor-core module to come prefuelled and/or be taken away after use for processing. Currently, Finnish nuclear legislation forbids the import or export of spent nuclear fuel – legislation which was written in 1990s to stop Loviisa NPP spent fuel exports to Russia. This legislation could be rewritten to allow for more flexibility regarding importing and exporting spent fuel while still keeping the original spirit of handling our nuclear waste responsibly.

Halting climate change demands rapid and deep decarbonization of our energy systems. Those energy systems go much beyond the electricity grid, and they also have distinct characteristics and demands. District heating is one of these systems. These local heating networks are currently served by combusting fuels in heat-only of combined heat and power (CHP) capable plants.

This study looks at the potential to deeply cut emissions in district heating networks with small nuclear reactors (SMRs) in the Finnish context, with a case study also included for Poland. What are the demand profiles of these networks, and how well they can be met with upcoming SMRs?

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