Sweden's future power and energy production scenarios

Project report ANItA project A1

Ane Håkansson[1], Simon Wakter[2], Staffan Qvist[2], Nils-Olov Jonsson[3], Erik Lundbom[4], Antti Rantakaulio[5], Ted Lind[6], Mats Johnson[7], Lena Oliver[8], Kyle Johnson[9],

1) Uppsala University, 2) Qvist Consulting ltd., 3) Inpoi, 4) Vattenfall AB, 5) Fortum Power and Heat Oy, 6) Uniper, 7) The Royal Institute of Technology, 8) Westinghouse Electric Sweden AB, 9) Studsvik Nuclear AB, 10)

Introduction

Sweden's future sustainable energy and power production system must be able to reliably deliver the mix of energy and power required by the planned developments of housing, industry, and transportation. Alternative forecasted energy and power consumption scenarios have been presented in analyses by e.g. the Swedish Energy Agency [1], Svenskt Näringsliv [2] and the Royal Swedish Academy of Engineering Sciences [3].

The first objective of this project was to assemble projected scenarios and decide on select scenarios that will be the reference against which coming projects within ANItA will be analysed regarding the nuclear part of the future sustainable energy. These research projects' research will consider SMRs for electric power production, SMRs for Nuclear-Renewable Hybrid Energy Systems, as well as SMRs designed purely for heat production. Numerous more-or-less mature SMR designs are presented by vendors and research institutes around the globe.

The second objective of this project was to define various performance indicators that were used to systematically establish the pros and cons of various SMR designs/types that have the potential to fulfil the selected scenarios of future Swedish needs for national energy and power production.

1. Considered scenarios for the future Swedish energy supply

The first objective of this project consists of two parts: first, to assemble scenario projections and second, to select a set of scenarios as the reference for the ANItAs analysis of the nuclear component of a future sustainable energy system. The ANItAs research programme will examine Small Modular Reactors (SMRs) for electricity generation, SMRs for Nuclear-Renewable Hybrid Energy Systems, and SMRs specifically designed for heat production.

It is widely recognized that predicting the demand for energy and electricity in the future is a complex task, as evidenced by numerous instances of overestimated consumption (as depicted in Figure 1 and Figure 2). However, there are also several examples of projections with relatively good accuracy, particularly those made within a 10-to-15-year horizon. A survey of electricity demand projections conducted by the North European Energy Perspectives Project (NEPP) arrived at the following conclusion [4]:

"By and large all official forecasts and scenarios for electricity use development made in Sweden during the last 50 years, has had a relatively good accuracy in the 10 - 15-year term. That also applies to the (subsequently heavily criticized) forecasts made around 1970. The accuracy in the longer term, i.e., in two to four decades' time, however, has been much worse. It certainly also applies to our scenarios. The uncertainty in the scenarios' development beyond 2030, and especially up to 2050, should therefore be considered large."

It is therefore advisable to keep these findings in mind when evaluating demand projections and trajectories.

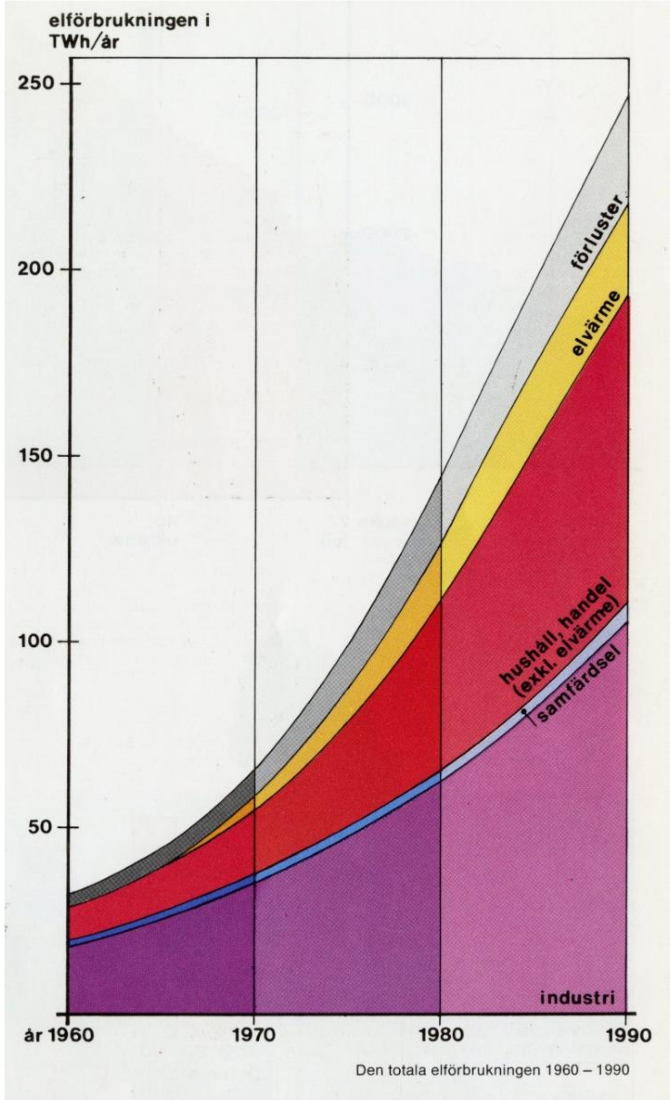

Figure 1. Estimate of future electricity consumption: around 250 TWh in 1990 was estimated in this prognosis from Centrala Driftledningen (CDL) in 1972.

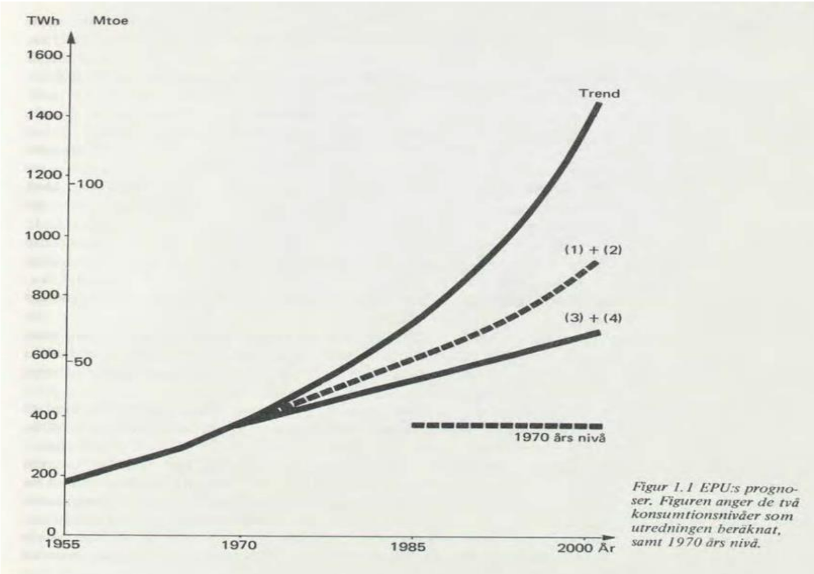

Figure 3. Three demand trajectories, as presented by the 'Energy prognosis inquiry' (Energiprognosutredningen, EPU) in the Swedish Government Official Report, SOU 1974:64.

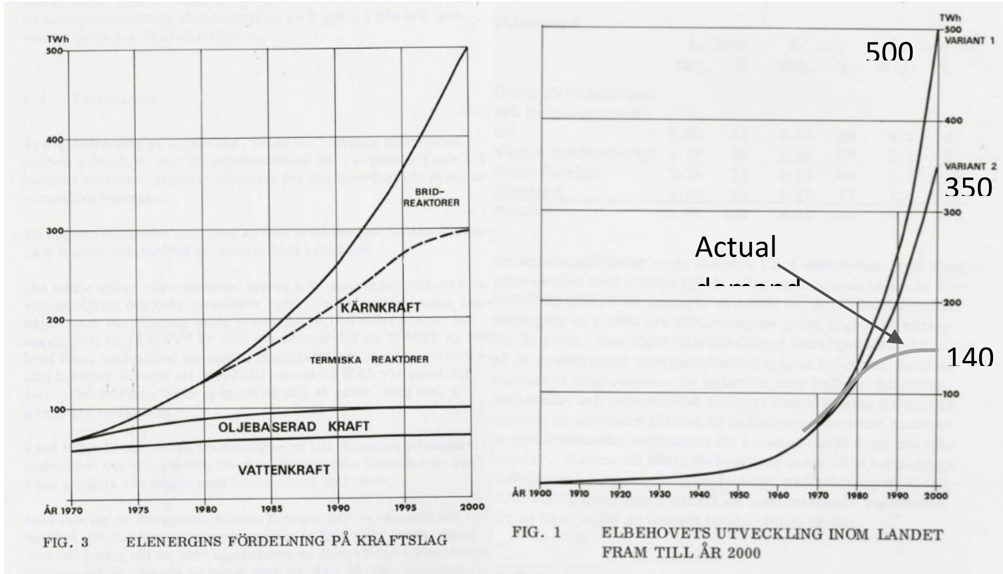

Figure 2. Projected Demand Trajectories from 1967 - The government's energy committee (right) forecasted a demand of 500 TWh of power by the year 2000. However, actual demand during the 2000s was around 140 TWh, as indicated by the green curve added to the two trajectories in the right image.

In addition to the aforementioned projections, there are also several "low scenario" projections that exhibit relatively high accuracy over a longer period, even extending several decades into the future. The lower demand trajectory [5] (represented by scenarios 3 and 4) in Figure 3 displays the total demand and is relatively consistent with the current total primary energy consumption, which was recorded at 508 TWh in the year 2022 [6].

The energy consumption in Sweden has remained static for approximately three decades, while global energy demand has increased by 60% and global electricity demand has doubled over the same period. It is anticipated that the demand for electricity in Sweden will experience significant growth, potentially surpassing 300 TWh by 2050, from its current level of approximately 140 TWh. As a result of an increasing number of industry transition projects, demand projections from various stakeholders are also increasing rapidly. However, there is still a substantial spread in demand trajectories, as illustrated in Figure 4.

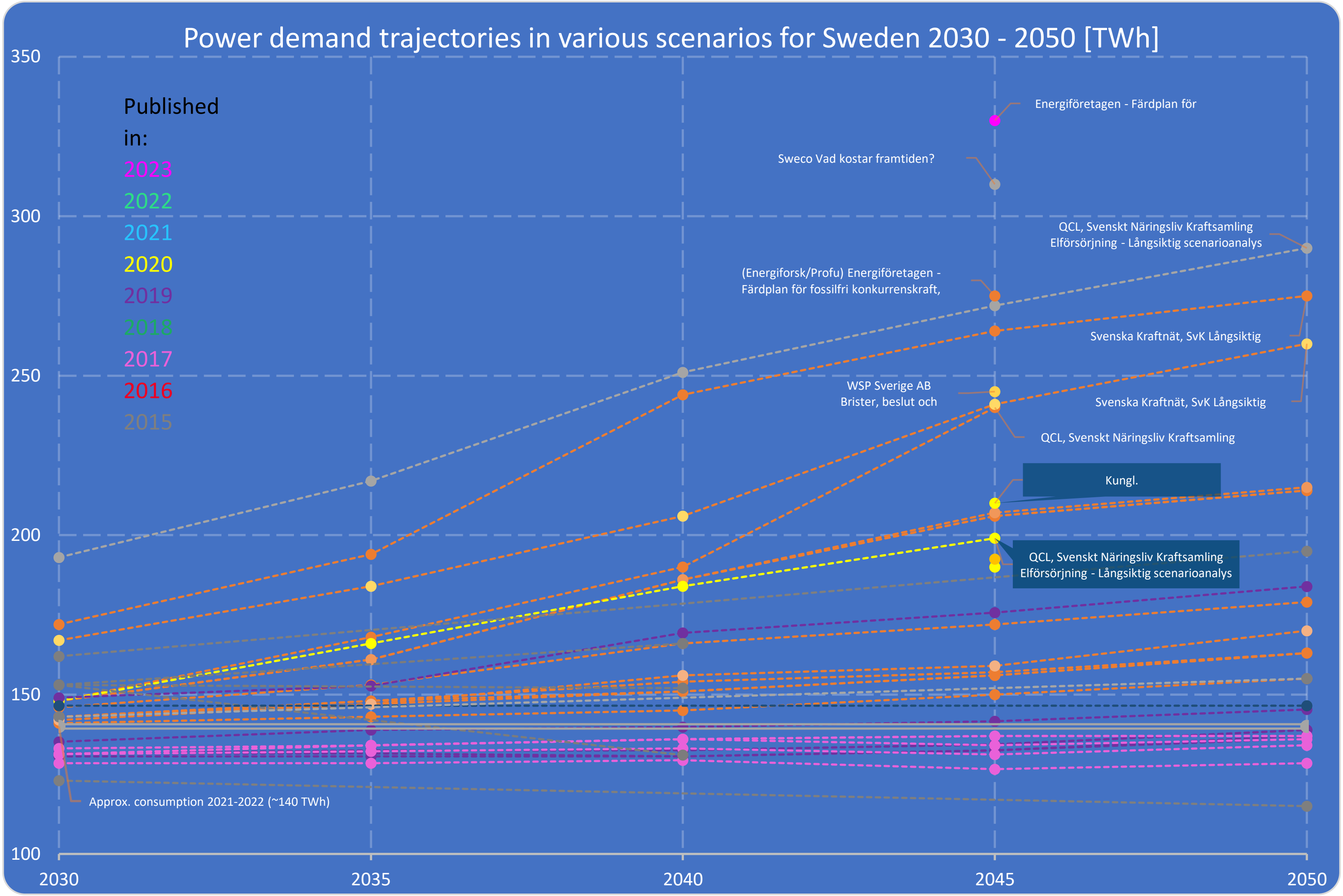

Figure 4. Power demand trajectories across different scenarios for Sweden. The scenarios were published between 2015 and 2023, covering the period up until 2050.

Table 1. Reports and studies with electricity demand trajectories studied for the project.

Author/publisher	Report name	Scenario name	Published	2030	2035	2040	2045	2050
QCL, Svenskt Näringsliv	Kraftsamling Elförsörjning - Långsiktig scenarioanalys	200 TWh	2020	148	166	184	199	
QCL, Svenskt Näringsliv	Kraftsamling Elförsörjning - Långsiktig scenarioanalys	240 TWh	2021	148	168	190	240	
QCL, Svenskt Näringsliv	Kraftsamling Elförsörjning - Långsiktig scenarioanalys	290 TWh	2022	193	217	251	272	290
Kungl. Ingenjörsvetenskapsakademien, IVA	Så når Sverige klimatmålen - syntesrapport		2020				200-220	
Kungl. Ingenjörsvetenskapsakademien, IVA	Vägval el		2016	128-165	128-165	128-165	128-165	128-165
Kungl. Ingenjörsvetenskapsakademien, IVA	Så klarar det svenska energisystemet klimatmålen - delrapport		2019				180-205	
Energimyndigheten	Energimyndigheten - Scenarier över Sveriges energisystem 2020	Referens EU	2021	143	148	151	156	163
		Lägre BNP	2021	141	143	145	150	155
		Lägre energipriser	2021	143	148	154	157	163
		Ytterligare åtgärder	2021	143	147	151	156	163

		Elektrifiering	2021	148	161	186	206	214
		Elektrifiering utan ny kärnkraft	2021	148	161	186	206	214
		Elektrifiering med lägre produktionskostnader för kärnkraft	2021	148	161	186	207	215
Energimyndigheten	Energimyndigheten - Scenarier över Sveriges energisystem 2018	Referens EU	2019	132	132	133	134	139
		Lägre BNP	2019	132	132	131	132	137
		Lägre energipriser	2019	135	139	140	142	145
		Högre elektrifiering	2019	149	153	169	176	184
		Varmare klimat	2019	131	131	131	133	136
		Reduktionsplikt	2019	132	132	133	134	139
Energimyndigheten	Energimyndigheten - Scenarier över Sveriges energisystem 2016	Referens EU	2017	131	132	133	131	134
		Hög BNP	2017	133	134	136	134	136
		Lågt pris+18TWh	2017	131	134	136	137	137
		Höga fossilpriser	2017	129	129	129	127	129
		Lågt elpris	2017	131	134	136	137	137
Svenska Kraftnät, SvK	Långsiktig marknadsanalys 2021	Småskaligt förnybart (SF)	2021	142	147	156	159	170
		Färdplaner mixat (FM)	2021	146	153	166	172	179

		Elektrifiering planerbart (EP)	2021	167	184	206	241	260
		Elektrifiering förnybart (EF)	2021	172	194	244	264	275
Svenska Kraftnät, SvK	Långsiktig marknadsanalys 2018	2040 Låg	2018	153		131		
		2040 Ref	2018	153		152		
		2040 Hög	2018	153		166		
North European Power Perspectives, NEPP	20 Resultat och slutsatser om elanvändningen i Sverige	Hög-scenario	2015	162				195
		Referens-scenario	2015	143				155
		Låg-scenario	2015	123				115
(NEPP)	Energiföretagen - Färdplan för fossilfri konkurrenskraft, elbranschen	NEPP	2020				190	
(Energiforsk/Profu)	Energiföretagen - Färdplan för fossilfri konkurrenskraft, elbranschen		2021				240-310	
	Energiföretagen - Färdplan för fossilfri konkurrenskraft, elbranschen		2023				330	
Energiforsk/Profu/NEPP	Scenarier för energi och klimat - Rapport 2021:771	Klimatscenario (NEPP)	2021				190	
WSP Sverige AB	Brister, beslut och balans i elsystemet – så kan ekvationen gå ihop		2021				215-275	

Sweco	Vad kostar framtiden? Elnätsinvesteringar för ett fossilfritt Sverige till 2045	2022	310	
Svensk Vindenergi/Svensk Solenergi/Power Circle/Vätgas Sverige	Antaganden om Sveriges elanvändning 2050	2021		500

The primary factor driving the increase in electricity demand is the transition away from fossil fuels. This shift often results in decreased energy consumption, such as when vehicles with internal combustion engines are substituted with more efficient battery-electric vehicles. The prediction of energy and electricity demand is challenging and influenced by various factors, particularly in the longer term. Nonetheless, certain key factors and projects, such as the transformation of the steel and iron manufacturing industry, new demands (e.g. new data centres or battery plants), and the transition of the transportation sector, will play a crucial role in shaping the future of Swedish power demand. It is anticipated that the demand for electrical heating in both residential and commercial buildings will decline due to advancements in building efficiency, the substitution of direct electrical heating with alternative heating methods, and the superiority of newly developed heat pumps in terms of efficiency in comparison to their older counterparts. One of the key determinants of future electricity demand is the improvement in efficiency.

In addition to the aforementioned challenges, other significant factors include shifts in behaviour such as altered consumption habits resulting from the impact of the coronavirus, as well as demographic growth and economic conditions. The NEPP [7] has identified several determinants of future electricity demand. A summary of the most critical factors is presented in the table 2.

Table 2. A collection of the most important factors and environmental variables that impact the evolution of the e-turnover, both presently and in the long term, has been compiled. A large check mark indicates a substantial impact, a small check mark indicates a moderate influence, and the absence of a check mark indicates a minimal impact from that particular factor.

	Residential demand	Services	Heating	District heating	Industry	Transportation
Population growth	X	X	X	x	x	x
Economic development (GDP etc.)	X	X			X	x
Structural changes (with consumers or in production)	x	x	x	x	X	X
Technological development	x	x	x	x	X	X
Energy efficiency	X	X	X	x	X	
Volume factors (number, area, production volume)	X	X	x	x	X	X
Political goals & incentives	x	x	x	X	x	X
Electricity prices trends (also relative to other energy sources)			x	X	X	
Consumer preferences	X	X	X			X

1.1 The fifth stage – a fossil free economy

Sweden can be said to have gone through four previous stages of electrification in its history:

- Early electrification
- Expansion of large-scale hydro power
- Expansion of nuclear energy
- Expansion of large-scale wind power

As of today, Sweden's final energy consumption consists of approximately 80 TWh of petroleum products (primarily in the transportation sector), 12-13 TWh of coal and coke (mainly in the steel industry), and 10-12 TWh of fossil gas (primarily in the industrial sector. The country is now entering a fifth stage of electrification, in which the reliance on fossil fuels is being phased out. This will occur through the transition to electric transportation (replacing petroleum products), the use of arc furnaces in the steel industry (replacing coal and coke), and the utilization of fossil-free hydrogen or hydrogen derivatives in other industries (replacing fossil gas and petroleum products). Sweden aims to achieve economic growth while eliminating greenhouse gas emissions from the entire economy, which is expected to result in an increase in electricity demand from the current 130-140 TWh/year to at least 290 TWh/year by 2050.

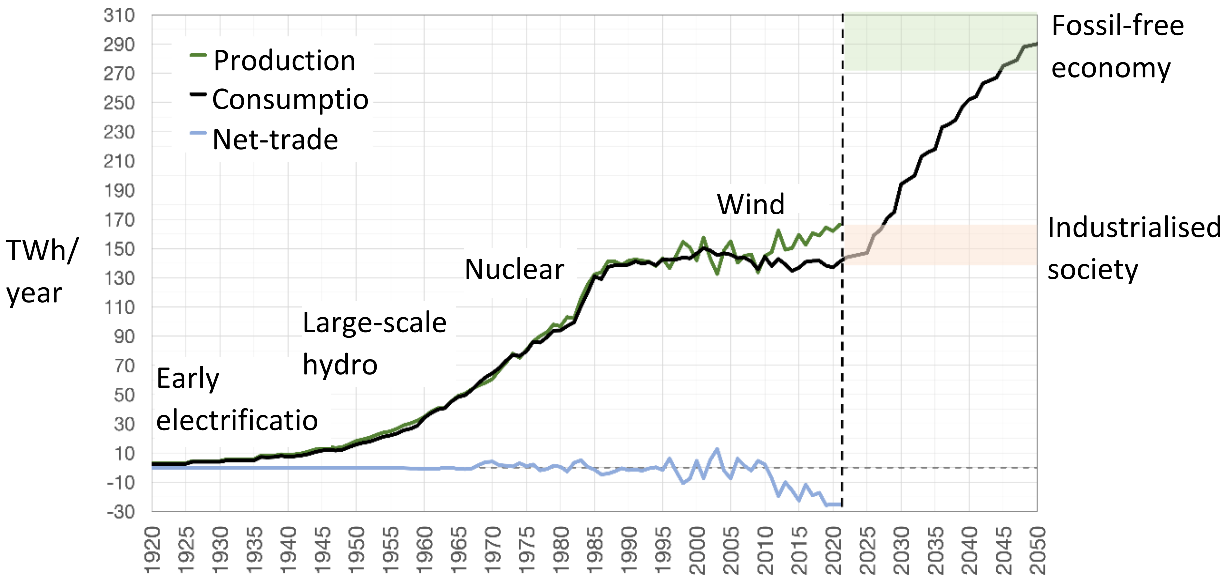

Figure 6. Sweden's five stages of electrification.

The projection [8] in Figure 6 is not a forecast for what is likely to happen but should rather be interpreted as a desirable future scenario for modelling purposes.

1.2 Heating scenarios

The energy sector plays a crucial role in addressing the challenge of climate change, however, energy encompasses more than just electricity, see figure 7. Electricity only accounts for a mere 20% of the global final energy consumption. Heat is the largest energy end-use – it constitutes 50% of the world's total energy consumption and is responsible for 40% of global carbon dioxide emissions, see figure 8.

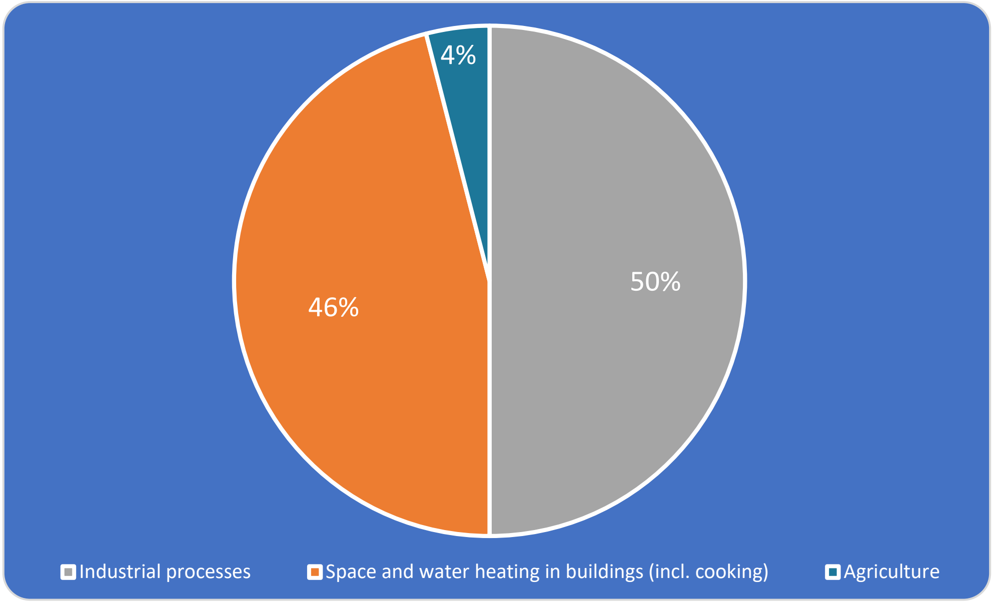

Figure 5. 2018 data from the IEA shows half of total heat used for industrial processes and half for building heating, cooking and a small part for greenhouse heating in agriculture.

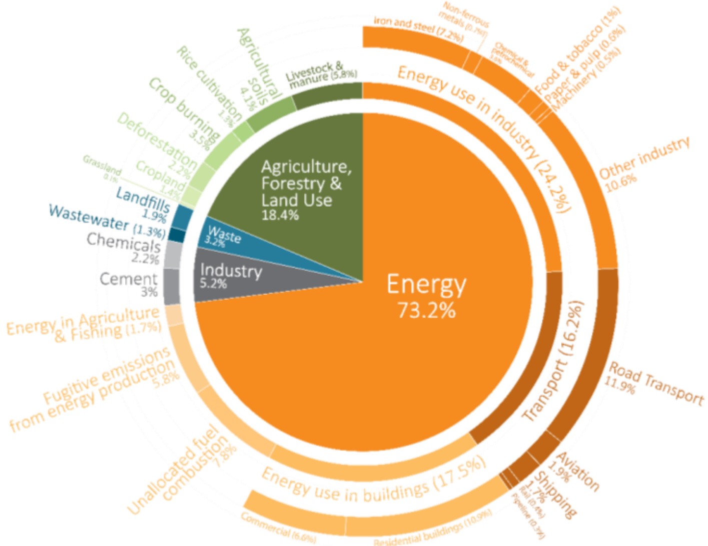

Figure 6. Global greenhouse gas emissions were 49.4 billion tonnes CO2eq in 2016, per data from Climate Watch and WRI (2020).

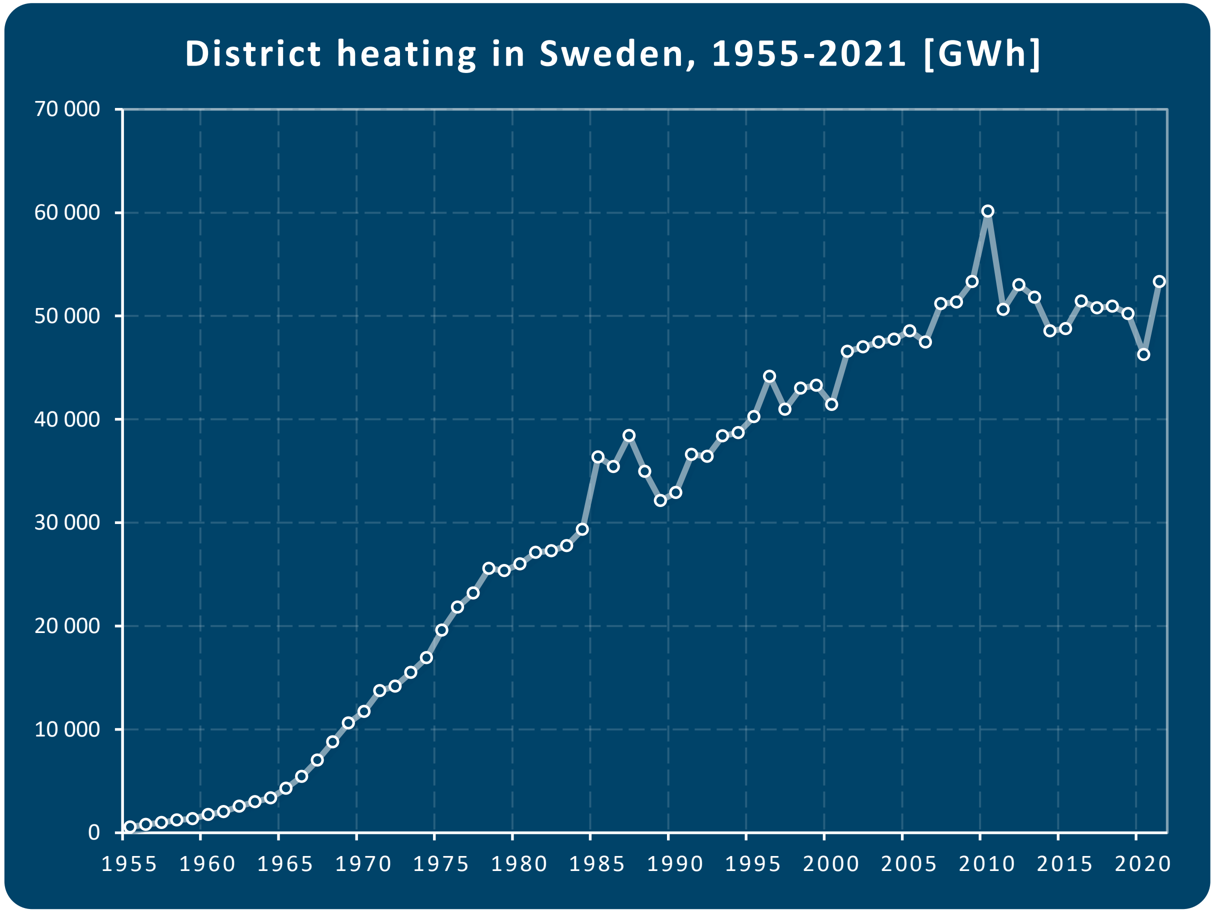

Figure 7. Total district heating energy delivered to Swedish consumers between 1955 and 2021, in GWh.

District heating made up 47 TWh in 2020, a significant share of Sweden's total energy consumption. It grew rapidly from 1960s to early 2000s but has remained stable in recent decades, see figure 9.

The energy supplied for district heat production between 1970 and 2021 is depicted in Figure 10 (see next page). The source of fuel for district heating is primarily biomass, with a significant portion still provided by fossil fuels, mainly in the form of fossil plastics from waste incineration. Despite its preferable nature as a source of energy for waste that cannot be recycled, this fuel source must eventually be replaced. As per a 2017 report [9] by Energiforsk, increasing competition for biomass is expected to result in more conflicts of interest. Biomass will play a crucial role in meeting climate change objectives, but sustainable biomass is a limited resource and its optimal utilization is not clear. The report did not evaluate the use of biomass as a feedstock for the petrochemical industry.

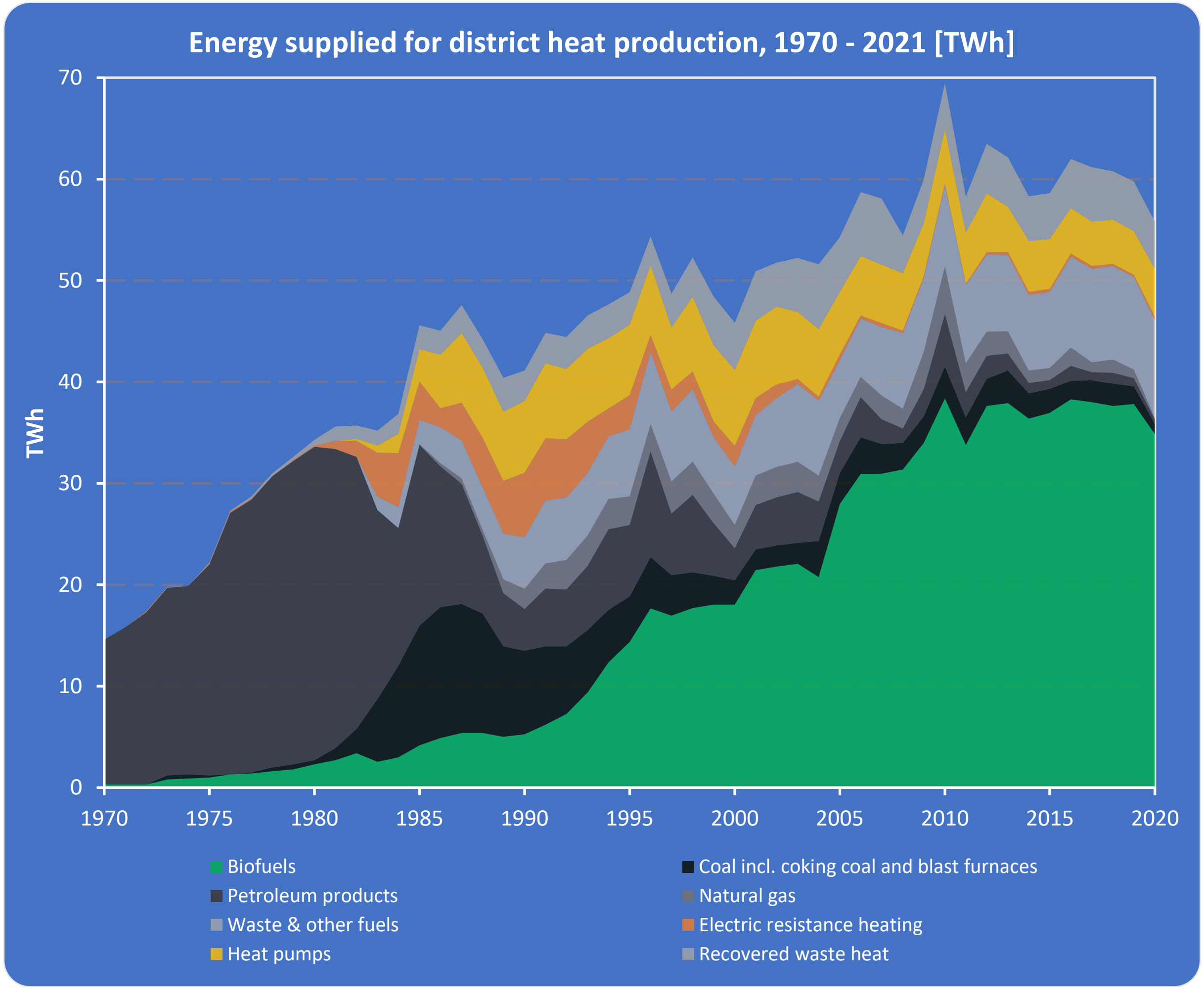

Figure 8. Energy supplied for district heat production, 1970 - 2021 in TWh.

District heating can be used not only for heating of residential or service buildings, but also in industry. According to a 2015 report from Energiforsk there is significant potential for district heating in industrial processes. The report [10] showcases two successful examples of district heating implementation in industry, at Toyota Material Handling Europe and Swerock's concrete plant in Länna, which replaced petroleum gas and oil-fired boilers, respectively. The report highlights that not all industrial processes are suitable for district heating, but that there are many that can benefit from it, with lower CO2 emissions and energy consumption, and that the cooperation of the district heating supplier, industrial customers, and other involved parties is crucial. The report also notes that district heating competition with low electricity and oil prices and low taxes on fossil fuels calls for favourable contract terms in terms of price, investment, and risk. There is also a 2016 handbook for district heating applications in industrial processes [11].

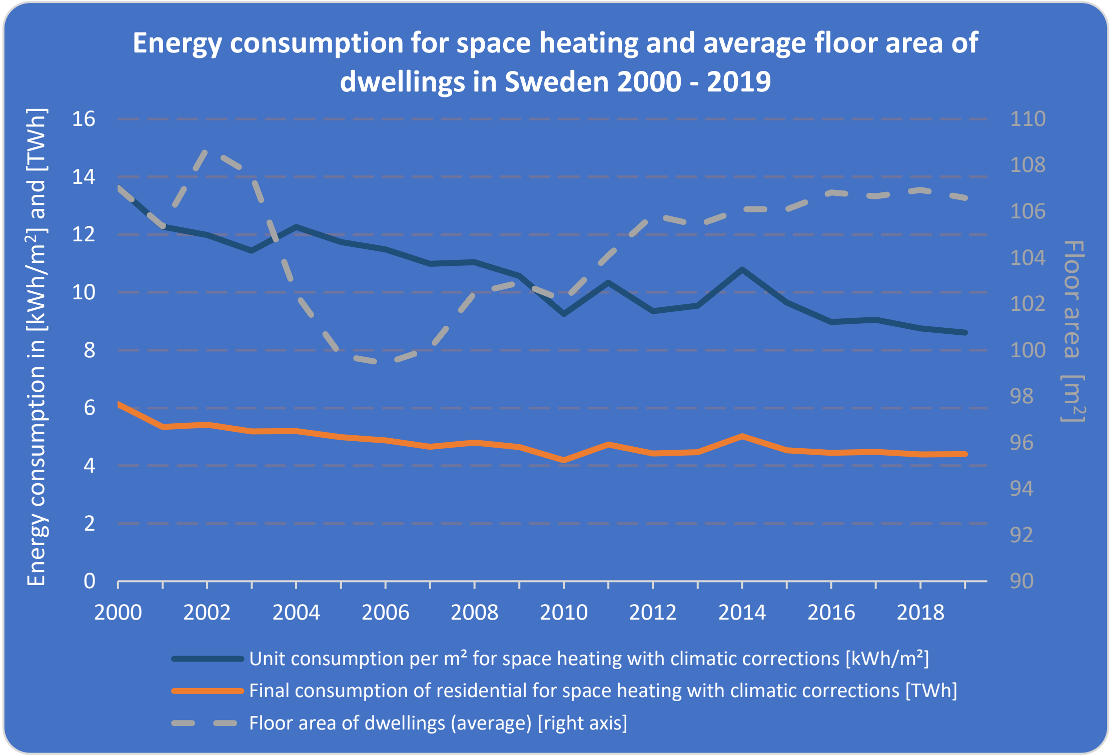

Figure 11. Energy consumption for space heating and average floor area of dwellings in Sweden 2000 – 2019. Consumption per square meter has decreased while floor area per dwelling has remained relatively stable, resulting in decrease consumption of residential units for space heating. Data with climatic corrections from the Swedish Energy Agency (STEM, Statens Energimyndighet) through Odyssee-Mure [12].

Despite an increase in population, the amount of district heating delivered to Swedish consumers has remained relatively stable, primarily due to energy efficiency improvements, see Figure 11. The potential for expanding the use of district heating to industrial processes remains significant.

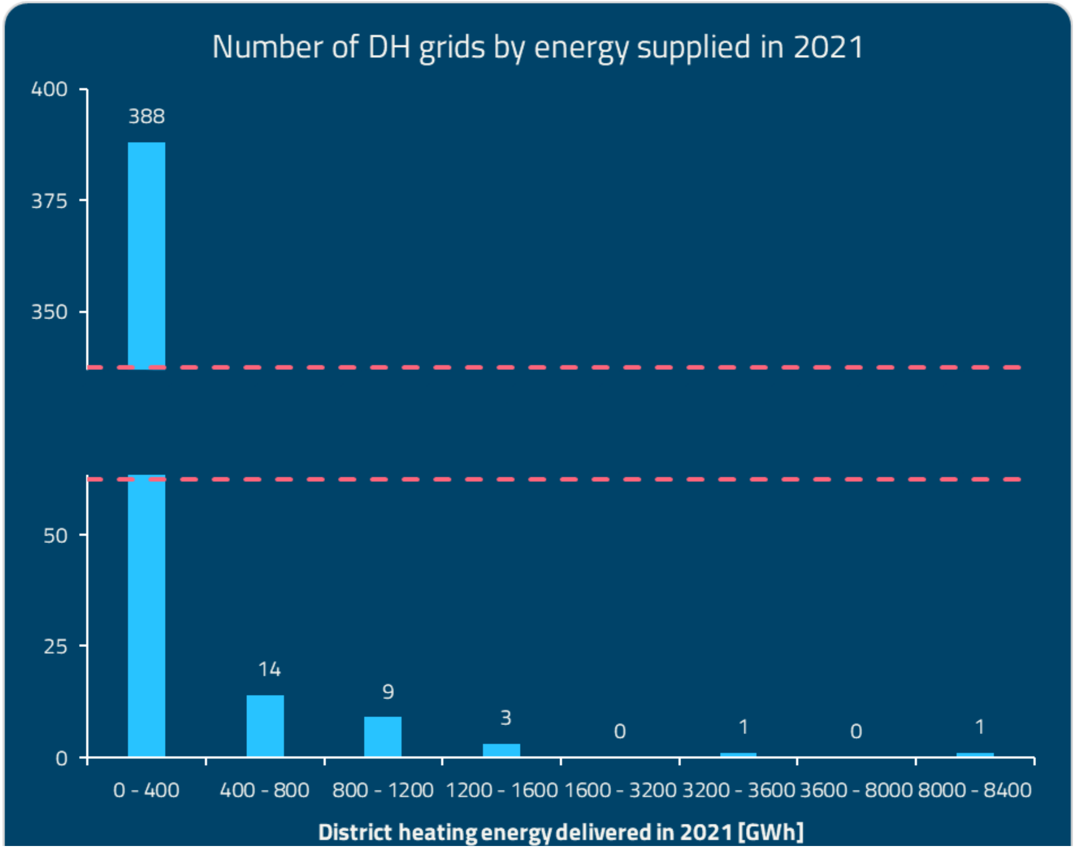

Figure 9. Histogram of number of DH grids by energy supplied in 2021 in GWh. Energy supplied is divided in bins where bins with zero-values have been joined for readability. The y-axis has been truncated for readability.

District heating grid size is crucial in order to evaluate district heating demand and its applicability for nuclear district heating**.** Figure 9 shows the number of district heating grids by size. The 14 largest district heating networks in Sweden account for around 50 % of the total district heating energy demand.

Figure 10 and Figure 11 on the following pages show the heating energy delivered per district heating network in 2021, divided by energy supply by grids over 100 GWh and under 100 GWh respectively. Only a few district heating grids are suitable for SMRs, which may have a nameplate electric power from 50 MW_e (NuScale recent NRC approval and codification, which will be uprated to 77 MW_e) up to almost 500 MW_e (in the case of Rolls-Royce SMR). This equals a thermal power around 150 MW_{th} to 1500 MW_{th}, which is a significant amount of heat for almost any district heat network, even when considering cogeneration with only limited energy and power going to district heating. Microreactors with a smaller output would be more suitable and some microreactors would potentially be suitable to heat and/or power both small towns or villages and even single sites such as small factory.

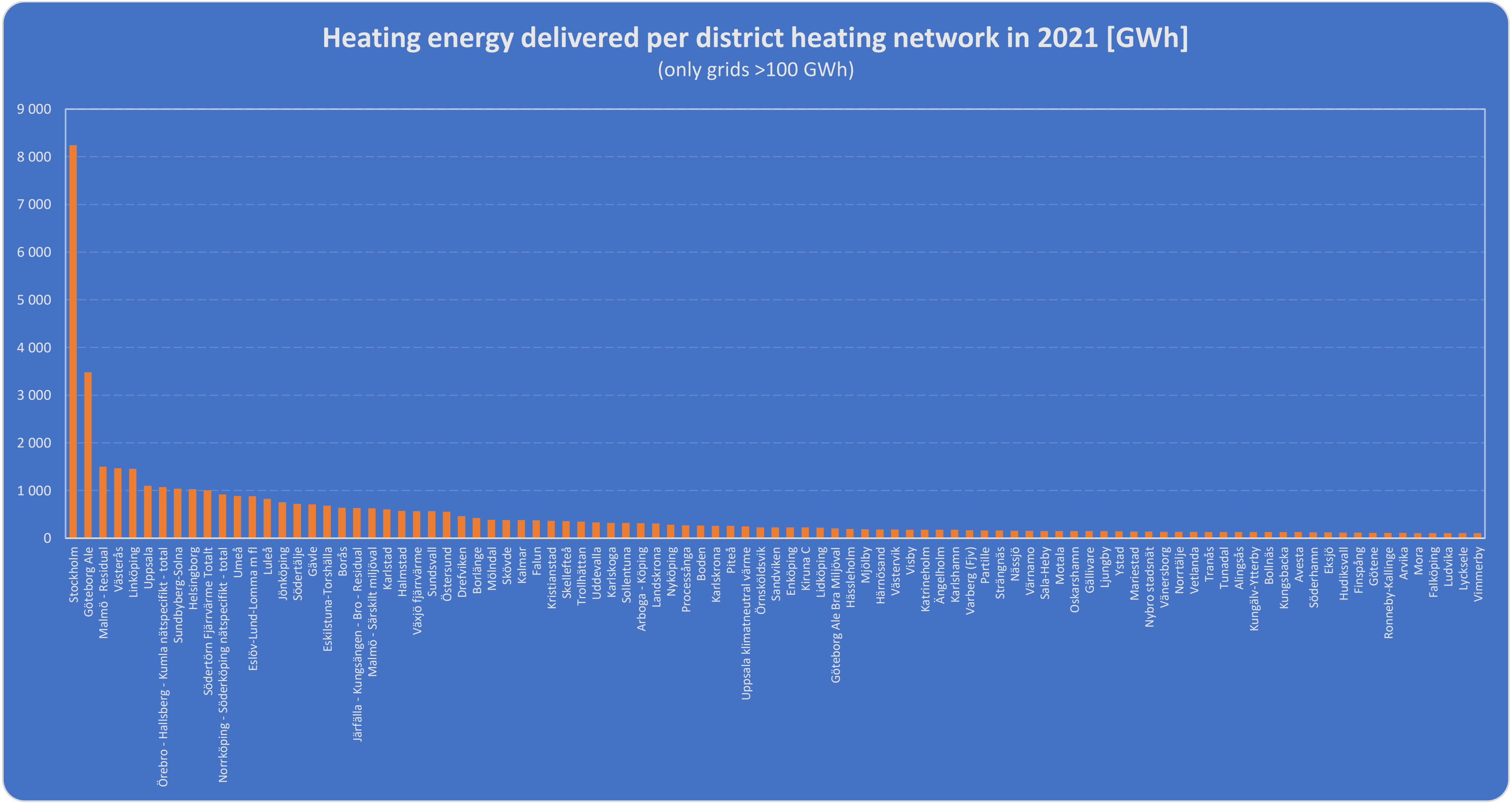

Figure 10. Heating energy delivered per grid in 2021 for a total of 95 grids with more than 100 MWh energy delivered. For practical and technical reasons there is some overlap in the reported numbers between different grids (e.g. several of the smallest grids are reported separately as subsections of larger grids, such as environmental parameters).

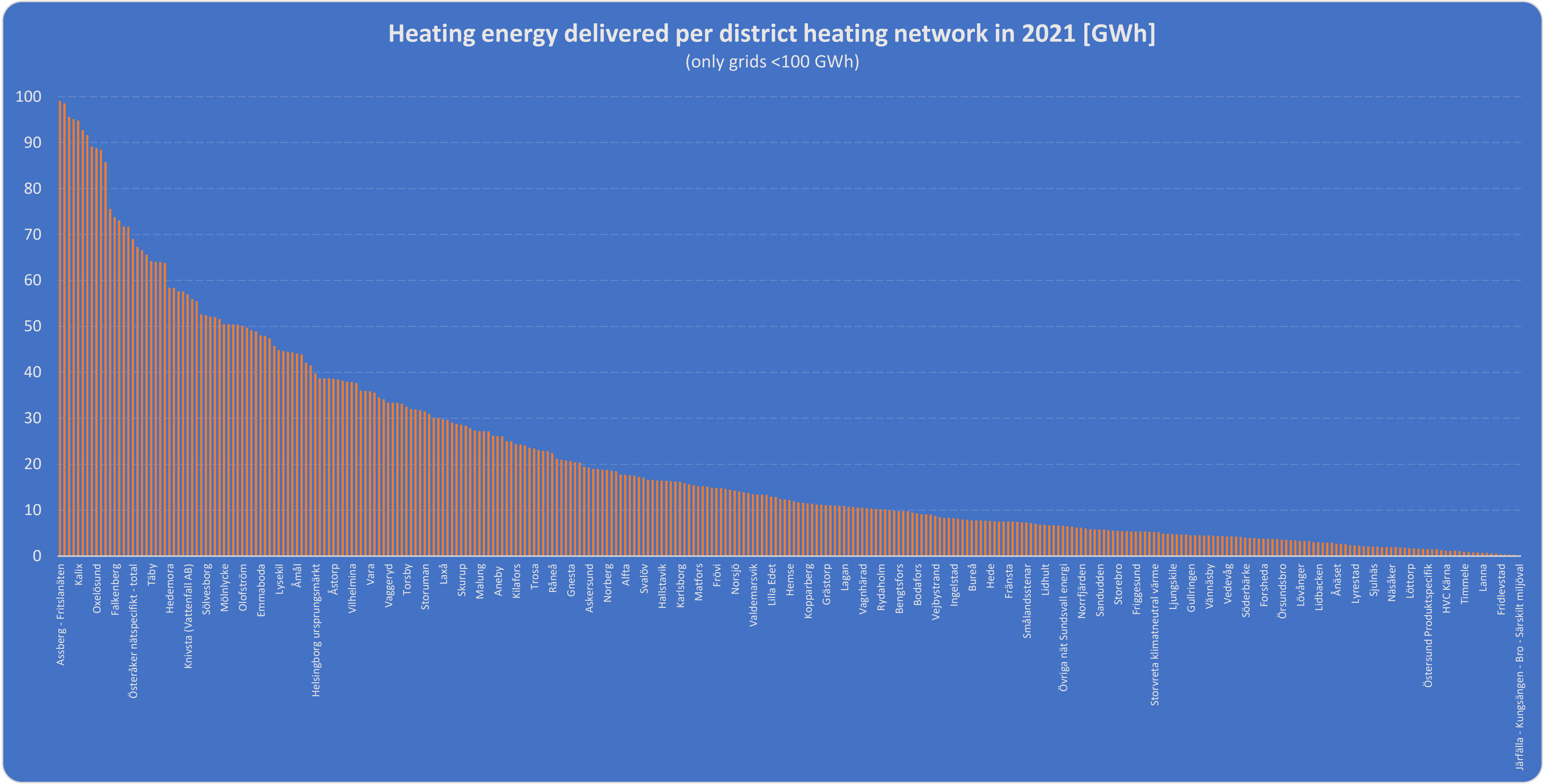

Figure 11. Heating energy delivered per DH grid in Sweden in 2021 for a total of 321 grids with less than 100 MWh energy delivered. For practical and technical reasons there is some overlap in the reported numbers between different grids (e.g. several of the smallest grids are reported separately as subsections of larger grids, such as environmental parameters).

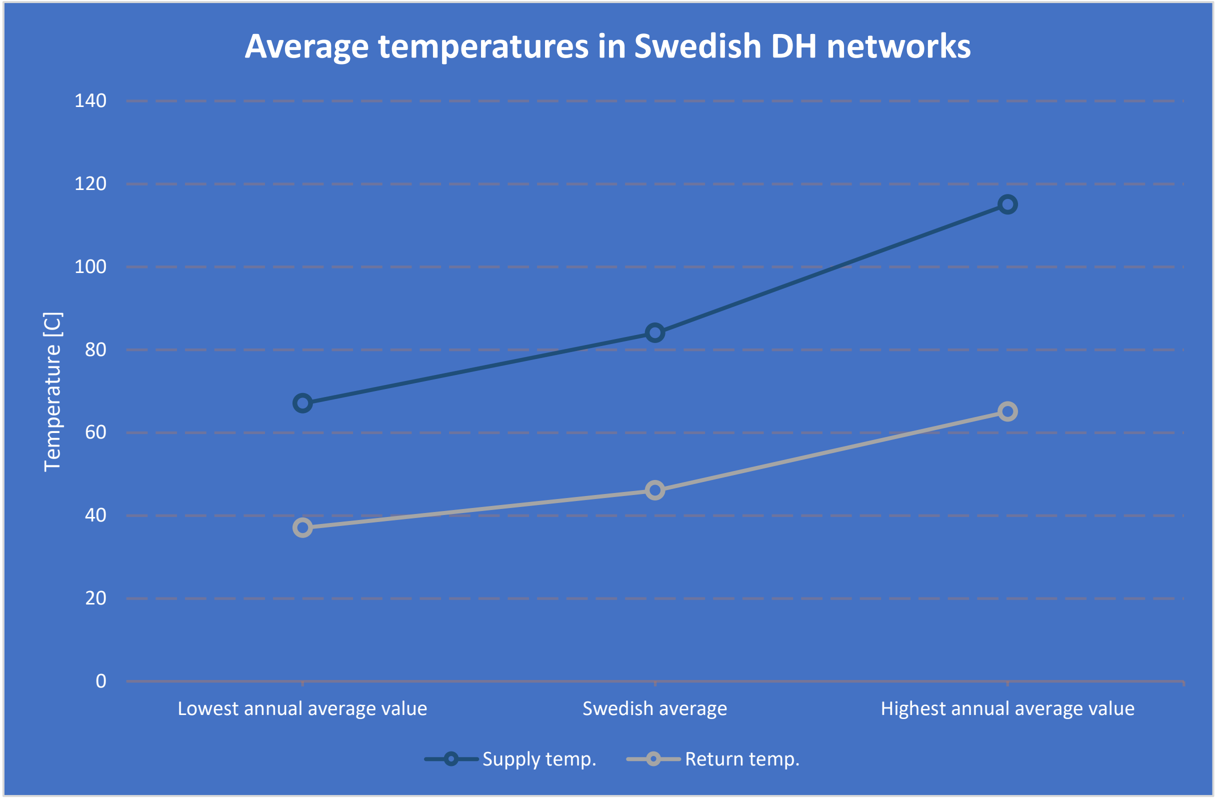

Figure 12. Annual average temperatures in district heating grids – showing lowest, highest, and average values for 201 grids (FVB, 2021). The average supply and return temperature are 84 °C and 46 °C, respectively.

In addition to district heating network size it is important to consider the temperature and variability of district heating networks as well. Figure 15 shows annual average temperatures in Swedish district heating networks. The average temperature for supply and return water is 84 °C and 46 °C, respectively. As lower temperatures carry a number of advantages (e.g. lower losses and the possibility of utilising more waste heat from different sources) there is a clear trend towards "fourth generation" district heating and lower temperatures overall. Future temperatures for supply and return water could decrease to around 55 °C and 25 – 20 °C respectively.

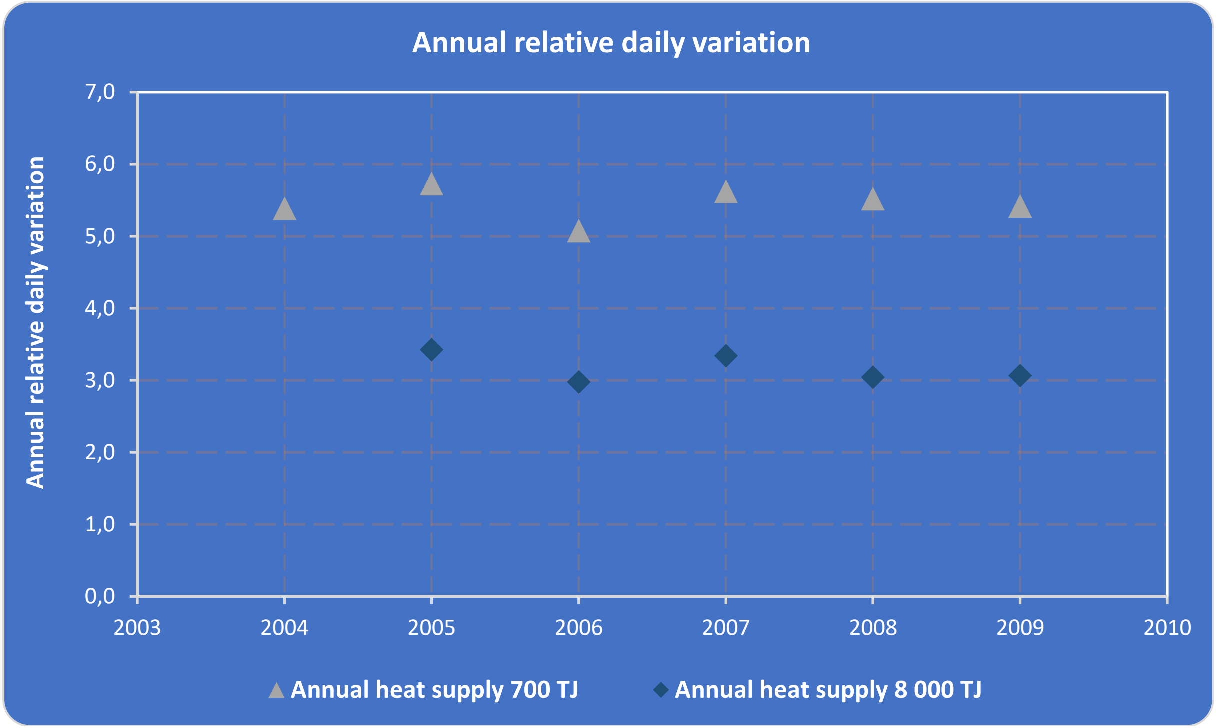

Figure 13. Annual relative daily variation between 2004/05 and 2009 for two Swedish district heating systems with an annual heat supply of approximately 700 TJ and 8000 TJ respectively. Adapted from Gadd & Werner, 2013 [14].

District heating reactors will be influenced by the temperature range of the network. According to a 2019 report [13], the maximum output temperature on the secondary side should be 90 – 120 °C, depending on the network structure and intended use. Since the reactor is connected to the network through heat exchangers, the operating temperature must be higher than 100 °C which requires operation at elevated pressure. Temperatures for district heating can be achieved at below 1 MPa pressure. This pressure only requires a reactor vessel a few centimetres thick, which leads to lower manufacturing costs, simpler quality control and a wider supply of industrial companies. The lower operating temperature also reduces the energy stored in the primary circuit and the required reactor containment. Small reactors intended only for district heating could potentially have several further advantages which would make them suitable for district heat applications. An example of an SMR for district heating purposes can be found in Finland where VTT are currently working on the first phase of development for that purpose[1].

Another aspect that must be observed is the variability of the heating power. This daily, weekly, monthly, seasonal land yearly variation can be significant. Figure 16 shows annual relative daily variation for two Swedish district heating networks with an annual heat supply of approximately

[1] See e.g. https://www.euronuclear.org/news/vtt-smr-district-heating/

700 TJ and 8 000 TJ (194 and 2 222 GWh) respectively. Smaller district heating systems can intuitively be expected to exhibit greater variations but variations are also highly dependent on the heat users in different systems, e.g. a system with many multi-family houses and little industry will behave differently to one with only single houses and more industry connected. According to a 2013 paper by Gadd & Werner [14] the average annual relative variation was estimated to 4.5 % for the 20 district heating systems evaluated, while the average annual relative seasonal variation was 24 %. The magnitude of the annual relative daily variation is thus small in comparison to seasonal heat load variations.

Gadd & Werner also found that the size of heat storage necessary to eliminate daily heat load variations is around 17% of the average daily heat supplied, or 0.05 % of annual heat supplied. They found that existing heat storages installed in district heating systems in Sweden are on average three times greater than required to eliminate daily heat load variations. According to their paper, for each TJ of heat supplied the annual average heat load becomes 32 kW, so with 3.6 h of operation (15 % of 25 h), this will give a demand for storing 410 MJ. Assuming a temperature difference of 40 °C for the heat storage, the heat storage size to eliminate daily variations is estimated to 2.5 m^3 per TJ (9 m^3/GWh) supplied heat annually.

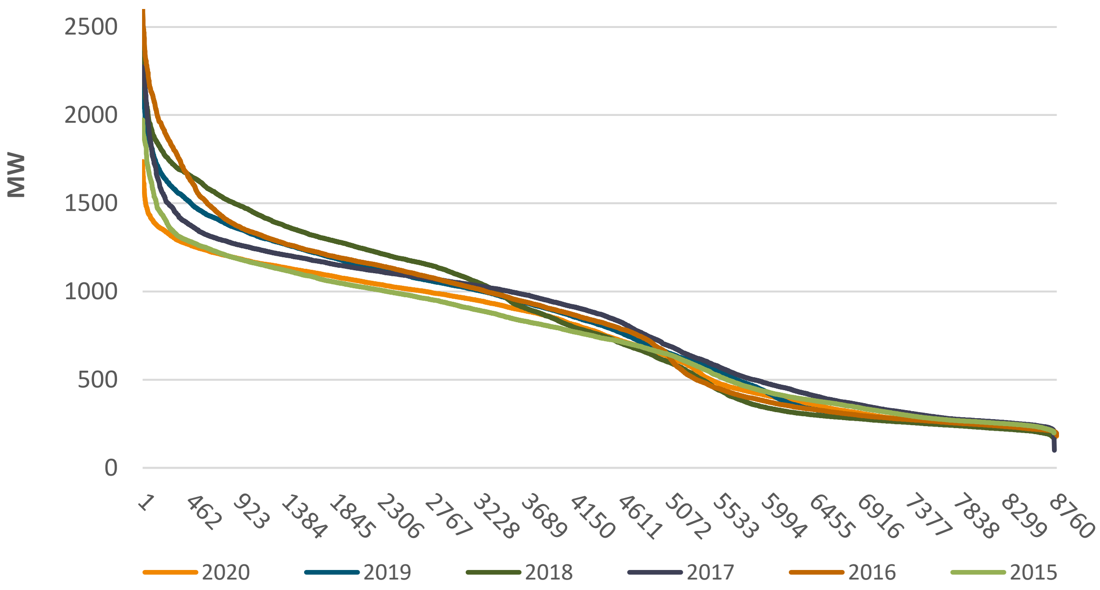

Figure 14. District heating production 2015 to 2020, Helen Oy, Helsinki.

Figure 18, from a 2022 report [15] from Energiforsk, show the high annual and seasonal variability. As can be observed from the graphs the winter peaks can be around ten times higher than the summer demand. Some estimates indicate that it is possible to remove all or almost all seasonal variation with a storage equal to around 25 % of annual heat energy demand.

19 shows district heating demand trajectories across various scenarios for Sweden 2030 – 2050. All trajectories fall roughly within the range of 55 to 65 TWh.

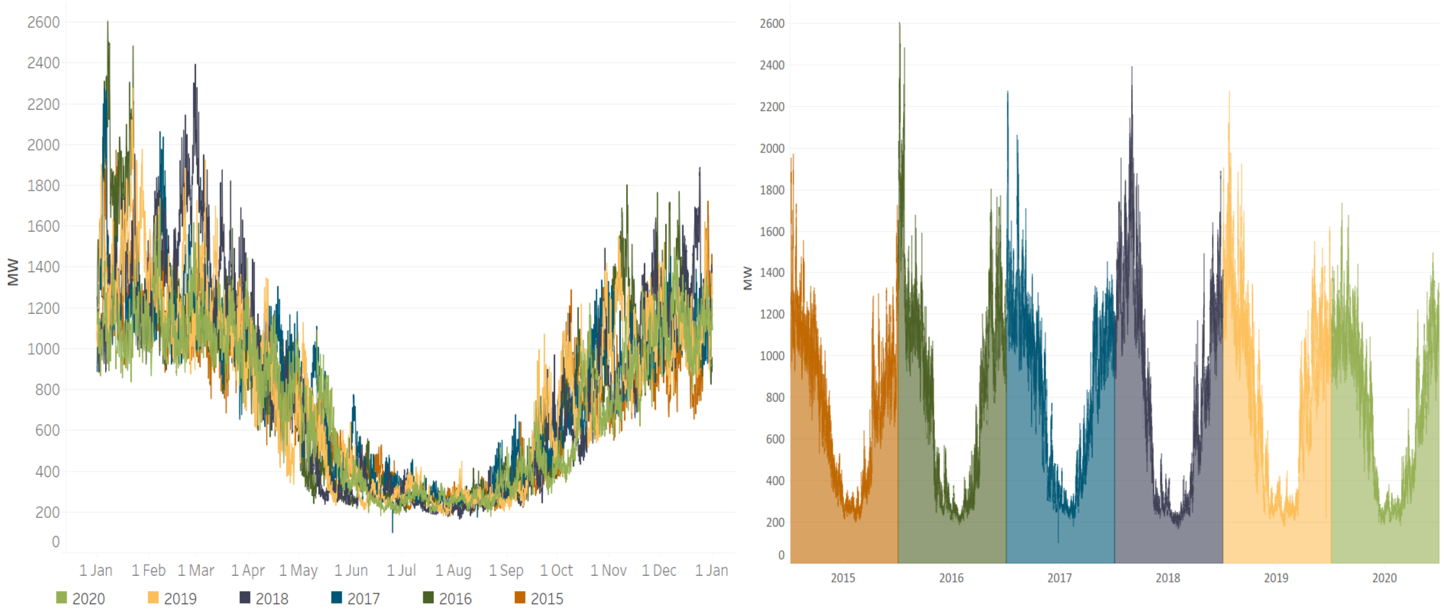

Figure 15. Baseload vs peak load - duration curve of district heat production from Helen Oy, Helsinki.

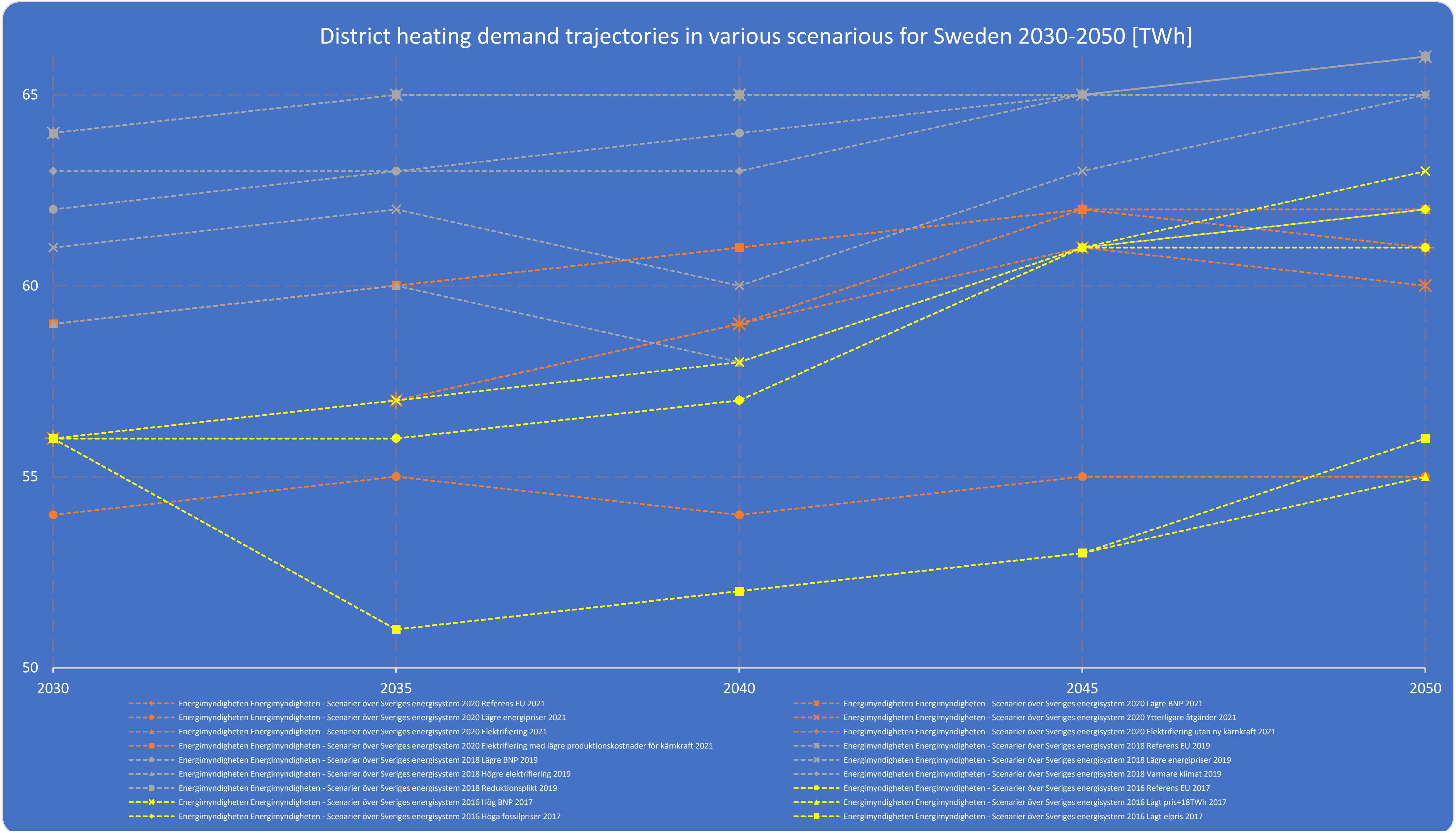

Figure 19. District heating demand trajectories in various scenarios for Sweden 2030 - 2050.

2. Role of SMR:s in the future Swedish Energy System

SMR:s may be suitable for a range of applications, among which are those indicated in the list below. These applications form the basis for this study and enable evaluation of the various reactor concepts' pros and cons in the energy system.

- Electricity production
- Heat production
- Hydrogen generation
- Maritime propulsion
- Desalination of sea water
- Production of radionuclides

Desalination of seawater and production of radioisotopes may not be considered as parts of the energy system per se but have been included in order to illustrate the versatility of new nuclear technology.

In sections 4 to 9, for each of the above applications, opportunities and obstacles/risks have been identified. Limitations that impact the use of SMRs in certain applications, such as the maximum operating temperature needed, whether steam shall be used directly or indirectly in industrial processes, localization at sites with proximity to population etc., have been included.

3. A preliminary identification of legal barriers

3.1. Various types of barriers

There are different types of obstacles, see figure 20, partly legal obstacles, and partly more practical obstacles. The obstacles affect differently depending on the actor and type of reactor. One example is the limitation to a maximum of ten reactors in the country, and that only existing sites may be used. In practice, this is not a significant obstacle for today's nuclear operators to build new full-scale reactors. On the other hand, it shuts out new actors, and in practice makes new plants based on many smaller identical reactors (SMR) impossible.

These legal barriers on the number of plants in operation and where they may be located will be removed if plans for changes according to a memorandum by the government are approved. The government foresees new laws in effect by March 2024. Additional laws and ordinances need be changed to fully acknowledge application of new types of nuclear power plants.

Policy documents and general instructions in the yearly regulatory letters to authorities, highlights the ambition to accomplish energy supply from primarily renewable sources. Although this does not explicitly exclude nuclear power to be developed and used, it is frequently understood by authorities to refrain from support to the area. The exceptions are few. Unfortunately, this results in low preparedness for understanding and implementation of new developments that would benefit reduction of greenhouse gases. In addition, it has had a negative impact on research and development and thereby on the availability of skilled resources to the nuclear power industry. Recent trends, however, show improvements in this area.

Since there is a need for significantly increase in electricity supply in the next half century at least, all fossil free sources should be promoted. In a country like Sweden there are specific benefits of using nuclear power since we have long experience in using it successfully and have accomplished a system that covers all aspect of its use. Therefore, a national policy paper on electric energy supply should be considered wherein the impacts from ambitions to establish a fossil free society are identified and necessary developments are highlighted. Similar actions have been implemented elsewhere, for example in the United Kingdom. However, currently, no promotion of nuclear power originates in a decision on a national level (government or parliament). Nor is promotion included in the instructions to any authority.

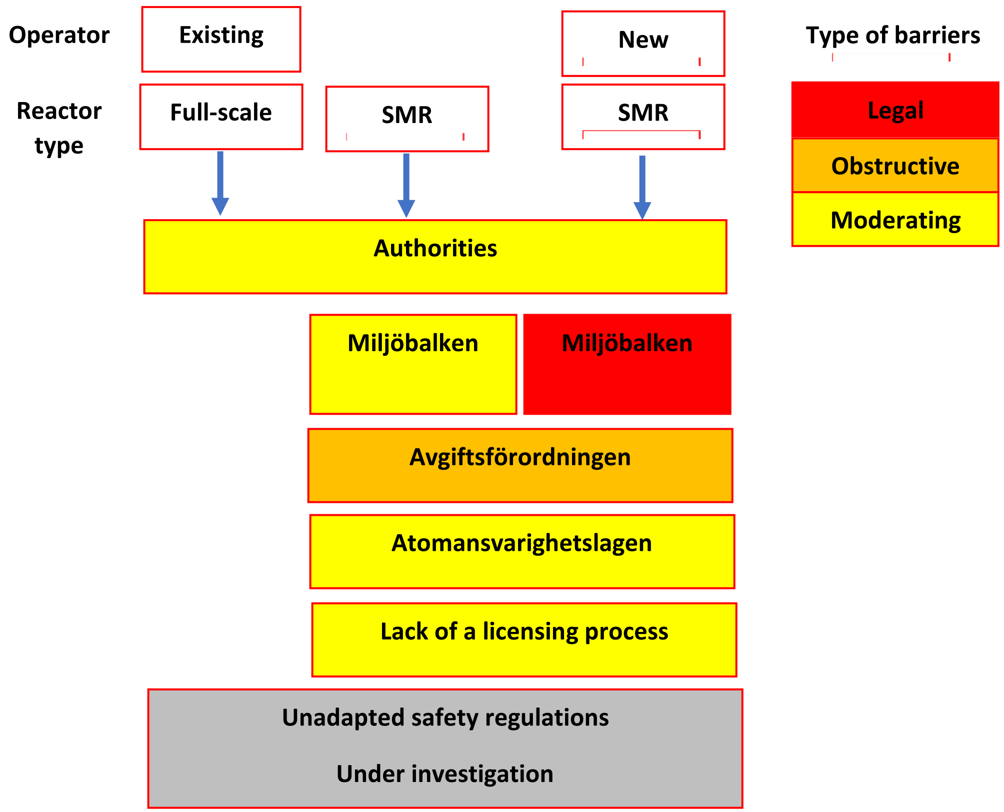

Figure 20. Summary of barriers for three different type cases: New nuclear power with existing operator using large-scale technology, existing operator installing SMRs, and new operator installing SMRs.

3.1.1 Existing actor, large-scale technology

Deciding to build large scale nuclear plants (1 GW or more) at existing sites is fully up to Vattenfall and Uniper/Fortum being the owners of these sites. There are no formal obstacles to execute such plans. The regulations issued by the Swedish Nuclear Safety Authority have been reviewed carefully by current permit holders and their application is clarified. An uncertainty is the impacts of the regulator's ambition to develop an additional series of detailed regulations. This ambition should be reconsidered after information exchange with potential applicants and their possible suppliers.

The decision on new plants at the current locations is thus a matter of long-term economic viability to the owners. This is impacted by the way the electricity is valued by the market mechanisms. Currently, in-sufficient value is attributed to the stability and consistency of the electric power generation from the nuclear power plants. These properties also support additional use of variable production of wind and solar plants. The market mechanisms need to be reconsidered to achieve the benefits.

The risks associated with the investment result in a request for high discount rates in the evaluation. Actions by the government and authorities impact on risk. Expressed political unity to use nuclear power for the foreseeable future will reduce risks to the financiers and the investors. Again, this points to the importance of a national policy paper[2] mentioned above.

Given that such additional clarity is provided, the actors will be capable of making appropriate decisions.

3.1.2 Application of Small Modular Reactors (SMR)

Until today economy of scale for electricity production by nuclear power has been reached by increasing the size of each unit with some units being offered at 1 700 MW electric output. Since a decade another approach has been investigated, i.e. to reach economy of scale by reproducing small reactors. The learning effects of supplying many similar or identical plants will reduce costs. This has been demonstrated also for large plants. Small reactors have been defined as plants providing about 300 MW_e or less – the limit is flexible. The fabrication and construction of such plants may be streamlined and even be performed in factories to a large extent. To achieve this their design is modular in the sense that several parts of the plant are put together first and then moved to the actual construction site to be installed. This is achievable thanks to the smaller size of the plant. The smaller size also makes it easier to locate the plant and, in many cases, it better fits a replacement purpose since many plants to be replaced may be in the 300 MW power range (in particular old coal fired plants). The smaller size of the plant also makes it easier to design a plant that prevents events to occur and also mitigates the effects of the events using passive functions, i.e., functions that need

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[2] In previous times guidance has been provided by Energy Commissions. At this time, it seems unnecessary to investigate the background and status anymore. The necessary information is at hand and the task is to conclude on it, provide direction for the future and demonstrate long-term unity in positions.

no power supply or other actions from the outside. Although none of these plants have yet been built, reviews by both future users of them and safety authorities have confirmed that vendor claims may be achievable. How quickly cost reductions may be achieved is not yet demonstrated by application. Vattenfall has participated in an evaluation of SMRs for application in Estonia and is now progressing its own investigation of application at Ringhals.

Currently it is legally possible to build SMRs at existing sites. However, no more than four, since total number of units may not exceed 10 according to the Environmental Code (17 chapter 6 a § 1 p. miljöbalken). There are other legal requirements that in practice makes it impossible – for example, the fees that are required are based on the idea that only full-scale nuclear power stations will be built and since the fees are fixed in the ordinance there is no way to adapt these the costs if the plant instead is a SMR. For example, the permit application fee for an application to replace a permanently closed nuclear power station is 101 400 000 Swedish kronor and more costs will arise later in the review process (see e.g., 5 and 7 § Förordning (2008:463) om vissa avgifter till Strålsäkerhetsmyndigheten). Having a fixed fee system regulated in an ordinance seems out of time given many factors and should be changed as quick as possible if there is a will to build new nuclear in Sweden. This is actually more important than changing the number of nuclear power stations in Sweden as it effectively limits also installation of SMR at currents sites. The Swedish legislation is in general only focused on large scale reactors and a lot of changes is therefore necessary in different laws and ordinances before SMR can be built, including the Act on Nuclear Activities (Lag (1984:3) om kärnteknisk verksamhet), and this type of work takes time. The act was rather recently reviewed by a governmental investigation where the main suggestions assumed that new Swedish nuclear power production was unlikely [16]. Therefore, the review process itself need adjustments. A challenge here is that there is practically no established review process covering the combination of the Environmental Code and the Act of Nuclear Activities. Current practice has been established by the nuclear regulator SSM. Any idea to include the review process in an adjustment of the Act on Nuclear Activities should be reconsidered – at least until the process has been reviewed for efficiency and applicability when considering its coupling between the Act on Nuclear Activities and the Environmental code. A full review of the nuclear legislation should be a high priority if new nuclear power production is the intention.

A potential exception to the readiness for legal and regulatory approval is the review process applied by the Swedish Radiation Safety Authority (SSM). Its major regulations were revised and published for implementation March 2022. These regulations apply to all nuclear power plants. The regulator announced its intention to adjust regulations for other designs than currently known large light water reactors. No schedule was set. August 2022 the government commissioned the regulator to investigate if and what kind of regulations would be needed for long-term operation of operating plants and for review and approval of new types of plants (for example SMRs). SSM has reported the first part of the task end of February 2023 and will report on the second (SMR) part end of July 2023. The first part of the reporting included a positive view on international cooperation in setting requirements on nuclear plants. This is appreciated since cooperation between regulators can improve safety and efficiency in regulatory review. It is key to the success of implementing new nuclear power plants that repetition of same review by several regulators is avoided.

The SSM review process for the SMRs may also have to consider the fact that construction of parts of the plant takes place at a factory away from the final construction site. This is not new in principle to construction of nuclear plants, but for SMRs – as well as for other highly modular designs – it will require adjustment of inspection procedures. Here, in particular cooperation between regulators in different countries become important. The multiple use of SMRs will also highlight the importance of being able to reconsider the requirements on emergency zones given the characteristics of the SMR designs.

From above it follows that it is necessary with a rather ambitious plan to adjust the permitting review processes. A few these changes are in progress, but others remain to be initiated. A very comprehensive investigation is therefore needed to clarify the need for new adapted and effective regulation, in particular for SMR. Project E2 within ANItA has been tailored to address the issues indicated above and, in addition, how the process to reform the current regulations could be carried out in order to achieve a fast process.

4. SMR use in electricity production

During the last decades there have been a couple of troubled conventional nuclear power projects ending with cost overruns and schedule delays. The ambition of most SMR concepts is to mitigate the risks experienced in these projects. Technical innovations, better data modelling, and modern building technology are making reactor construction easier. The number of components is reduced. This is expected to make SMR reactors easier to build, operate and maintain, which reduces costs [17]. It is important to recognize that the main troubles with the conventional nuclear power projects have been associated with First-of-a-kind (FOAK) issues mainly regarding licensing and supply chain. These areas are national (licensing) and specific to the plant supplier/design (supply chain). Thus, the first SMR reactor designs may face the same type of FOAK issues. These aspects will be further studied in ANItA project E1 (Implementation of SMRs – effects of serial production on management of plant projects).

Currently, there exist around 100 different SMR concepts and most of them are not yet commercially viable technologies, so-called advanced reactors AMR. However, several companies are developing SMRs with *mature technology*, i.e. Light water reactors LWR. Expected FOAK construction and licensing for SMRs with light water technology are in the coming five-year period.

The developers of light water SMR:s has different concepts which will affect the deployment of each design. Which concept to be at a specific site is a latter decision but the general pros with SMR are that:

- SMRs can be located close to the power consumer, e g close to a factory requiring process heat. SMRs can be located to other sites than conventional nuclear power plants due to lesser need of cooling water. For some designs the emergency planning zone could be smaller and hence this power plant can be located closer to consumer(s). This would require a modified licensing process in Sweden.
- A site consisting of SMRs can grow or decrease over time, for example by starting with one unit and then adding a second unit, these eases both the project and the financial structure of the venture.
- During operation, a fleet of SMRs creates greater redundancy for the system during outages or unplanned shutdowns. An outage of an SMR will not affect the system in same way as when a large power plant is down.
- Most of the SMR developers claim their designs to support load following which would be beneficial in the present and future electricity mix.
- Expansion of nuclear power, SMR or conventional power plants, will support the grid with ancillary services which could be beneficial for continued growth of electricity production from wind and solar.

The focus for ANItA is currently on the light water technology but as the AMR technology matures both concepts need to be monitored.

5. SMR use in heat production

Heat is used to heat buildings (district heat) and in different industry processes (process heat). Heat is produced in different kind of power plants:

- heat only boilers (HOB)
- combined heat and power production (CHP)

In non-nuclear domain that source of the energy is usually coal, oil, biomass or natural gas. Nuclear power plants are also used in some countries [22]. Nuclear heat production for domestic use was also in operation in Sweden as the 65 MW Ågesta reactor generated 55 MW district heating and 10 MW electricity between 1963 and 1974.

Typically, water either in liquid or gas phase is to transfer the heat. District heating is used to heat buildings and warm tap water within both residential and commercial applications. Process heat is used in various industry processes such as pulp, petrochemical industries etc. Transportation of heat in long distances may not be economically feasible due to pumping costs and heat losses. This would imply that the power plants should be located near the consumers. However, whether this statement is strictly true or not will be one of the subjects for ANItA project A4. In addition, this brings additional questions related to licensing (e.g., emergency planning zone), permits of the site etc. which needs to be investigated more in later phases.

Various applications have their different requirements for the needed enthalpy (i.e., temperature) and form of the heat (i.e., liquid or gas). Table 4 gives a few examples on temperature levels relevant for different applications and corresponding nuclear technologies.

Table 4. Technology vs. various applications

Temperature level	Application	Technology
90-120 °C	District heat	LWR
200-400 °C	Pulp and paper	LWR / HTR / Fast reactors
> 300 °C	Petrochemical	HTR / Fast reactors
> 300 °C	Oil	HTR / Fast reactors
> 400 °C	Hydrogen	HTR
> 700 °C	Steel	HTR

In this context it should be stressed that heat production for domestic use require changes in the current legislation and this issue will be addressed in ANItA project E1.

5.1 Heat only boiler

Heat only boilers are mainly used to produce district heat and their only product is heat. Nuclear heat boiler concepts are being developed for example in China and Finland [21], [22]. The technical concept is rather simple. The reactor heats water (i.e. primary circuit) which flows into heat exchanger which is connected directly to end user network (i.e. district heating network) or to secondary circuit which is then connected to the end user network. This way it is ensured that primary circuit water is not in direct contact with the district heating circuit.

The reactor core can be in a pressure vessel or in a non-pressurised open pool. Heat only boiler reactors also have less systems than power plants which produce electricity and therefore are smaller plants. Due to smaller primary circuit pressure, smaller reactor core and other features it has been suggested that emergency planning zone could be smaller than "conventional nuclear power plants". This means heat only boiler reactors could be situated in cities or near them. This would require modifications in the legislation.

None of the SMR designs outlined in Table 3 is directly designed for heat only generation. From a technological point of view conventional nuclear power plants could be used to produce only heat but from neither an economical nor a practical point of view would such a use be feasible.

5.2 Combined heat and power

Combined heat and power mean that part of the steam in turbine island is used to produce heat in a separate heat exchanger instead of producing only electricity in turbine-generator system. This decreases electrical power level but enhances the overall efficiency of the power plant. Typically, the ratio of the conversion is at least 1:4, i.e., with one lost electrical unit four units of heat is gained.

There are multiple ways to arrange this but here are few examples [23]:

- bled steam either from the turbine or from reheater (condenser)
- back-pressure turbine (without condenser)

The steam is directed to heat exchangers which are connected to district heating circuit directly or via another circuit.

Depending on the design of the turbine island plant, the power output levels can be controlled from their nominal levels. Typically, CHP plants provide base load during heating season which is typically from October to April. Thus, power levels are not changed that often. However, as district heating demand is not high in summer times plant operator could want to produce only electricity.

Back-pressure turbine configuration is interesting option when there is no access to heat sink. In these cases, the district heating network is the heat sink. However, if there is no need for district heat then electricity cannot be produced either.

6. SMR use in hydrogen generation

Hydrogen is a common chemical feedstock used in today's chemical process industry. The global demand in 2021 was roughly 100 MT. A little less than half of the current hydrogen is used in the refining industry. Despite this, it is predicted that in the net zero scenario (NZE) demand will have doubled already by 2030 and if all the proposed electrolyzer projects are realized it is estimated that the total installed electrolyzer capacity will be between 130 - 240 GW by 2030 [24]. Currently less than 1 % of the hydrogen is produced by low carbon sources but IEA estimates that by 2030 more than 60 MT, roughly a third of all the hydrogen, will be produced from electrolysis.

The total hydrogen produced from electrolyzers can be estimated using eq. 1

$$Hydrogen_{Production} = \frac{Installed\ Capacity \cdot Efficiency \cdot Capacity\ Factor \cdot (1 - Distribution\ Losses)}{Theoretical\ electrolysis\ energy\ need}$$

Using eq. 1, where the minimum theoretical electrolysis energy is fixed at 39.4 kWh/kg and distribution losses can be assumed to be 5 %, installed capacity at 240 GW and an electrolyzer efficiency of 60 % which is common for conventional commercial alkaline and PEM electrolyzers, it's clear that to get even remotely close to the target of 60 MT the capacity factor must be close to unity. Out of all the low carbon sources it's only nuclear that can operate with such a capacity factor. Not only is the capacity factor important for decreasing the effects of bottlenecks caused by insufficient electrolyzer deployment, capacity factor has also been shown to be the most important cost driver when for the levelized cost of hydrogen (LCOH) [25]. In 2022 the Swedish energy agency released their future hydrogen scenario [26]. There they anticipate that there might be bottlenecks in the electrolyzer production capacity but they nevertheless anticipate that Sweden will have 5 GW of electrolyzers installed by 2030 and 15 GW by 2045. With their assumed capacity factor of 96 %, 126 TWh of electricity will be required to power the electrolyzers.

6.1 High temperature steam electrolysis

Another interesting benefit for nuclear based hydrogen production is high temperature steam electrolysis (HTSE). Using a solid oxide electrolysis cell (SOEC), which is in essence a reversed fuel cell, electrolyzer efficiencies above unity is the. The working temperature of such a HTSE process usually ranges between 750-850 °C but both lower and higher temperatures can be utilized. The higher the temperature the lower the need for electricity input (at 2500 °C no electric input is necessary, this is called thermolysis).

Unlike wind and solar PV which only produces electricity, a nuclear power plant (usually) produces both electricity and heat. Nuclear power is therefore well suited for HTSE. Some advanced nuclear concepts, such as high temperature gas-cooled reactors, produce heat at those temperatures directly but conventional light water reactors produce steam with a temperature of roughly 300 °C, there one would ideally increase the steam temperature using various heat exchangers to increase efficiency. NuScale has simulated that when using their 250 MWt/77MWe module in combination with a HTSE-system, the setup can produce more than 50 tons of hydrogen per module and day. In this study they find that upgrading the necessary amount of steam from 300 °C to 850 °C is achieved using only 2 % of the total electricity produced [27].

6.2 Thermochemical splitting

Another interesting hydrogen production pathway is thermochemical splitting. As the name suggests, thermochemical splitting is doesn't need any electric input. There are several hundreds of proposed cycles where the sulfur-iodine cycle has long been of key interest. The peak temperature of the S-I cycle is 850 °C and the cycle has a thermal efficiency around 50 %. Since it uses only thermal energy the overall efficiency of such a process is vastly higher than conventional electrolysis. In addition to this, a dedicated reactor wouldn't need a generator further decreasing costs. However, the reactor designs needed to produce 850 °C are outside of the main scope of ANItA.

7. SMR use in maritime propulsion

In this section, the main findings of several studies are compiled. In this sense, it is by no means complete but may serve as a basis for formulating more comprehensive projects on the subject. The idea pursued here is also to find routes where possible work within ANItA in this field can connect to ongoing work in Norway [28].

Historically, four nuclear-propelled cargo ships have been operated: NS Savannah (US) 1962-1972 (16.4 propeller MW), NS Otto Hahn (West Germany) 1968-1979 (8 propeller MW), NS Mutsu (Japan) 1974-1992 (8 propeller MW) and NS Sevmorput (USSR) 1988-today (30 propeller MW). Except for Sevmorput, these ships are usually considered as proof-of-concept although they were in operation across the globe, often hitting difficulties to get permission to access ports.

The aspects of maritime nuclear propulsion considered in this section is: technology, economy, regulations, public perception and the viability to create a Nordic cooperation within the field and some concluding remarks.

7. 1 Technology

7.1.1 Light-water reactors

While ship construction is more or less independent on propulsion technology (several of the above-mentioned ships were refigured to conventional propulsion systems), the reactor technology is crucial for maritime applications. Not only shall the reactors be physically small, but they also need to fulfil operative requirements that their land-based counterparts do not. For example, the obvious problem with movements aboard a ship require a reactor construction where the primary cooling system contains a one-phase coolant. The four ships mentioned above thus relied on pressurised water technology (PWR).
The vast majority of today's nuclear ships, be it either military vessels or state-owned icebreakers, also exploit PWR technology and have done so successfully for over sixty years. There is thus a considerable experience of nuclear propulsion using this technology. The use of standard low-enriched fuel is advantageous from several perspectives:

1. There is a well-established infrastructure concerning fuel manufacturing, fuel handling and waste disposal.
2. At least in the short-term perspective, the challenging safeguards implementation foreseen in maritime applications would greatly benefit from using established technology and regulations.
3. The operative costs are likely to be in par with the land-based reactors i.e., comparably small.

7.1.2 Advanced concepts (Generation IV reactors)

A special class of nuclear ships were the "Alfa" class submarines developed during the Soviet era where fast reactors, cooled with a lead-bismuth eutectic, were utilised [29]. This technology, for simplicity here called lead-cooled fast reactors (LFR), is of interest mainly due to the comparably small size and the high efficiency achievable. However, this type of reactor poses some problems when used in commercial shipping as, for example, that commercial low-enriched fuel cannot be used.

The inclusion of bismuth in the coolant may give rise to radiation protection concerns due to the production of the highly radioactive ^{210}Po through neutron capture. A way of solving the latter problem is to use pure lead as coolant instead but this will create other problems such as severe corrosion on internal structures. One remedy for this is to carefully control the oxygen content in the coolant [30], which, however, complicates the construction and safety arrangements considerably. New materials [31] may also take care of the corrosion problem but this is still a subject for demonstration. In addition, the military application hitherto makes it hard to find reliable information about the operative experience with this type of reactors.

One type of Generation IV reactor that has been in commercial operation since 1980 [32] is the sodium-cooled fast reactor. The use of sodium as coolant makes this reactor concept rather unfit for maritime applications because sodium reacts violently in contact with water. Although this property should not be a problem during nominal operation, it could escalate an accident at sea to unacceptable levels. For this reason, this reactor concept will not be further treated.

An interesting, albeit premature, reactor concept is the molten-salt reactor MSR. There are several kinds of MSRs but the archetypical one is where a molten salt both contains fuel and serve as a coolant. This principle is technically interesting for several reasons since, for example, the notion of core meltdown becomes a non-issue. As with the LFRs, MSRs operate at atmospheric pressure and thus possess a very small volume-to power ratio. Further on, the possibility to on-line separation of non-fissile or fertile materials is also an attractive asset for future ambitions to close the fuel cycle.

Although the principle of MSRs has been successfully demonstrated [33], no commercial development has been carried out until quite recently in China, the US and Canada, to mention a few countries. In Europe companies such as Moltex [34], Seaborg Technologies [35] and Copenhagen Atomics [36] have taken on interesting development work.

How well various reactor concept comply with vital engineering and regulatory parameters are important issues to address for maritime application. Here "engineering" connects primarily to the maturity of the various concepts. Obviously PWRs exhibit few engineering challenges while several such can be found in both LFRs and MSRs. A few of them has been pointed out above and must be the subject for further studies.

Safeguard ability is another parameter of utmost importance, both from an engineering as well as from a regulatory viewpoint. This parameter refers to how well various concepts lend themselves for safeguards and inspection. As the maritime application implies severe safeguards challenges, PWRs have an advantage because the current safeguards regime is reasonably well adapted to LWRs. This is in contrast to LFRs and MSRs that violate current basic safeguards principles. For example, in LFRs the fuel is immerged in opaque lead and is not easily verified while in MSRs, the fuel may even not be in a structured form. If adding on-line separation to the MSRs additional safeguards concerns arises, when using thorium-based fuel. It can, however, be anticipated the research and development work within safeguards have solved the most concerning issues in the long-term perspective.

"Sustainability" is a parameter that addresses how well various reactor concepts utilise natural resources. While light-water reactors do produce immense amount of energy using a small amount of fuel, they utilise the energy content in uranium ore to only one per cent, approximately. In this respect, LFRs and MSRs are without competition since their theoretical utilisation of natural resources can reach about a factor of hundred times more than LWR technology. The big issue here is that to accomplish this, the reactors need to be part of a complete system that closes the fuel cycle. This means that facilities for recycling and fuel production must be in place as well as well-adapted logistics. None of these are currently in commercial operation and the question is when such systems can be available? The main obstacle here is that the well-functioning fuel cycle of today must be replaced and there are no commercial incitements to do so. MSRs have an advantage in this respect due to the possibility to on-line processing but, as outlined above, poses some safeguards issues.

7.2 Economy

The economy of nuclear propulsion is a multifaceted issue and there is no space to comprehensively cover it here. However, work has been done on this subject, see for example [37]. While many studies focus on the "hardware" such as the reactors, fuel costs etc, aspects such as safeguards implementation, back-end, i.e., waste management and final storage, and decommissioning also need to be considered in the total budget. How such costs shall be accounted for may vary but, as an example, according to the Swedish Nuclear Technology Act, the costs for back-end and decommissioning are the responsibility of the operators who, in turn, put these costs on the electricity bill. The immense amount of electricity produced during a long period of time implies that these costs per kWh is fairly small for the consumers. The example indicates that the costs associated with decommissioning and back-end must be related to the commercial gains of using the technology. For maritime applications, this seems to be an under-researched area that needs to be properly addressed to correctly estimate the total economy.

Generally speaking, the front-end costs associated with reactors and other technical means for nuclear propulsion will with certainty exceed those of conventional propulsion with several factors. On the other hand, fuels like LNG, ammonia, hydrogen etc may add considerably to the total cost via a bulky and complex infrastructure and if not produced in an environmentally sound way, which may turn out to be expensive, these fuels will not add much value.

Other economic factors using nuclear propulsion that need to be thoroughly studied should include the economic benefit of drastically decrease transport time. For example, a nuclear ship can be operated in speeds exceeding the fastest ships of today with a least a factor of two where the speed limit is not governed by fuel cost. Further on, in practice the need for frequent refuelling disappears as a nuclear ship can be operational for ten years or more on one fuel batch where, in addition, the fuel is relatively cheap and readily available. How such factors influence the total economy should be an ingredient in future studies.

7.3 Regulations

As indicated in the economy section, there are other important aspects to consider besides operative ones as, for example, decommissioning of reactors. The current law in most countries provides for a process that is both (in absolute terms) expensive and lengthy and it is hard to see any possibility to find shortcuts in these legislations. Likewise, the international non-proliferation regime imposes that every nuclear installation shall be subject to safeguards. It is reasonable to think of these two examples as constants in the discussion while other legislations and regulations could be subject for reformations or adjustments to promote maritime applications of nuclear technology. It is here important to point out that several regulations even today rely on various technological means to control and verifying compliance with the regulations such as international safeguards. Technical development work in order to enhance the regulators' capability to detect any breaches of compliance is therefore of utmost importance for promoting maritime applications.

International treaties that hit directly on maritime applications are the Convention on the Physical Protection of Nuclear Material and Nuclear Facilities [38] and various conventions about liability. These treaties are designed for land-based nuclear installations and currently fit quite badly maritime operations. Probably these treaties can be equipped with addendums but how these should be formulated is not clear. Also, the fact that ships today often are operated under "flag of convenience" and not national flags, introduces additional problems because relevant international treaties lie on the state level and not company level.

A particular complicated problem to consider is how to provide nuclear security around reactors on commercial ships. The problem arises from the fact that nuclear security is currently a responsibility for each country (and will probably be so) and the security approach may thus vary from country to country. How to harmonise these approaches so to fit an application where reactors move around the seas is a completely open question, which needs to be addressed in coming work.

The main regulatory issue unique for maritime propulsion is thus the need for an international consensus regarding nuclear liability and other aspects described above. Other regulatory issues (e g emergency planning in ports, licensee responsibilities and security) are common with other applications.

Other regulatory concerns for example the size of emergency zones in ports. If the regulatory framework requires the same size of these zones as those used for full-scale reactors, it is difficult to see a future for commercial nuclear ships. In addition, local authorities may also deny entry to ports. This is certainly something that needs to be addressed.

7.4 Public perception

Since the early seventies, nuclear power has been questioned from, in particular, the environmental movement. Rightly or wrongly, the perceived danger of nuclear power among the public is a reality and should be carefully considered when new nuclear applications are proposed. However, several opinion polls show a sharp increase in support for the use of nuclear power, where a reasonable interpretation is that more and more people consider nuclear power to be an important tool for meeting several of society's challenges [39] and this may open for even such a radical application as nuclear propulsion of civilian ships. In contrast to LWR technology, the public may regard LFRs and MSRs as “new” technologies and therefore accept them more than LWRs. Whether this is so or not may be an interesting subject for research.

7.5 Concluding remarks

From an engineering perspective, the maritime use of PWRs is of comparably little concern. Regarding LFRs and MSRs, the situation is harder to assess because it depends on the success of finding viable solutions to 1) critical engineering problems and 2) adapted licensing processes and formalities surrounding new technologies. Further on, the argument of using such reactors in maritime applications because they “close the fuel cycle” is generally not correct. To fully exploit the potential of those reactors, they need to be a part of a currently non-existing Generation IV system. This is not necessarily true for some MSR concepts with their possibility for on-line separation but the safeguard issues such a system exhibits have not yet been addressed thoroughly and it is hard to see practical solutions coming up soon.

It may therefore be concluded that the “safest” investment in maritime nuclear propulsion would be the well-proven PWR concept, at least for the coming few decades. Although studies should address LFRs and MSRs and primarily their implication on operative safety and thus create a strategy to pave the route for the future.

Even using PWR technology, this is by no means an easy undertaking given a whole range of regulatory hurdles and not the least, the public perception. But given the harsh emission requirements put on the shipping industry and thus anticipated large costs, it may very well be worthwhile to initiate studies to go deeper into the subject.

The focus of such studies should primarily be put not on technology (besides such technology that can strengthen the regulatory framework) but on economy, law, regulations, safeguards, and security. As has been indicated above, there is a range of very complicated issues that need to be addressed, which most probably must be done in cooperation with both national and international regulatory bodies together with the shipping industry.

The ongoing project in Norway [28] in collaboration with ANItA would put the Nordic countries in a good position within a potentially important development for the future.

8. SMR use in desalination of sea water

Desalination is a necessity for meeting the growing freshwater demand in many countries. The main challenge with desalination is the energy required to run the process. The energy required for producing freshwater from seawater ranges from 2.58 to 8.5 kWh/m3 [40].

There are two general groups of desalination processes, thermal and membrane technologies. The thermal technologies are based on evaporation through boiling and subsequent condensation of water while membrane technologies usually refer to reverse osmosis. In the former case, the process is driven by heat and electricity while in the second case, only electricity is required to run the pumps that build up the pressure necessary to drive the process [41]. Among the thermal processes we find multi-state flash distillation (MSF), multi-effect distillation (MED), mechanical vapor compression (MVC) and thermal vapor compression. Using multistage process schemes it is possible to reduce the external heat demand considerably. This can be achieved by heat recovery and recirculation of brine. In these desalination plants it is possible to reduce the salinity from 70 000 mg/L to 5-25 mg/L. To improve efficiency, thermal and membrane technologies can be coupled into so-called hybrid desalination (HD) techniques [42].

SMRs have been proposed as stable, reliable and climate sustainable sources of both heat and electricity to drive desalination plants. In such a case, the purpose of the SMR is to generate energy for the desalination plant and to produce electricity. While the amount of heat and electricity available from large-scale nuclear power plant is sufficient to run a large-capacity desalination plant (> 10 000 m3 of freshwater produced per day), the amount of heat available for non-electric applications from an SMR is limited [43]. Consequently, desalination plants powered by single SMRs will have lower capacity. For comparison, the tap water consumption in Sweden is 140 litres per person and day [44]. Hence, a desalination plant with a capacity of 10 000 m^3 of freshwater per day would be sufficient to provide water for around 70 000 people (based on Swedish consumption). This corresponds to a power requirement of 1.1 – 3.5 MW.

Optimization of the desalination process is a crucial part of the coupling of desalination plants to SMRs. In a recent work, several coupling schemes along with different standalone techniques were assessed [45]. The assessment was performed using the IAEA Desalination Thermodynamic

Optimization Program (DE-TOP) [46]. It was suggested that the best option is to utilize steam from the low-pressure turbine. The relatively hot water of the SMR condenser is the used as feed water for the desalination plant. This set-up is argued to decrease the environmental impact. The cost reduction following this configuration was calculated to 6.4% and 7.6% with reverse osmosis combined with multi-state flash distillation and reverse osmosis combined with multi-effect distillation, respectively [45].

9. SMR use in production of radionuclides

Radioactive isotopes have a variety of uses within medical, industrial, and research applications. The production of these isotopes can be broken down into two basic categories:

- Fission product-derived isotopes such as ^{99}Mo, ^{99}Tc, ^{131}I, et al., which are produced by the irradiation of fissile isotope targets such as ^{235}U, ^{239}Pu, or other, and which require highly enriched targets as well as infrastructure for fuel dissolution and chemical separation for production of the desired isotope.
- Activation-derived isotopes such as ^{60}Co, ^{192}Ir, ^{223}Ra, ^{177}Lu, which are produced by the irradiation of inactive targets of natural Co, Ir, etc, and whose production scheme may vary by the isotope and desired application.

In both cases, the most important parameter for isotope production in a nuclear reactor is the magnitude of the thermal neutron flux where the local neutron flux is determined by the power density (not the reactor power), so a smaller reactor/SMR would probably have a slightly lower power density than Gen III+ reactors but still sufficient to show potential for isotope production.

Production of short-lived isotopes require sufficiently high thermal neutron flux since they will start decay during production and hence the lower production rate cannot be compensated by longer irradiation times. SMR designs based on PWR or BWR technology would not show a significant difference in terms of thermal neutron flux but PWR generally have a higher power density than BWR. A high and stable thermal neutron flux results in a smaller sample material that would be easier to fit in the radiation field in the reactor.

The adequacy for an LWR as a production unit for medical isotopes depends on:

1) The selected technique for insertion and removal of irradiation samples
2) The number of available irradiation sites in the core
3) The medical isotope of interest
    a. A major part of medical isotopes currently in use have half lives in the range 1 day to 100 days, which means that they will reach the saturation limit within a fuel cycle and most will even need to be harvested several times during a fuel cycle in order to

effectively utilize the irradiation slots. The level of the saturation limit is determined by the cross section of the precursor and the thermal neutron flux, but any requirements on the magnitude of the flux, need also to consider the enrichment of the precursor prior irradiation as well as possible enrichment of the nuclide post irradiation. In general, if a high neutron flux be desirable, but a lower neutron flux can partially be compensated by enrichment processes.

4) Logistical considerations in the preparation of final sources including lead times from the isotope supplier to the source manufacturer, in turn dependent upon logistical and transport considerations, source treatment and handling, final manufacturing and sealed source verification (if required), as well as lead times between the manufacturer and the end-user.

Present large LWRs do not have system parts designed to introduce and remove material from the core region during full power operation but such system parts can be introduced in a new reactor design, in both SMR or large LWR. In present large LWRs, the following opportunities have been identified:

- BWR
    - Penetrations in containment used for neutron monitoring in case sufficient dimension for introduce/remove material, i.e. TIP (Transverse In-Core Probe)
- PWR:
    - MIDS (Moveable In-Core Detector System)

To add new penetrations to a design that do not have that initially is technically difficult and probably not even realistic to perform and in addition would require re-licensing of the design.

An example of an SMR used for isotope production was the NRU, CNL (135 MW_{th}). The demands for a high thermal flux points to a design using heavy water or graphite for moderation as there is less parasitic absorption, although there is a definite trade-off between the number of reactor positions attaining high thermal neutron flux which is certainly higher in a large LWR vs a smaller LWR.

Large LWRs provide a high number of relatively low neutron flux positions (on the order of 1E14 n/cm2*s) which could permit several long-term irradiation campaigns occupying high flux positions), though overall this would lead to a high production of relatively low quality, low specific activity samples compared to other reactor types.

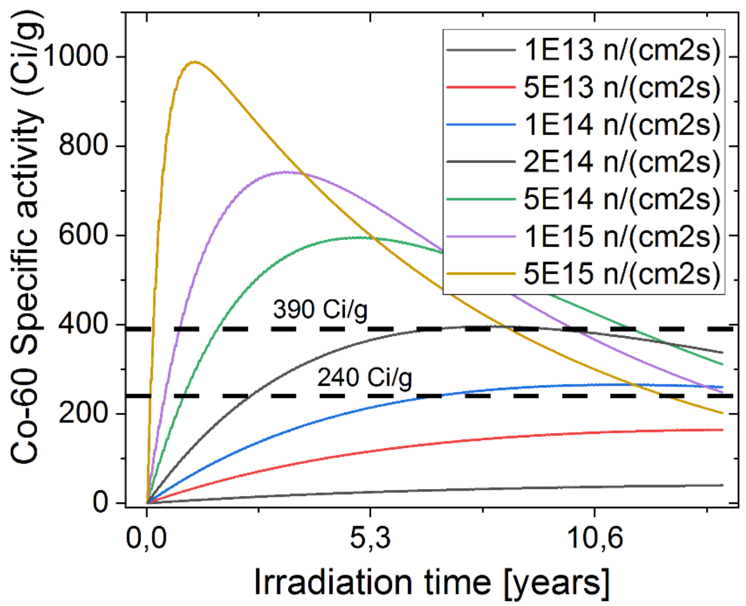

Figure 21: Specific Activity vs Irradiation time and Flux

The potential of a given concept to satisfy end-user needs is highly dependent upon the isotope and its ultimate end-use. For example, to maximize therapeutic potential, it is highly desirable to use ^{60}Co sources of very high specific activity, where 240 Ci/g is considered to be "break-even" for use in most applications, and "high quality" sources are considered to be in excess of 390 Ci/g.

As seen in Figure 21, while PWR systems can theoretically produce sources of sufficient activity to satisfy commercial demand, lead times in transport and manufacturing would lead to a short commercial lifetime, motivating the high use of higher thermal flux facilities for shorter irradiation windows and longer commercial lifetimes.

The use of an LWR SMR can defray many of the complexities above by the benefit of more flexible operations but given enhanced neutron leakage it is very likely that the peak thermal neutron flux, and the overall number of positions available at peak thermal flux, will be lower. Possibly so low that the industrial production of isotopes will not be profitable. For this reason, a heavy water / graphite moderated reactor SMR design is regarded as more suitable to achieve desired thermal neutron fluxes.

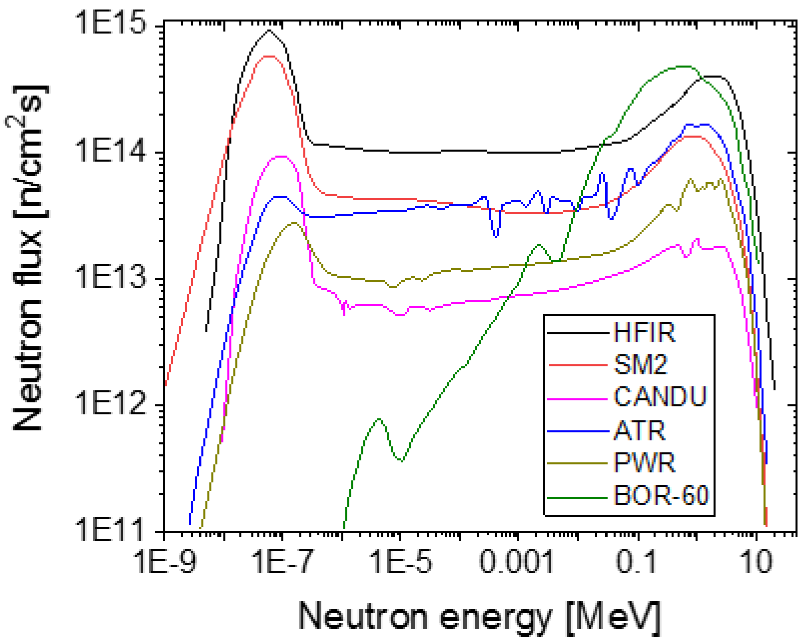

Figure 22: Select Reactor Types and respective thermal neutron flux

For example, as seen in Figure 22, a comparison of thermal neutron fluxes for different type of reactors, including commercial units such as PWRs and CANDU, as well as mixed-use facilities such as HFIR and SM2, are presented. As seen, heavy water moderated reactors such as the CANDU provide nearly an order of magnitude higher thermal neutron flux relative to their light-water moderated counterparts. In case isotope production should be one application for a particular nuclear reactor design it should be taken into consideration already in the initial design stage. The benefits with standardization of a new reactor design would be compromised in case new added features are added for specific customers.

10. Roadmap for implementing SMR:s in Sweden

Svenskt Näringsliv has laid out a roadmap for what needs to change from the perspective of the law/regulator/government. The last pages specify a timeline or road map of when these things should happen to allow for new nuclear power plants.

10.1 Startprogram för ny kärnkraft [47]

From the perspective of a potential future owner/builder/operator there are a number of other actions, milestones and phases that need to be considered. The preparation for building a nuclear power plant can be summarised as five questions:

1. Do we want to?
2. Are we allowed to?
3. Are we able to?
    - What abilities are required?
4. Are we sure?
    - Can we control the risks?
5. Are we able to make the decisions?
    - What decisions and what stakeholders are involved?

This section lays out a preliminary road map which may be of some aid in answering those questions. The process can be said to consist of three phases:

1. Preparations
2. Project delivery
3. Production

These can be further broken down into:

1. Pre-study
2. Preparatory works
3. Decision
4. Implementation
5. Operation and expansion

Major milestones with suggested years for completion:

- 2025 - Application for establishment of regional and municipality plans (as specified by Planning and building Act)
- 2025 - Site identifications & investigations
- 2025/26 – Identify Owners, Operator and Licensee.
- 2026 - Finalise Governance system of Organisations.
- 2026 - Application for permission to build plant (Environmental Impact Assessment – consulted upon; Safety demonstration to SSM; Additional demonstrations for international review)
- 2026 – Site acquisition negotiations, preliminary contracting and final contracting
- **2026 – application, review, establishment and appeals of regional and municipal plans**
- **2028 – Permissibility by government**
- **2028 – LEC ruling**
- 2028 – Plant definitions and specifications
- **2029 – LEC of Appeal ruling**
- 2029 – Application for construction permit/SSM review (unit 1)
- 2030 – Assurance of financing options and conditions
- 2030 – Final contracting of major parts of plant and associated infrastructure.
- 2030 – Application for Construction Permit/SSM review (unit 2)
- **2030 – Construction Permit Unit 1**
- **2030/31 – Construction Permit Unit 2**
- **2033 – Operating Permit Unit 1**
- **2034 – Operating Permit Unit 2**
- **2034 – First plant complete commissioning**

A separate roadmap is required for each of the following:

- Permitting
    - Meeting the nuclear act
    - Meeting conditions on site & infrastructure

    - Meeting the environmental Act
    - Meeting the Planning and building act
    - Meeting other legal requirements (e.g. Esbo convention, Euratom)
    - Need to acquire the following
- Acquisitions
    - Site identification & investigation
    - Site acquisition
    - Plant definition and specifications
    - Identification of plant unit designs and vendors
    - Acquisition strategy
    - Information exchange agreements
    - Financing options and conditions
    - Contracting for training, operations and maintenance
- Organisations
    - Establish program and project
    - Finalise a development agreement
    - Identify owners, operator and Licensee
    - Finalise shareholder agreement
    - Finalise Governance system of organisations
    - Resources of organisations and verification of capabilities
    - Administrative procedures and instruction, including verification of their completeness
    - Support organisations
    - Training organisation
    - Financial capabilities of organisations
- Plant Evaluations
    - Licenseability/permitting
    - Technical and operational characteristics
    - Commercial viability

- Project implementation capabilities
- Risks
- Suppliers and technologies assessed and verified

- Enabling functions
  - Configuration management
  - Information management
  - Quality management
  - Requirements and compliance V&V Management
- Risks
  - Technology risks
  - Commercial and financial risks
  - Schedule risks
  - Implementation risks
- Decision making ability

11. Conclusion

Sweden has set ambitious climate goals and are aiming to become climate neutral before 2050. While Sweden, since the build out of its nuclear fleet in the 70s and 80s, has enjoyed a stable and clean electricity grid, planned electrification and decarbonization of other sectors will require an unprecedented deployment of low-carbon power to ensure security of supply and while retaining the climate friendly footprint that the power-grid currently enjoy. The general consensus as of now is that the need for clean electricity will more than double to above 300 TWh compared to the 140 TWh that are used today. While the current plans of the Swedish government and industry will require vast amounts of clean electricity, other types of energy, such as heat, will also be essential. In this report we have shown that LWR SMRs are likely to be a key technology for achieving these ambitious targets owing to the fact that SMRs are able to produce both heat and electricity at a low economic and environmental cost.

The majority of the increase in electricity can be attributed to the nascent hydrogen sector where the industry is hoping to produce vast amounts of hydrogen through various forms of electrolysis. Hydrogen production is likely to be one of the most important use cases of SMR:s where the smaller size, flexibility, high-capacity factor, and safety of SMR:s make them an ideal choice for hydrogen production, especially in remote or off-grid locations where traditional nuclear reactors may not be feasible.

District heating is widely adopted in Sweden and is currently to large extent being powered by burning of residue streams from the forestry industry in CHPs. Nuclear heat for district heating can potentially come in two distinct forms, either as a part of an NPP that functions as a CHP plant which then produces both heat and electricity or as a dedicated district heating reactor. While the need for district heating usage is not projected to increase nearly as much as the electricity usage it is nevertheless projected to increase slightly, with this in mind and the fact that EU are potentially moving to classify even residue streams from forestry as unsustainable there might be an important void to fill for LWR SMRs in the district heating sector as well.

While merchant electricity, hydrogen production, and district heating are looking to be the most important sectors for SMRs the utility of SMRs is not limited to these areas, another, more unconventional uses case is maritime propulsion. The maritime industry is perhaps one of the most difficult to decarbonize sectors and here nuclear can play a crucial role, either by providing low carbon hydrogen for e-fuels or through direct powering of the vessels. Technically this is not something new, there have been both merchant and military vessels power by nuclear but legislation will likely play a key role in determining whether or not nuclear power propulsion can help reach the climate targets of the maritime industry.

Overall, it’s clear that from a technical viewpoint SMRs can play a major role in the decarbonization journey a head of us. The major hurdles are likely to be legal and perhaps economic uncertainties. These subjects will be dealt with in other ANItA projects where the ultimate goal is to determine the optimal design of a future Swedish power system containing SMRs.

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