FACULTY OF TECHNOLOGY

THE POTENTIAL OF SMALL MODULAR REACTORS IN INDUSTRIAL DECARBONIZATION: CASE STUDIES FOR SSAB, OUTOKUMPU AND KOKKOLA INDUSTRIAL PARK

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ABSTRACT

The potential of small modular reactors in industrial decarbonization: case studies for SSAB, Outokumpu and Kokkola Industrial Park

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The objective of this thesis was to review the energy consumption of Finnish industries, and to assess what share of it could be electrified or decarbonized by hydrogen. In particular, the thesis investigates if small modular nuclear reactors (SMRs) could be the source of electricity and hydrogen to this effect. The potential of decarbonization is evaluated through three case studies of energy-intensive industries. Further, the thesis reviews the challenges and limitations of deploying SMRs, including economic, social and technical constraints.

In the theory part, the thesis reviews the energy consumption and associated greenhouse gases emissions of Finnish industries, especially due to fossil fuel consumption. The review focuses on the technology industry, chemical industry and forestry industry, and their decarbonization roadmaps based on industries federation’s research and publications. Further, the current state of SMR development is outlined, with special focus on LDR-50 SMR design under development in Finland. The differences between conventional nuclear power reactors and SMRs are also illustrated. Additionally, the challenges or limitations of deploying SMRs are identified, including investment costs, social acceptance, legislative gaps and other technological limitations. The costs of SMRs are still high and construction times of demonstration sites are delayed, which hinders further commercialization.

In the experimental part, three case studies are evaluated based on the green transition roadmaps of the companies; SSAB Raahe factory, Outokumpu Tornio plant, and Kokkola Industrial Park. The focus is thus on the metallurgy sector and technology industry, where there is the highest potential of decarbonization by SMRs. In the case of Kokkola

Industrial Park, the assessment is done from the perspective of Kokkolan Energia due to lack of publicly available data.

The results show that one micro-reactor PWR-20 is sufficient for Kokkolan Energia, to meet the industrial and district heat demand of Kokkola Industrial Park and Kokkola municipality. When it comes to SSAB Raahe, three to four DF300 or GTHTR300 can cover the electric power and thermal power demand of SSAB Raahe. As for Outokumpu, at least two 300MW reactors are needed with excessive heat generation, such as DF300, GTHTR300, or PWRX-300.

The thesis concludes that the high costs and long construction times of SMRs limit their potential for industrial decarbonization. In terms of public acceptance, the general attitudes toward SMRs are positive in Finland, however, people are more vary about a close location of SMRs to municipalities. Finally, renewing Finnish legislation on nuclear power made accommodations to SMRs, but technological evaluations on safety will still be necessary, to pave the way for SMRs in the future.

Keywords: Decarbonization, Energy consumption, Hydrogen, Industry, Small modular nuclear reactors

FOREWORD

This thesis is part of HYDRA project, coordinated by WE3 unit, Oulu University and supervised by Dr. Antonio Caló and Prof. Eva Pongrácz. I would like to give my highest gratitude for their supervision, and it's also my great hour to work in WE3 unit during my study in Finland as a summer trainee and research assistant.

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Thanks for the meeting of friends and teachers here, Oulu. It will be an unforgotten memory and experience during my whole life. I am really appreciated my opportunity to study and travel in Europe for around 2 years when I am still young, which inspires me to think more and know myself better when I live in a totally different culture and environment from China. Lastly, a special thanks to the musicians and songs which accompanied me when I wrote the thesis, like G.E.M.

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Buyu Zhao

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SYMBOLS AND ABBREVIATIONS

C	Hydrogen consumption coefficient for direct reduction iron [kg/ton]
C_E	Required capacity of electrolyzer for SSAB Raahe [MW]
C_{E1}	Required capacity of Alkaline electrolyzer [MW]
C_{E2}	Required capacity of SOEC electrolyzer [MW]
C_{Outo}	Capacity of electrolyzer for Outokumpu [MW]
CE	Conversion efficiency of bioreactor [%]
CF	Capacity factor of SMRs [%]
CF_1	Capacity factor of the electrolyzer [%]
C_{MOE}	Consumption coefficient [MWh/ton]
$ED_{Outo,all}$	Electricity consumption using the alkaline electrolyzer [MWh]
E_{Outo}	Electricity demand of Sunfire Hy-Link Alkaline electrolyzer [TWh]
E_{c1}	Total electricity consumption through alkaline electrolyzer [TWh]
E_{c2}	Total electricity consumption through solid oxide electrolyzer [TWh]
E_D	Energy density of hydrogen [MWh/ton]
E_{D1}	Electricity demand for hydrogen generation through electrolysis [TWh]
E_{D11}	Electricity demand for hydrogen generation of Alkaline electrolyzer [TWh]
E_{D12}	Electricity demand for hydrogen generation of SOEC electrolysis [TWh]
E_{D2}	Electricity demand for EAF and other processes [TWh]
E_E	Conversion efficiency of electrolyzer [%]
E_{MOE}	Electricity consumption using MOE technology [TWh]
$EP_{Kokkola}$	Electricity power demand of SMRs for Kolkola Energia [MW]
H_D	Hydrogen demand for SSAB [TWh]
HD_{Outo}	Hydrogen demand of Outokumpu in Tornio [TWh]
$HD_{Kokkola}$	Heat demand of Kokkola industry park except recovered waste heat [GWh]
Me_D	Synthetic methane demand [TWh]
P_D	Power demand of SMRs [MW]
PD_{Outo}	Power demand of SMRs [MW]
TD	Thermal demand for biogas by 2040 [TWh]
TD_{all}	Total thermal demand for Outokumpu [TWh]
TPD	Total thermal power demand [MW]
TP_{D1}	Thermal power demand for replacing biogas [MW]
TP_{D2}	Thermal power demand for pre-heating pellets and hydrogen [MW]
TP_{D3}	Thermal power demand for direct reduction process [MW]

TP_{D4}	Thermal power demand of SOEC for low-temperature external heat [MW]
TP_{D41}	Thermal power demand of SOEC for high-temperature external heat [MW]
TP_{El}	Thermal power demand coefficient of SOEC electrolyzer [KW/MW]
$\mathrm{TP}_{Kokkola}$	Thermal power demand of SMRs for Kokkola industry park [MW]
TP_{Outo1}	Thermal power demand of SOEC for Outokumpu [MW]
TP_{Outo2}	Thermal power demand of Tornio Outokumpu for process steam [MW]
TP_{Outo3}	Thermal power demand of carbon capture technology [MW]
TP_{Tornio}	Thermal power demand of Tornio district heating[MW]
V	Rated production volume [Million tons]

BF-BOF	Blast furnace and basic oxide furnace
BECCUS	Biogenic carbon dioxide capture storage and utilization
CCUS	Carbon capture utilization and storage
EAF	Electric arc furnace
EVs	Electric vehicles
GHGs	Greenhouse gases
IAEA	International Atomic Energy Agency
ICT	Information and communications technology
KIP	Kokkola Industrial Park
LNG	Liquified natural gas
LULUCF	Land use, Land-use change and forestry
MOE	Molten oxide electrolysis
SAF	Submerged arc furnaces
SDG	Sustainable Development Goals
SMRs	Small modular reactors

1 INTRODUCTION

Human activities have unequivocally caused global warming, primarily due to greenhouse gas emissions (GHGs), with global surface temperature increasing around 1.1 °C in 2011-2020 compared to the 1850-1900 period, and the GSGs emissions driven by human activities per year continue to rise. There is no doubt that global warming has imposed impacts on the whole ecosystem, including the biosphere, cryosphere, ocean, and atmosphere, causing substantial damage, and losses to human society. Meanwhile, energy accounts for more than three-quarters of total GHGs emissions across the world, and approximately 35 thousand Mt CO2eq. emitted from fuel combustion in 2022 across the world (IEA 2024). The industry sector accounts for around a quarter of the global energy system CO2 emissions with 9 Gt in 2022 (IEA 2023). Against this kind of background, decarbonizing different sectors in the whole energy system, including electricity generation, transportation, and buildings, especially for the industries sector, which this thesis mainly focuses on, and accelerating energy transition, it is imperative to mitigate global warming.

The Paris Agreement, pledges to constrain the global average temperature to well below 2°C above pre-industrial levels and pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels. However, the average global temperature in 2023 was 14.98 °C, 1.48 °C warmer than the 1850-1900 pre-industry levels (Copernicus 2024), already close to the limitation of 1.5 °C. The European Unition (EU) aims to be carbon-neutral by 2050 and initiates a 2050 long-term strategy, while Finland proposed the Climate Change Act, which aims to be carbon-neutral in 2035 and reduce emission by 90%-95% by 2050 compared to the level in 1990. Subsequently, many measures are proposed for achieving these targets in different sectors, such as renewables (E.g., wind power farms, solar power, bioenergy, hydropower) for electricity, heat pumps for buildings, electric vehicles (EVs) for transportation, etc.

Against this green transition background globally, hydrogen has gained lots of attention recently. Hydrogen is a carbon-free energy carrier based on renewable energy systems, and generation methods, or utilized with carbon capture utilization and storage (CCUS) technology for synthetic fuel or other purposes. It is a possible method for hard-to-decarbonize sectors, like heavy-load transportation, steel industries, and substituting fossil chemical feedstock. Besides, it can be stored for a long time and transported, also it is part of the Power-to-X value chain.

Small modular reactors (SMRs) together with hydrogen provide a potential transition pathway to decarbonize the industry sector, especially when the industry sector is different to be electrified or decarbonized. SMRs can generate clean electricity for industries, and the waste heat can be utilized for industries and district heating systems or other applications. Moreover, it is also feasible to generate hydrogen utilizing electrolysis technology powered by SMRs or other emerging technologies. This thesis expects to get the answer to Finnish industries' current energy demand and how SMRs can contribute to decarbonization and Finnish carbon neutrality strategy through the integration of SMRs.

The HYDRA project, which is funded by the Research Council of Finland and coordinated by the Water, Energy, and Environmental Engineering research unit at the University of Oulu, aims to explore the potential transition pathways to realize carbon neutrality in Finland and develop the hydrogen economy (University of Oulu 2023). This thesis is part of the HYDRA project, and targets to answer the following questions when SMRs are integrated into energy systems for decarbonizing industry sector in Finland:

1. What the current energy need of the Finnish industry is and to what degree they can be electrified or decarbonized with hydrogen?
2. How many and what size SMRs would cover this need (sizing study)?
3. What are the potential impacts, challenges, and limitations of deploying SMRs?

2 INDUSTRY ENERGY CONSUMPTION AND DECARBONIZATION

The value of sold industry output was around 95.6 billion euros in Finland in 2023 with the most important sector metal industry accounting for around 42.3%, the chemical industry accounting for 22.2%, the forestry industry and food, beverages, and tobacco accounting for 17% and 11% respectively (Statistics Finland 2024a). In 2023, Finnish industries consumed 34.1 TWh of electricity (Finnish energy 2024a) while Statistics Finland discloses consumption of 34.47 TWh electricity for industries and construction total (Statistics Finland 2024b).

When it comes to heat consumption of industry in 2023, the district heat delivered to customers was 33.2 TWh with industry accounting for 9%, which is equal to around 2.988 TWh (Energiateollisuus ry 2024) while 2.823 TWh is delivered to industry customers in another dataset revealed by Finnish Energy (Finnish Energy, 2024c). In the meantime, according to Statistics Finland, 3.51 TWh heat was consumed for industrial buildings in 2023, and less heat was delivered to industrial buildings compared to other building types like residential buildings (Statistics Finland 2024c). The total production of industrial heat was 44.951 TWh with most of them 36.518 TWh coming from renewable sources, like black liquor and other wood fuels, nevertheless, there was still much heat derived from conventional fossil fuels with an amount of 6.139 TWh, including oil, natural gas, peat, and other fossil fuels which accelerate global warming (Statistics Finland 2024d). As for final energy consumption of the industry sector, it consumed 122.211 TWh in 2023 (Statistics Finland 2024e), and accounting for around 43.6 % of the final energy consumption, however, according to another dataset of Statistics Finland, the total energy use in manufacturing by industries was 126.006 TWh in 2023 (Statistics Finland 2024f).

This thesis currently mainly focuses on the following sectors: chemical industry, metal industry, and forestry industry because of higher energy consumption share and potential decarbonization. Besides, it is worthwhile to mention that the GHGs emission without Land use, Land-use change and forestry (LULUCF) in Finland in 2023 was 41.103 million tons (Mt) while 53.102 million tons with LULUCF. The industry processes and products use amounts to 4.719 Mt CO2 eq. emissions and energy utilization for manufacturing industries and construction emits 5.052 Mt CO2 eq. so that the total emission of industry in Finland in 2023 was 9.771 Mt CO2 eq. (Statistics Finland 2024g). The data for 2022 was 10.848Mt CO2 eq. for the sum of both which indicates a 1.077 Mt CO2 eq. drop and progress.

2.1 Chemical Industry

In 2023, oil production occupied 51% of the turnover of the chemical industry in Finland, followed by chemicals and chemical products at 29%, pharmaceuticals at 12%, and plastic and rubber products at 8% in 2023. The ambitious target of the chemical industry in Finland is to achieve carbon neutrality by 2045 (Climate roadmap 2035 2024). The largest chemical industry clusters of Finland are in Porvoo, Kokkola, Harjavalta, Oulu and Turku (Vasara et al. 2020).

Direct emissions (scope 1) and indirect carbon dioxide emissions (scope 2) by the companies committed to the Responsible Care program in 2023 were totally 4.45 Mt CO2 eq. of which 83% deriving from direct emissions and left 17% comes from indirect emissions (Kemianteollisuus ry 2024). The emission of chemical industry was 4.6 Mt CO2 eq. with 3.5 Mt CO2 eq. coming from scope 1 and 1.1 Mt CO2 eq. coming from scope 2 in 2022 (VTT 2024). Scope 1 or direct emission means the sources of emission are controlled by a company, like process emissions from manufacturing of a company, while scope 2 or indirect emission means the emission coming from purchased energy, like electricity, steam, heating and so on. Besides, scope 3 normally means the emissions from the value chain, comprising upstream and downstream. Since the first roadmaps initiated in 2019, most of the companies have joined this program which accounts for 97% of the sector’s production and 96% of the industry’s energy consumption (Climate roadmap 2035 2024). The total energy consumption of the chemical industry was 21.033 TWh in 2023 with 5.951 TWh for electricity and 3.596 TWh for heat, left energy consumption comes from the utilization of oil, natural gas etc. (Statistics Finland 2024f). However, according to another dataset of Statistics Finland, electricity consumption was 6.391 TWh of in 2023 by the chemical industry (Statistics Finland 2024b).

The research conducted with the cooperation of technical research center of Finland (VTT) and the Chemical Industry Federation of Finland gives five definitions for the classification of chemical industry companies in Finland now, which comprises energy-intensive chemical industry, inorganic chemistry and battery materials, reactive chemistry, formulating, and converters. The most energy-intensive and GHGs emissions are concentrated in the first two categories. Companies in Formulating have the lowest emissions and direct emissions only account for 1% of the chemical industry's total emissions while the second lowest CO2 emissions is the converters category, and most of the energy usage by converters has been already clean. As for reactive chemistry, the most of energy usage is electricity and 50% has come from low-carbon sources, meanwhile, the renewable and recycled raw materials are higher than the fossil raw materials (VTT 2024).This thesis primarily focuses on the companies classified as energy-intensive chemical industry and inorganic chemistry including battery materials companies to identify the main contributor of GHGs emissions and the potential to eliminate the emissions.

Neste is the biggest company to produce renewable diesel and jet fuel refined from waste and residuals, also it produces sustainable aviation fuels, marine fuel, plastics, and chemical products. There is only one refinery in Finland located at Porvoo. To decarbonize the refinery in Finland, Neste signed a purchase agreement of solar energy for the refinery in Provoo, Finland at the end of 2023 and expected to start in spring 2024 with a total capacity of around 24 GWh. The climate target is to achieve carbon neutrality in 2040, covering scopes 1, 2, and 3 for the whole value chain. In addition, Neste has constructed high voltage charging stations for light and medium-duty electric vehicles in Finland although Neste still purchased 11.7 Mt crude oil for refining and oil production in Finland in 2023 (Neste 2024) and it has been working on the 120 MW electrolyzer project to generate green hydrogen in Porvoo and expected to start generation in 2026, which will replace the hydrogen produce from fossil feedstock and be utilized in refinery's processes (Neste 2023).

Borealis produces basic chemicals, polyolefins, and has sold its nitrogen, fertilizer melamine, etc. business to AGROFERT in June 2022. There is one production facility in Porvoo, Finland named Borealis Polymers Oy which produces polyolefins and basic chemicals with a production capacity is 0.74 million tons (Borealis 2024). Kemira is a company providing chemical solutions for water-intensive industries, like industrial and municipal water treatment operators with tightening regulations, and the pulp and paper industry among others. There are six production facilities in Finland, including Oulu, Kuusankoski, Joutseno, Pori, Sastamala, and Harjavlata, to produce chemical products and the production volume is 4 856 000 tons in 2023 (Kemira 2024). Yara, there are three manufacturing facilities in Finland, including Siilinjärvi, Uusikaupunki, and Kokkola. The energy consumption is significantly driven by ammonia production, which is the key component of fertilizer, and accounts for around 86% of energy consumption for Yara company, meanwhile natural gas is the main fuel source accounting for 94% of total fuel consumed (International ASA Yara 2023).Tetra Chemical Europe has a production facility in Kokkola, Finland, which has been manufacturing Calcium Chloride and providing warehouse service. The carbon capture technology has captured around 75% of the emissions of this production unit and provided captured CO2 to industrial gas manufacturing in Kokkola Industrial Park. In the meantime, the scope 1 emission of Tetra company is 0.051257 Mt CO2 eq. so the emission in Finland's facility is much lower, and CO2 is captured in Kokkola. It is not much imperative part of decarbonization compared with other chemical companies in Finland (Tetra 2024). The emission of these primary chemical companies in 2023 is shown in Table 1.

In the carbon neutrality scenario conducted by VTT, the main technologies and assumptions utilized in the chemical industry for decarbonization are carbon capture and utilization (CCU), carbon removal, chemical recycling, more efficient chemical process technologies, and replacement of feedstock by renewable or synthetic raw materials. The chemical industry will nearly achieve carbon neutrality by 2045, which has transitioned away from fossil fuels and emissions including scopes 1 and 2 are close to zero through a carbon-neutral energy system after 2030 and feedstocks transition by 2045. Scope 1 emission will be reduced to close to 0 by electrification and renewable feedstock. The assumption for green hydrogen production is 0.2 million tons and the clean electricity is 19.2 TWh, the biggest emission deduction will happen in 2035 in this roadmap due to assuming the stop of the crude oil refinery in 2035 (VTT 2024).

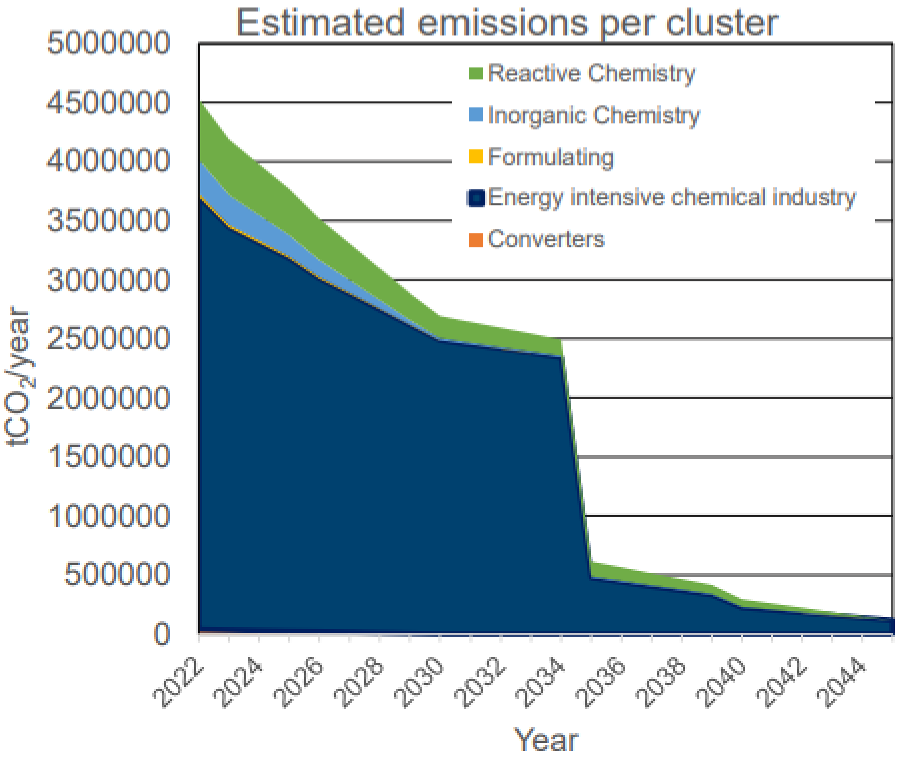

Figure 1. Climate neutrality scenario roadmap of the chemical industry (VTT 2024)

2.2 Technology industry

Technology industries encompass the metals industry, the electrotechnical and electronics industry, the machine and metal product industry, information and communications technology (ICT), engineering and management consulting, etc. branches. Most of the GHGs emissions are derived from metal processing and the mining of metal ore and industrial minerals, with the left branches like the electrical and electronic industry, etc. only accounting for 2% of emissions of this sector's total emissions (Paloneva and Takamäki 2021a). In 2022, the direct emission was 5 Mt CO2 eq. and indirect purchased energy use emission was 1.2 Mt CO2 eq. The roadmap assessed the indirect emissions for scope 3 for the first time and found that the indirect emissions amounted to 78% of total technology industry sectors' value chain emissions mainly produced by scope 3 because the machines or equipment produced by the technology industry need energy to operate and emit many GHGs during operation. Meanwhile, the total emission including scopes 1,2, and scope 3 amounts to 29 Mt CO2eq.The current fossil fuel consumed by the technology industry accounts for around 41% of whole industries' fossil fuel consumption in Finland (30TWh), which equals 12.3TWh and 95% comes from metal processing and mines. However, according to the data from Statistics Finland and the bar chart in the slides of Roadmap for the technology industry of Finland, the consumption of fossil fuel is around 12.4 TWh (Vassinen et al. 2024). Currently, the fossil fuels consumption was 13.485 TWh in 2023 with 9.16 TWh electricity consumption and 2.55 TWh heat consumption, which includes mining and quarrying, manufacturing of basic metal, manufacture of electrical and optical equipment, machinery and metal manufacturing based on the Technology Industry Federation of Finland and Statistics Finland (Statistics Finland 2024f). The GHGs emissions of technology in 2023 are missing now, the latest research only reveals the emissions in 2022.

To dig deeper into decarbonizing in the metal manufacturing process due to high fossil fuel consumption and emission, the crucial companies related to metal production should be identified and recognized first.

SSAB has two manufacturing facilities in Finland, which are located in Hämeenlinna and Raahe. The primary products are cold-rolled, metal- and color-coated steel in coils, strip and slit strip in Hämeenlinna, and hot-rolled plate and strip in the Raahe facility respectively. And the target of SSAB for GHGs emissions is decreasing 35% in emissions between 2018-2032 for scopes 1 and 2. The annual carbon dioxide emissions of SSAB in Finland correspond to approximately 7% of total national emissions, which most emission for scope 1 comes from the conventional blast furnace for iron ore reduction using coal or coke and basic oxide furnace for iron refining. According to SSAB’s annual report 2023, the sum of direct and indirect emissions in Finland in 2023 is 4.485 Mt CO2 eq. in 2023. In terms of the energy consumption of SSAB, 1 042 GWh natural gas, 995 GWh propane, and 199 GWh oil are consumed in the Nordic region, namely Sweden and Finland, purchased electricity is 1 581GWh and purchased heat is zero (SSAB 2024). According to other data sources, the factory in Hämeenlinna consumes 400GWh of natural gas and 200GWh of electricity every year (Lepisto 2024). SSAB reveals that the Raahe factory consumes 0.8 TWh of electricity per year and consumes 1560 kt coal every year. Although the Raahe factory will consume zero coal in the future, the sources of planned consumption of 0.4-1.4 TWh biogas per year, 43kilotons biocarbon, and 0-1300 million cubic meters of hydrogen annually still need to be produced (Lilja 2020). meanwhile, total energy consumption in Raahe is 12-13TWh per year if energy carrier raw materials are included, average energy consumption per ton of steel of SSAB Finland is around 4 MWh, of which the exact data and share of energy source is confidential (Motiva 2020).

As for the Outokumpu company, it is committed to decreasing 42% emissions per ton of stainless steel by 2030 compared to 2016 for scope 1, 2, and 3 emissions, and the long-term target is to achieve carbon neutrality by 2050 in scope 1 and 2 emissions. In Finland, there are two factory sites in Tornio and a mine in Kemi, which produces stainless steel and ferrochrome with raw materials coming from the mine in Kemi. In 2023 Outokumpu made an investment decision on a pelletizing plant to produce biocoke at Tornio and start production in mid-2025, which means that the Outokumpu still utilizes coal/coke for the reduction of chromite ore to extract chromite for ferrochrome production in Tornio, and the annual sustainability report 2023 also indicates that majority of direct CO2 emissions originate from coke in ferrochrome production. In Tornio, three submerged arc furnaces (SAF) ferrochrome smelting furnaces are utilized. For stainless steel production, they utilized EAF for recycled steel scraps, which is regarded as a more environmentally friendly method for production if electricity is used from renewable energy. In the meantime, the natural gas propane and a small amount of oil are consumed for heating. The short-term strategy is replacing propane with natural gas where reasonable and using biofuels at some sites. To reduce indirect emissions, purchasing low-carbon electricity and heat is essential.(Outokumpu 2024a)

Outokumpu’s direct emissions are mainly derived from the use of fossil coke, which is utilized as the reductant in ferrochrome production and produces the majority of direct CO2 emissions, liquified natural gas (LNG) and CO gas, although Outokumpu decided to invest in a pelletizing plan to produce biocoke replacing the fossil ones in Tornio for a short-term target, which can help reduce carbon emissions by 82 000 tons. In the long run, Outokumpu investigated replacing the coal-based reductant. To reduce the emissions from the utilization of heating fuels, replacing propane with natural gas and using biogas are considered effective measures together with digitalization projects (Outokumpu 2024a). It is worthwhile to notice that biocoke is the currently best available technology for the alternatives of fossil coke in the production of ferrochrome, because hydrogen cannot be utilized as the reductant in the ferrochrome production process due to the required high temperature for chromium ore reduction. The production of the pelletizing plant is biocarbon and biocoke, which can be utilized in stainless steelmaking and ferrochrome production respectively (Outokumpu 2023).

Outokumpu manufactured 2 247 726 tones stainless steel, 395 379 tones ferrochrome and 1 154 798 tones slag are in 2023, which consumed 209 992 tones coal/coke, 1 469 tones biocoke, 5 800TJ natural gas, 449 TJ diesel, light and heavy fuel oil and 1 663TJ propane. (Outokumpu 2024b). In 2019, the energy consumption of the Outokumpu production facility in Tornio, Finland was 4.9 TWh of which electricity consumption is 2.9 TWh, natural gas consumption is 0.9 TWh and heat consumption is 0.4 TWh, although the reference indicates 0.4 GWh heat consumption, which might be wrong unit and this thesis adopts 0.4TWh.The carbon monoxide gas consumption, which comes from the process of ferrochrome production, is 0.4TWh. Procured coke is feedstock and not utilized for energy providers. (Motiva 2020)

In terms of Boliden in Finland, there are two smelter facilities and one mine, which refer to Boliden Kokkola, Boliden Harjavalta, and Boliden Kevitsa. Kokkola facility produces word-class zinc with Boliden Harjavalta producing copper and nickel. Boliden is committed to a 42% reduction in scope 1 and 2 and 30% in scope 3 by 2030 compared with 2021. When it comes to the energy consumption of Boliden company, coke/coal, oil, and fuel gases are mainly used for the reduction and smelting of copper, lead, and zinc concentrates. The electricity consumption in Finland is around 2TWh. (Gasum 2020). In 2019, the energy consumption of the Boliden zinc mill in Kokkola Industrial Park was 1.4TWh of which 1.2TWh is electricity, accounting for the electrolysis process for manufacturing zinc. For copper and nickel productions in the Harjavalta and Pori electrolysis unit, the total energy consumption is 562GWh (Motiva 2020).

Ovako has only one facility in Imatra, Finland, and the steel materials entirely are based on recycled scrap. This company offset all the emissions in 2023 with carbon offset and the emission of the Imatra factory is 42 kt in 2024 which is achieved by transiting to fossil-free electricity in 2018 and retrofitting the bloom furnace with less natural gas consumption in 2023.(Ovako 2025). The natural gas consumption is 169.383 GWh and the electricity consumption in January is 17.956 GWh in 2022 (Jere 2023), while in 2018, the energy consumption was 442GWh of which half was electricity consumption and another half was natural gas consumption (Motiva 2020).

The strategy for decarbonizing the technology industry is to reduce the GHGs in scope 1,2 and 3, which refers to direct emissions and indirect emissions. For scopes 1 and 2, the primary solutions are electrification of process, replacing fossil fuels with renewable fuel, like synthetic fuels or bio-based fuels, improving efficiency, CCUS, hydrogen as the reduction, reducing the purchased energy carbon footprint, etc. measures. As for scope 3, cooperation among the whole value chain is imperative, for example, the design of products that utilize the low carbon fuels or consume fewer materials and use eco-friendly materials to decarbonize the upstream carbon emission and the use phase, also tap the potential for the circular economy, low carbon packaging and materials, prolong the life cycle of products, etc. solutions decrease the emission of scope 3. However, in the low carbon reformer scenario conducted by Gaia, the electrification of manufacturing is assumed to have 0 potential GHGs emission reduction (Vassinen et al. 2024). Although promising technology exists now, for example, MOE (molten oxide electrolysis) for steelmaking, and solutions for metal processing have 6 Mt emissions reduction potential, which might be the assumption of hydrogen utilization, and the detailed decarbonization roadmap of the technology industry is shown in the following figure. The most decarbonization potential for the technology industry is SSAB company with 4.485 Mt CO2 emissions for scope 1&2 in Finland 2023 and the maximum decarbonization potential using hydrogen is 6 Mt CO2 eq with zero potential for electrification.

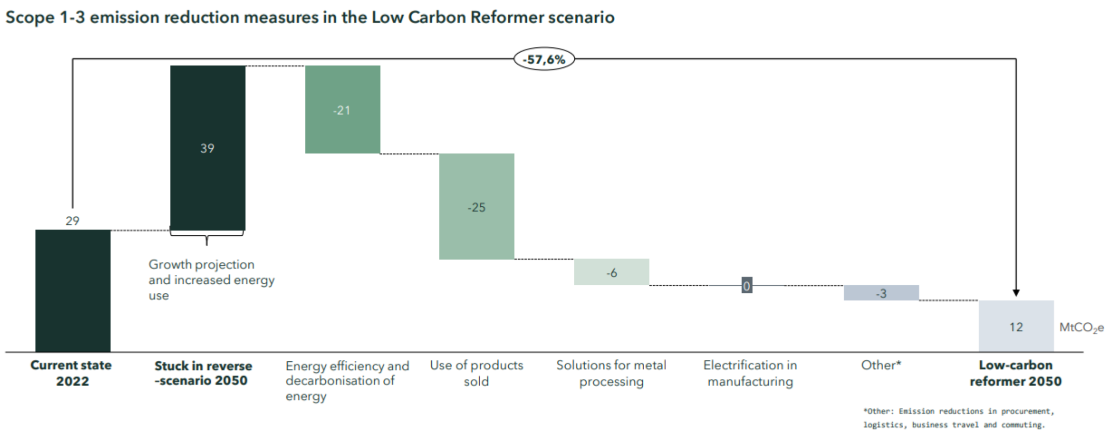

Figure 2. Roadmap of the technology industry (Vassinen et al. 2024)

2.3 Forestry industry

The Finnish Forestry Industries Federation comprises 62 member companies that operate in the pulp, paper, paperboard and packaging industries together with wood products industry, like industrial sawmills, wood-based panels companies, carpentry products and wood construction sector, also represents Finland’s entire pulp, paper, and paperboard industry as well as about 65 per cent of the wood products industry. (Finnish Forest Industries Federation 2024) In 2017, the annual climate-positive impact of the forest industry was estimated to be 16 million tons, which is the result of wood-based products replacing products that generate more fossil emissions. The emission from plants was around 3 Mt CO2 in 2017 (Paloneva and Takamäki 2021b). The forestry industry mills will phase out fossil fuels nearly by 2035 and the electricity consumption was 14.363 TWh in 2023 (Statistics Finland 2024b).

The forestry industry and wood-based products have the potential to combat climate change by replacing conventional plastic or fossil-based products, also bio-based fuels can decrease fossil fuel dependency and GHGs emissions. For example, lignin is anticipated to be utilized in the battery as a substitution for oil-based materials and as an insulation material, also many kinds of biofuel can be produced by biorefineries, like bioethanol, biodiesel, etc. Moreover, pulp attracts more and more attention being used in textiles, 3D printing, the pharmaceutical industry, and composites. The positive climate impact of Finland's forestry industry output is abating 16 Mt CO2 eq per year. Due to urbanization, population growth, legislation and rules, and so on factors, global marketing for forestry industry products is increasing, besides, circular carbon and circular economy accelerate the economy, create jobs, and mitigate climate change. The global market for wood products is estimated to grow by 200 billion euros from 2012-2023. (Finnish forestry industries 2020)

Currently, the fuel consumption of forestry in Finland in 2023 is 178 565 TJ of which 92% come from renewable energy, so the share of fossil fuel consumption is significantly low now, fossil fuel consumption is around 8% of current fuel consumption, which equals to around 3.96 TWh in 2023 and this amount of energy has the potential to be decarbonized. (Finnish forestry industry federation 2024). The main methods utilized to achieve carbon neutrality and climate targets include biogenic carbon dioxide capture storage and utilization (BECCUS). By 2040, BECCUS could be 6 Mt CO2 per year of which 1 Mt CO2 will be stored, and 5 Mt CO2 will be utilized as industrial raw material. Besides, substituting conventional fossil fuels (like peat, oil, natural gas, and other fossil fuels consumed in 2023) with bio-based fuels in 2035 and phasing out fossil fuels. The BECCUS plans to be implemented during 2030-2035, which is a crucial practice for decarbonization, and a turning point for achieving the climate targets. The carbon neutrality is nearly achieved in 2035 and after that, it is negative carbon (Silver and Tuokko 2024). There are potentials or attributions of the forestry industry for decarbonization target, firstly, the fossil fuel consumption decreases, secondly, the forestry resources have the potential of carbon sink to increase an amount of 3550 Mt CO2 forest resources in 2035 and around 3800 Mt CO2 in 2041-2045 by proactive forestry management. (Finnish forestry industries 2020)

The emission of forestry mills or plans in Finland was around 3 Mt CO2 eq in 2017 and is projected to be around 0.3 Mt CO2 eq in 2035 (Finnish forestry industries 2020), which is nearly zero and achieved by replacing fossil fuel, electrification (like a dryer or electric boilers etc.) and energy efficiency measures, meanwhile, digitalization is highlighted in updated low carbon sectors roadmap in Finland in 2024. The potential utilization of SMRs or hydrogen is the combination of clean hydrogen with BECCUS to produce value-added products or synthesis fuels, although the roadmap of forestry indicates replacing fossil fuel with bio-based fuel. As indicated from the below decarbonization roadmap of the forestry industry, electrification and improvement the energy efficiency will deduct around 0.3 Mt CO2 eq. by 2023, and electrification will decrease emissions while increasing energy consumption. The role of hydrogen is not significant from the roadmap point of view, but the BECCU can be utilized with clean hydrogen. Eventually, the forestry industry will become carbon neutral by 2035 based on the roadmap below.

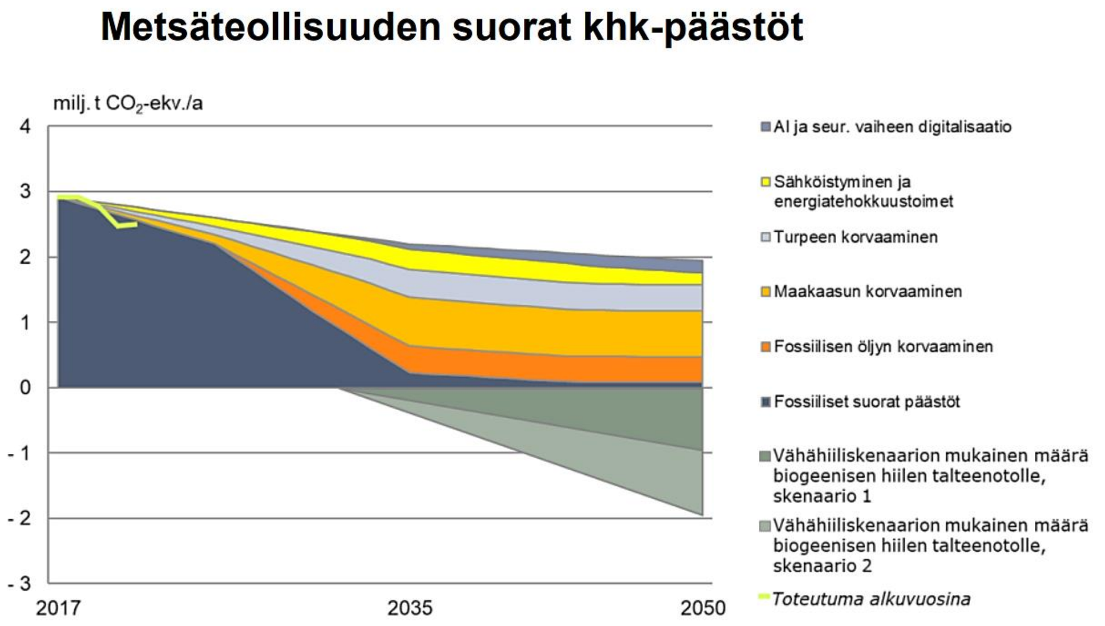

Figure 3. Roadmap of the forestry industry in Finland (Petri, 2024)

2.4 Projected energy consumption

Based on FINGRID's forecast for Q1 2024, the electricity consumption projects are to be 131 TWh by 2030 with 22TWh for industry and data centers, and 17 TWh for hydrogen production (Fingrid 2024). According to the low-carbon roadmap 2024, the electricity demand projects to be around 230TWh in 2040 for a low-carbon scenario, even in the baseline scenarios the electricity production amounts to around 130 TWh in 2040. (Silver and Tuokko 2024) As for the technology industry, TIF (Technology Industries of Finland) anticipates that the electricity consumption in the technology industry projects to be 23TWh in 2035 and 91 TWh in 2050, and hydrogen consumption for the steel industry in 2040 is 6TWh (Vassinen et al. 2024). The Chemical Industry Federation gives the carbon neutrality scenario which indicates the energy consumption with 19.2 TWh of electricity and 3TWh of others, hydrogen production is 0.2 Mt.

Table 1. Summary of main companies' emissions in Finland 2023 (Energiavirasto 2024)

Company	**Emissions (tons of CO2)**
SSAB Europe Oy	3 805 494
Neste Oy	2 529 098
Outokumpu Stainless Oy	632 428
Borealis Polymers Oy	466 839
Boliden Harjavalta Oy	71 614
Boliden Kokkola Oy	7 969
Ovako Imatra Oy Ab	35 192
Yara Suomi Oy	51 321

Table 1 shows that the most important and highest decarbonization potential companies mentioned in this thesis. Neste emits the most emissions for the chemical industry in Finland, which processes crude oil for oil products and produces renewable diesel and jet fuel etc. renewable fuel. In terms of the technology industry, SSAB and Outokumpu have the biggest contribution to fossil fuel consumption, especially the coal/coke consumption of SSAB for steelmaking and Outokumpu for ferrochrome production. When it comes to the forestry industry, although most of the fuel consumption now is renewable (mainly black liquor), the remaining fossil fuel still needs to be phased out by using bioenergy and BECCUS technology should be utilized for carbon sequestration, storage, and utilization of industrial raw materials later. The forestry industry's fossil fuel consumption is around 3.96 TWh in 2023, which shows the potential to be decarbonized in the future and related federation or government seems to tackle this issue by utilizing bioenergy and BECCUS for carbon sequestration, storage, and utilization for industrial raw materials. Based on the primary companies and carbon roadmap of sectors, the following chapters illustrates the small modular reactors, and it is potential to produce hydrogen and industrial heat for decarbonization together with three case studies, namely SSAB Raahe, Outokumpu and Kokkola Industrial Park (KIP).

3 SMALL MODULAR REACTORS

Nuclear power plants utilize the energy derived from nuclear fission or fusion, which means the nuclei of atoms split into several parts or fuse respectively to release energy, and the operational nuclear power plants nowadays are based on nuclear fission technology while harnessing nuclear fusion as an energy source is still under research and development.(Galindo 2022) Figure 4 illustrates a general process of nuclear fission which is triggered by a neutron hitting fissile nucleus so that the nucleus splits into two or more smaller nucleus while energy is released and additional neutrons are generated to hit other nucleus again, then the chain reaction is achieved to sustain the energy production.

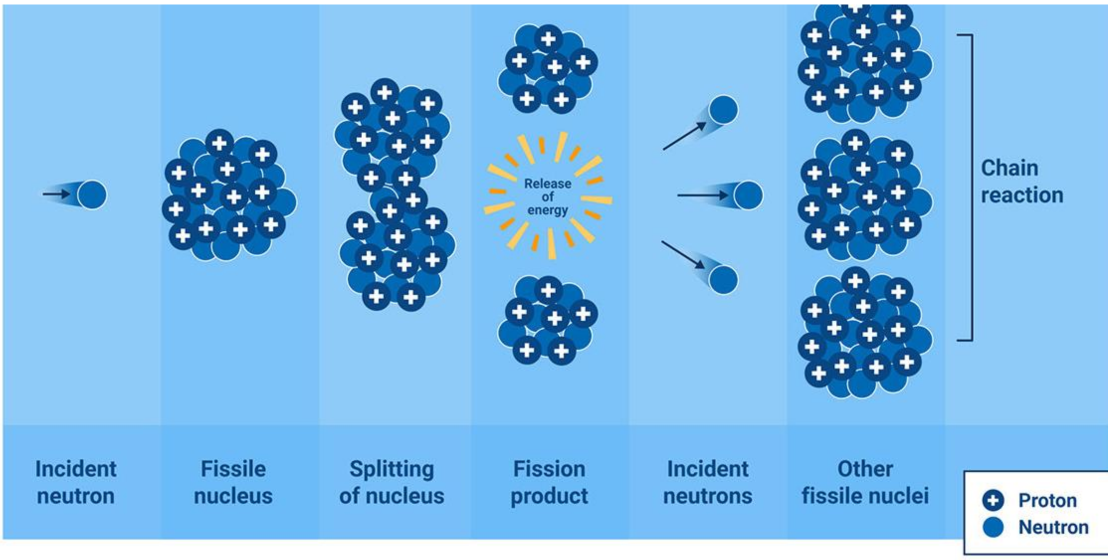

Figure 4. Nuclear fission process (Galindo 2022)

The simplified process of a pressurized water reactor, which is the most common type of reactor nowadays, is shown in Figure 5 below. Obtained energy from nuclear fission reaction is utilized to generate steam which will drive the turbines to generate low-carbon electricity, and the electricity is transferred and distributed later. Inside the steam generator, energy coming from the reaction core is transferred to coolant, normally water, not only to generate high-temperature and pressure steam for driving the turbines and activating the electric generator but also to sustain the heat balance of the nuclear power plant and secure safety. Control rods are designed to slow down or speed up the reaction rate by inserting the rods into the core or withdrawing them, because of the neutron absorbing ability of control rods' materials, such as boron or cadmium, etc. materials. The steam leaving the turbine goes through a condenser and is condensed before going back into the steam generator, the external cooling sources, such as a lake or ocean, will be used to cool the condenser.

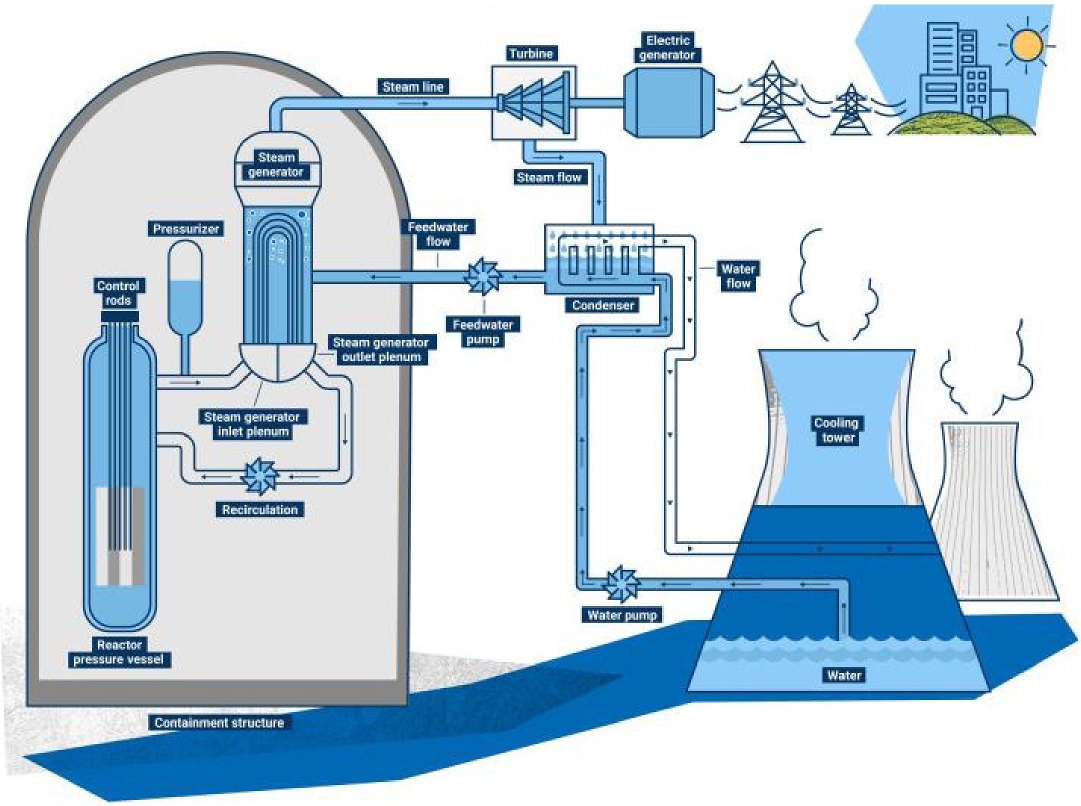

Figure 5. Working principle of pressurized water reactor (Galindo 2022)

Small modular reactors (SMRs) are a type of advanced nuclear reactors with a power capacity of up to 300MWe per unit which harnesses nuclear fission energy as well. Compared with conventional large nuclear power plants, SMRs have a smaller power output and can be expected to be sited in locations currently incompatible with conventional large nuclear reactors; furthermore, their modular design is expected to enable SMRs to be assembled on-site when prefabricated units are manufactured and shipped (Joanne 2021) Because of this, SMRs are expected to have the potential to be deployed for various applications, such as coupling renewable energy to partially compensate for intermittency, or providing the required heat to industries and district heating.

There are currently over 80 SMRs designs under development (Joanne 2021), among them, the LDR-50 is currently under development now in Finland with the goad to be deployed exclusively for district heating by 2030 without electricity generation. Figure 6 shows the design detail of LDR-50, based on the current pressurized water reactor and passive safety design. Heat is generated by a nuclear fission chain reaction and transferred into the coolant which flows between the fuel rods, a secondary circuit or loop is in the middle to receive the heat from the reactor and then transfer it to the district heating network using a heat exchanger. LDR features low operation temperature and low pressure because the required temperature for district heating normally is from 65°C to 120 °C rather than around 300°C in conventional nuclear power plants for electricity generation so the design is expected to be simpler, such as the thinner wall of pressure vessels and simpler safety design The LDR-50 is designed to include natural circulation, with coolant flowing upward after being heated and heat transferred to the secondary circuit through a heat exchanger. (VTT LDR-Reactor 2025)

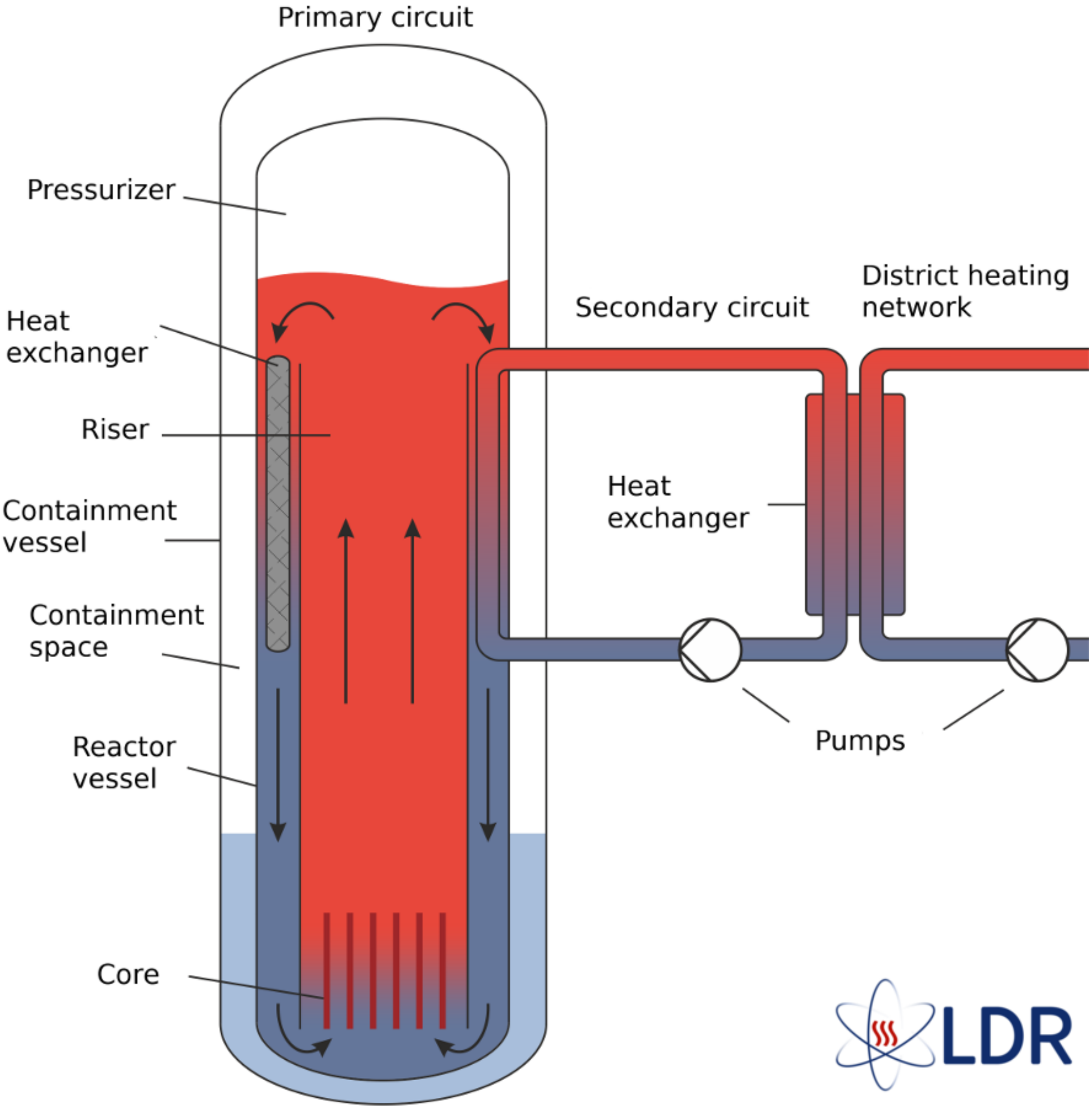

Figure 6. Schematic diagram of LDR-50 (VTT LDR-Reactor 2025)

3.1 Current SMRs development state

There is a new global consensus on accelerating the development and deployment of nuclear energy to contribute to decarbonize and achieve net zero carbon emissions, especially in hard abate areas like industry. More than 20 countries attending the United Nations Climate Changes Conference (COP28) in 2023 supported the pledged to triple nuclear power capacity by 2050. SMRs are developing across various technologies and mainly comprise water-cooled SMRs, gas-cooled SMRs, molten salt SMRs, liquid metal-cooled fast-neutron SMRs, and micro-reactors. (IAEA 2024a) In Finland, initiated on 20 June 2023, the government continues to finance nuclear power, especially for typeapproved SMRs, and explore possibilities to streamline the permission procedure for SMRs (Finnish Government 2023)

Globally, there are currently two nuclear power plants (NPPs) with SMRs in operation, the first one is the Russian Federation's Akademik Lomonosov, which is the first floating nuclear power plant, has begun commercial operation in May 2020. It comprise two KLT-40S reactors with 35MWe output for each reactor and had been refueled in 2023 for the first time. The other one is in China, a type of high-temperature gas-cooled reactor (HTGR) named high-temperature reactor-pebble-bed module (HTR-PM) with a total 200MWe output, which commenced commercial operation in December 2023. Meanwhile, four more SMRs are under construction in Argentina, China, the Russian Federation, and the USA, the types of SMRs are CAREM-25, ACP100, BRESTOD-300, and Hermes respectively, and they are expected to be operational before 2028. Meanwhile, 32 and 28 types of SMRs are under the basic or detailed design stage and conceptual design stage respectively in 2024, although most of the types are under the design stage or conceptual design now, many countries have initiated strategies for constructing SMRs or novel designs in the near future with various capacity and purposes; for example, Canada plans to construct BWRX-300 reactors in 2025 and connect to the grid in 2028, while Japan has 6 SMRs under designs and one test reactor with a thermal power of 30MW which is operational and targeting hydrogen production. Other countries are also considering SMRs as energy sources or monitor development trends. (IAEA 2024a)

Finnish SMR developer Steady Energy company said it will start to construct the LDR-50 pilot SMR plant with a thermal output of 50MW and operation at around 150 °C for district heating in Finland in 2025 in three potential candidate cities, including Helsinki, Kuopio and Lahti. (World nuclear news 2024a) Meanwhile, Kerava Energia in Finland has signed an agreement with Steady Energy Oy to develop the deployment of SMRs as a measure for district heating. The LDR-50 SMR construction is expected to begin by 2028 and operate by 2030 (World nuclear news 2024b).

3.2 SMRs types

SMRs can be generally divided into generally 5 categories. If the SMRs are utilized for industrial heat or other heating applications, Figure 7 gives a general illustration of the thermal power output and output temperature. It shows that the highest temperature SMRs can reach is around 1000 °C, which is achieved by gas-cooled reactors and fast neutron liquid metal-cooled reactors.

Another popular SMR reactor, BWRX-300 proposed by GE Hitachi Nuclear Energy has a single core thermal power of 870 MWth, and the net electricity capacity is 300 MWe. As for the heat application, the available temperature as the process heat source is from 100 to 260 Celsius degrees (GE Hitachi Nuclear Energy 2023).

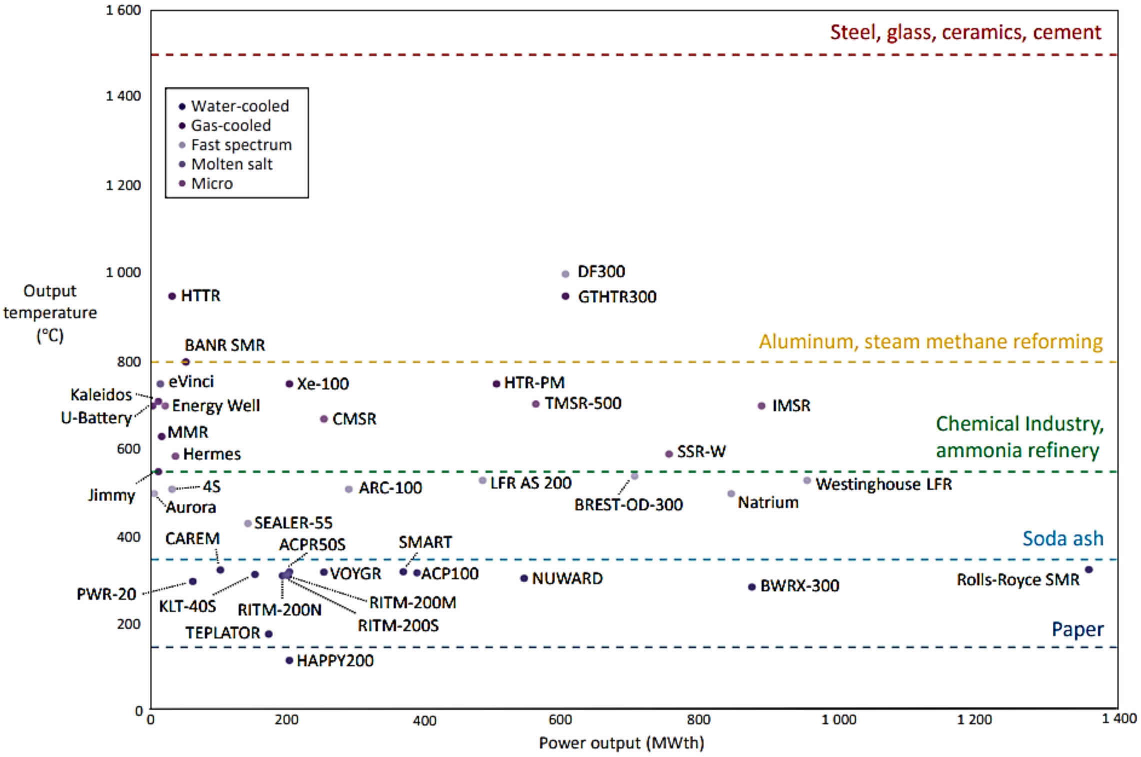

Figure 7.SMRs- range of size and temperature (Nuclear energy agency 2023)

As for other types of SMRs listed in this figure, more details can be found in the small modular reactors catalogue 2024 published by IAEA (International Atomic Energy Agency) and their developer companies or institutions. For instance, the reactor used in the Kokkola Industrial Park case study PWR-20, which is proposed by Last Energy company in the USA with the 80 MW thermal capacity and 20MW electrical capacity respectively. The operation pressure is 15.5 MPa and 2.8MPa for primary loop and secondary loop respectively with 331 Celsius degrees outlet coolant temperature. Targeted application is distributed baseload power including industrial siting and combined heat and power production. The spent fuel management strategy for PWR-20 is repurposing the reactor vessel as a spent fuel cask to ensure the safety of the environment and human beings, aligning with regulation as well (IAEA 2024b).

3.3 Economic challenges of deploying SMRs

Although there are many advantages and progress related to SMRs, uncertainties and challenges still exist, like fuel supply and fuel cycle back-end solutions, manufacturing measures for novel components, the applicability of existing standards, etc. factors, besides, the economic performance of SMRs should be evaluated for feasibility.

One common issue for conventional large nuclear power plants and SMRs are financial delays and cost overruns. SMRs are thought to operate under different economy of scale due to smaller size and rated power compared with large reactors although SMRs are also argued that the modularity has potential to lower costs and provide more flexibility than large reactors. However, the advantages of SMRs for economy feasibility are expected to rely on co-site economy, construction time reduction, fast learning, cogeneration and simplified designs. These factors have various potential to reduce the costs of SMRs. Van Hee et al. give the estimated overnight capital cost of SMRs for harmonized currency and time differences in 2023, and it varies between 3160 euros per kilowatt to 20 153 euros per kilowatt with an average value is 7031 euros per kilowatt, together with the estimation of economic deduction potential for the factors previously mentioned. Compared with large reactors, most of the studies find that the capital cost is 36% higher for SMRs (Van Hee et al. 2024), resulting in more challenging economic infeasibility. As for the O&M and decommissioning cost, further research is needed for a proper estimation(Van Hee et al. 2024) Ultimately, the economic feasibility heavily depends on the specific project and site.

Currently, the SMRs are still projected to be too expensive as mentioned above, and the projected construction time to be much longer than SMRs proponents optimistically state and argue. The projection for costs of SMRs has been increasing based on the operational already SMRs of China and Russia, meanwhile, the estimation of SMRs costs in Argentina, which is under construction, has increased up to 700% from initial estimates. Furthermore, the SMR costs of NuScale company more than doubled from 2015 to 2023, increasing from $9 964 per KW to $21 561 per KW resulting in the cancellation of the company's signature project. Similarly, this trend can be seen for X-Energy and GE-Hitachi companies' SMRs projects, even before the actual construction of the SMRs. The Institute for Energy Economics and Financial Analysis thinks that the cost increases will continue due to SMRs-related work, like additional design work and licensing issues. Also, substantial schedule delays are anticipated resulting in higher costs. Uncertainties exist without doubt about the economy of scale because it depends on how many and which kind of reactors will be built although many designs are proposed (Schlissel and Wamsted 2024). However, although SMRs seem initially costly and have many uncertainties now, they also provide an opportunity to boost the national economy and employment at the same time through direct and indirect influences, for example, projects of SMRs are labor intensive and high paying, also substitute outdated infrastructure by new infrastructure which accommodates SMRs facilities.

Apart from the continuously rising costs, construction time is quite longer than proponents' estimates. The SMRs, which have been built in China and Russia with one under construction in Argentina, show a delay of construction time, around 12-13 years, although the projected schedule construction year is around 3-4 years. The same trend also occurs in US SMR project development presentations. For instance, the 195MW mPower PWR project initiated in 2009 was targeted to be operational by 2022. However, eventually, this project was canceled in 2017 after $500 million had been spent on the reactor design, which indicates indirectly that the whole process of SMRs referring to the design, manufacturing, and regulatory process are complex and costly propositions. NuScale also sees the same situation when this company cancels its SMRs project in November 2023, which was initially planned to be a commercial operation in 2024. Although modular design, technology, and construction are regarded as a measure to reduce construction time and save the budget, Vogtle 3&4 reactors with modular technology are still long delayed and over-budget projects. (Schlissel and Wamsted 2024) SMRs of China spent around 10 years, which is the maximum construction time for Chinese reactors (Schneider et al. 2024). The reduced construction time seems a little opposite with real-world experience until now no matter for large reactors or SMRs. It is imperative that financial risks can be mitigated by multiple stakeholders or investors, stable funding, short construction time, and reduced upfront investment, etc. measures, besides, the required expertise in the nuclear field for operation and maintenance may be absent for some companies if companies plan to construct their SMRs for decarbonization and energy security so that the possible centralized services are needed, while the same situation can be seen for waste and spent nuclear fuel management.

3.4 Regulation and legislation challenges of SMRs

When it comes to the regulation and legislation of SMRs, related regulation needs to be updated for accommodating SMRs. Licensing time is one of the barriers to SMRs development because it is hard to modify the regulatory and legal systems in favor of SMRs, also the regulatory approval-related costs are higher because the new SMRs technology triggers more cost uncertainties compared with large reactors now. Besides, there are uncertainties about interpreting and applying the rules, because the precedent regulation does not exist for SMRs, and uncertain situations or alternative procedures should be discussed before making a decision for specific SMR projects. Also, some old regulations may be applied for part of the process, and the need to avoid repeating the process is essential when the regulation is updated.

The possible licensing process in Finland will separate the decision-in-principle procedure, which is a political decision purely, a technological decision, and a siting decision so that this procedure can be done simultaneously or at different paces (Torkkola 2024). Although the SMRs can be located closer to urban areas according to the latest regulation update, safety should be justified, and the regulation for emergency planning zone is regulated to a maximum of approximately 20KM distance and not exceed 10 mSv within 48 hours after exposure (STUK 2024). In addition, the regulation and expertise required for the innovational design of SMRs are needed compared to regulation before, which may hinder the development of new type reactors due to opposition of laws or regulations. Ensuring the regulatory update to streamline the licensing process for SMRs and provide flexibility for licensees is crucial without compromising technological safety and social sustainability. As mentioned before, Outokumpu has cooperated with Fortum to look for SMRs routes for the decarbonization of steel production. In Finland, Helsinki, Kuopio, and Tornio have already identified candidate sites for nuclear power considering heating, or cogeneration.

Additionally, harmonizing the licensing framework internationally is another issue that needs to be countered, legitimacy of SMRs deployment depends on the flexibility of country-specific nuclear regulations, such as a technology-neutral licensing frame, which means the licensing focus on the technology performance and safety rather than specific technologies used, will be more flexible and accommodatable for SMRs deployment than a technology-specific licensing process. To achieve a faster technology readiness level and large-scale deployment of SMRs, early-stage international cooperation for licensing, codes or standards will be significantly crucial so further international cooperation is needed to ensure licensing SMRs in different regulation regimes (Nuclear Energy Agency 2024).

3.5 Social acceptance of SMRs deployment

Public acceptance or social license is another inevitable factor for nuclear power deployment and trust from the public is a key to introducing SMRs into real life and various applications. The public generally tends to perceive nuclear power plants as riskier and focus more on the consequences rather than on the probability of nuclear power incidents. To solve this challenge, education on the benefits of risky activities and avoiding the possible risky incidents of technologies is crucial. The inherent passive safe designs of SMRs also respond to public concern and increase the safety of operations (Nuclear Energy Agency 2024).

Finland has a better relationship with less controversy between society and nuclear companies compared to other countries because of the engagement of the public and higher trust for experts. 68% of respondents have a positive attitude toward deploying SMRs for district heating (Keto et al. 2023). Based on the resident survey conducted in the Helsinki metropolitan area in 2021 and 2022, residents mostly accept the SMRs and perceive this kind of nuclear power as mostly safe with the most concerned themes being safety and risk, sitting and residents, nuclear waste of SMRs. There is a big difference gender gap in attitude, with females tend to oppose SMRs and regard them as unsafe especially for the closer location of SMRs to their municipalities, while males have a high level of acceptance and perceived safety for SMRs. Apart from the gender-specific factor, political affiliation, trust for STUK and authorities also have impacts on the acceptance of SMRs, together with attitude towards carbon neutrality, etc. elements (Karvonen et al. 2024). For example, opponents of the deployment of SMRs trust environmental organizations more while supporters choose to trust the Radiation and Nuclear Safety

Authority, VTT, and universities, and the trust for different associations will affect the opinions of the public. The result of generally increasing acceptance of nuclear can be found in another research conducted by Finnish Energy, due to climate change, energy security, and crisis, the acceptance of nuclear power as an energy source is six times higher than the opposition in Finland in 2024, although there is a slight decrease from 2023, and the same trend can be seen in rest of EU countries with more momentum for nuclear power (Finnish Energy, 2024d). Although the trend towards nuclear power utilization increases, only 13 % would choose district heating produced with small-scale nuclear power as the heating method for their home, and even fewer would accept a power plant close to their home (Vainio and Kojo 2025).

The spent nuclear waste management also triggers a debate about SMRs providing energy in a decentralized way, which means nuclear power will be generated around the country together with nuclear waste. 41% of respondents agree that nuclear waste can be stored in Finland's bedrock while 27% disagree with that, meanwhile, 37% of the respondents agree that not every plant site or the smallest operators can be required to make their waste management agreements. However, it is interesting that the centralized waste management method is supported, but only 30% agree that the waste should concentrate on final disposal in Eurajoki (Kojo et al. 2023). It is also worth to point that the Eurajoki municipality is already concerned about the additional disposal of spent nuclear fuel in the future, which is the spent fuel repository already for Olkiluoto reactors (Koskinen et al. 2022).

The management of SMR fuels referring to its source is also a factor to consider for SMRs. (IAEA 2024a) Including refueling and nuclear waste management. Three strategies can be utilized for spent nuclear fuel and other radioactive waste generated by SMRs in Finland, namely decentralized, hybrid, and centralized nuclear waste management. Decentralized waste management refers to all handling, treatment, processing, and interim storage measures to be taken locally. This strategy still seems not feasible for all the SMRs, economically, technically, and socially. Centralized waste management means all the spent fuel and other waste will be transferred from every SMRs sites to a centralized site for waste management (Keto et al. 2022). It is also important to point out that the waste management process is itself influenced by SMRs deployment methods, ownership base, responsibilities division among various actors and the license holder factors. Transfer waste management obligation to other parties is possible under current legislation, although this has not yet been done in Finland and will start with a small amount of decommissioning waste from a research reactor. The feasible measures for waste management of SMRs still need to be researched in the future considering the business models as well, not just policy points of view. (Keto et al. 2023).

4 CASE STUDY

The European steel industry has an ambitious target to cut emissions by 55% by 2030 compared to the 1990 level and realize carbon neutrality by 2050. The Technological Readiness Level (TRL) is at least 7 out of 9 for the projects announced by companies in the low-carbon steel industry across the EU (European Steel Association 2022). SSAB is a steelmaking company in Finland, its primary products include hot-rolled plates and strips in the Raahe factory. The direct emission (scope 1) of SSAB Raahe integral in 2023 is 3.964 Mt GHGs and the indirect emission (scope 2) is 389 thousand tons GHGs. The emission of SSAB accounts for around 7% of the total emission of Finland together with another production site in Hämeenlinna, Finland. The target of SSAB for GHGs emissions is to decrease by 35% in emissions between 2018 and 2032 for scopes 1 and 2. (SSAB 2024) To achieve the climate target at the EU level or Finland's national level, phasing out fossil fuel consumption and deploying innovative technology are crucial for SSAB Raahe, the potential of SMRs or hydrogen utilization during the transition of SSAB Raahe is evaluated by case study 4.1.

4.1 Sizing SMRs for SSAB Raahe

Current methods utilized for steel manufacturing in SSAB Raahe refer to the conventional blast furnace (BF) -basic oxygen furnace (BOF) route and these processes are emission-intensive (Lilja 2020). The detailed process of this route is depicted in Figure 8. The first step is to process the iron ore into sinter or pellets in dedicated plants which require around 1200-1500°C by combusting coal or natural gas. The sintering process converts iron ore fines into larger agglomerates which are suitable for blast furnace operation further as for physical and metallurgical characteristics as well as gas permeability. However, pelletizing is also needed some time to produce fired pellets, which are also suitable for blast furnaces, due to some limitations of sintering, and especially when there is a distance from the ore mine and blast furnace, fired pellets are durable and easy to transport, while sintering usually occurs around steelmaking sites (Lu and Ishiyama 2015; Zhu et al. 2015; Somers 2022). The coke plant processes coking coal or metallurgical coal into coke at around 1000°C, which is a refined coal derivative. Then the coke, sinter, or pellets are injected into a blast furnace operating at 1500°C to reduce the metallic iron from iron ore together with lime which works as a fluxing agent and facilitates the removal of impurities. The molten hot metal exiting the blast furnace will go into a basic oxide furnace to reduce carbon content to steel grade level, after that the crude steel will be continuously cast or rolled into different steel products (Somers 2022). The primary chemical reactions happening in blast furnaces with temperature increasing to reduce the iron ore into metallic iron are listed below, although there are reactions between carbon and humidity, carbon and oxygen, etc. (Yang et al. 2014).

$$3\mathrm{Fe_2O_3} + \mathrm{CO} = 2\mathrm{Fe_3O_4} + \mathrm{CO_2} \tag{1}$$

$$\mathrm{Fe_3O_4} + 4\mathrm{CO} = 3\mathrm{Fe} + 4\mathrm{CO_2} \tag{2}$$

$$\mathrm{Fe_3O_4} + \mathrm{CO} = \mathrm{CO_2} + 3\mathrm{FeO} \tag{3}$$

$$\mathrm{FeO} + \mathrm{CO} = \mathrm{Fe} + \mathrm{CO_2} \tag{4}$$

BF-BOF route refers to significant coal or coke consumption no matter for feedstock as a reductant or burning to supply heat demand so that a huge amount of CO2 emission will be generated. Blast furnace is responsible for more than 50% of total CO2 emissions during manufacturing processes, emissions derived from other processes primarily come from fossil fuel combustion to meet high temperature and heat demand. On average, the carbon emission of this conventional steelmaking route is 1.9 tons of CO2 per ton of crude steel (Somers 2022), and the exact emissions depend on countries, specific plants' energy efficiency, and so on elements.

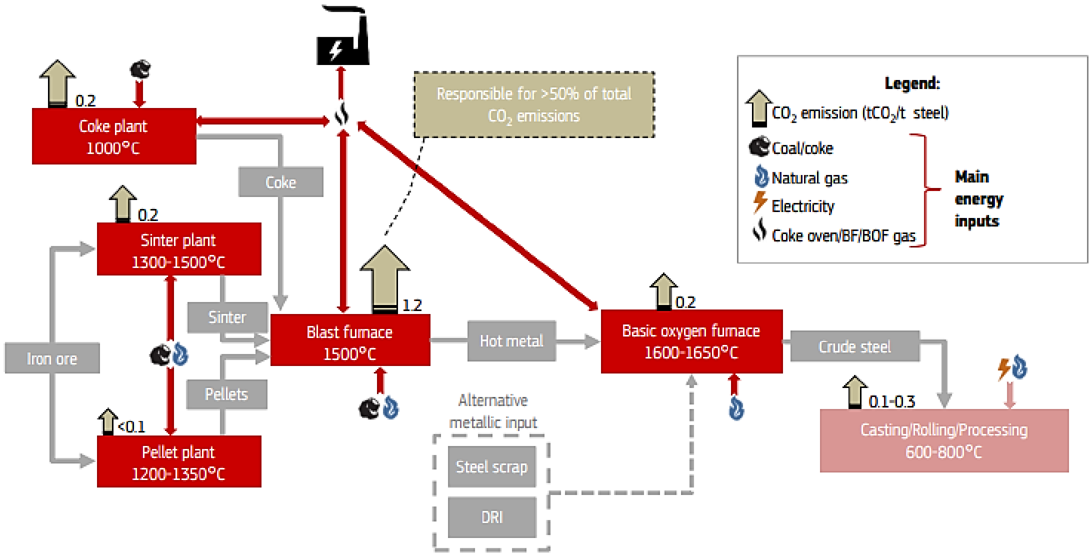

Figure 8.Steelmaking process and emissions factor based on BF-BOF route (Somers 2022)

SSAB company cooperates with LKAB and Vattenfall to initiate HYBRIT technology, which indicates replacing conventional coke with renewable hydrogen as a reductant to produce hydrogen-based direct reduction iron (H-DRI) and utilizing electric arc furnace (EAF) to process H-DRI or scraps. The renewable hydrogen is generated by the electrolysis route, where water is decomposed into hydrogen and oxygen, powered by renewable electricity (Öhman et al. 2022), a simplified process of the H-DRI process is shown in Figure 9 to show the temperature requirements for different steps. The general chemical reaction in the H-DRI process is shown in the equation below and only water is generated as a by-product without CO2 emissions. If renewable hydrogen and electricity are utilized, this route nearly eliminates all the emissions, although there are remaining CO2 emissions from graphite electrodes, carbon-containing materials added, and upstream processes, such as ore mining. However, the remaining emission is around 30-70 kg CO2 per ton of steel (Somers 2022), compared with an average of 1.9 tons CO2/ ton crude steel, the emissions are deducted much.

$$Fe_2O_3 + 3H_2 = 2Fe + 3H_2O \tag{5}$$

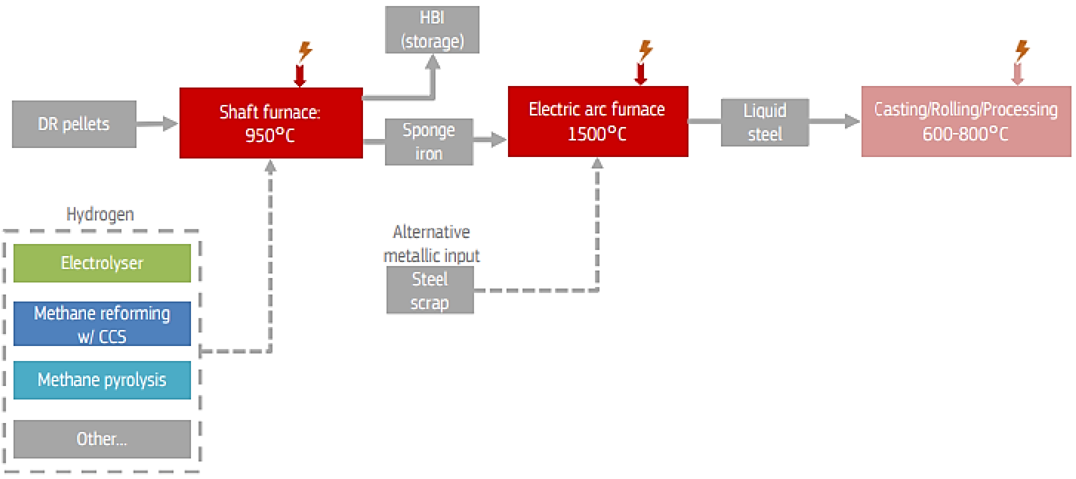

Figure 9. Process of hydrogen-based DRI and EAF for steelmaking (Somers 2022)

4.1.1 Hydrogen demand and electricity consumption of electrolyzer

As mentioned in section 2.2, the current electricity consumption in the Raahe factory of SSAB is around 0.8TWh and the industry electricity consumption in Raahe municipality in 2023 is 1 063 GWh (Finnish energy 2024b). The transition of SSAB steelmaking mainly is achieved by hydrogen utilization, which means utilizing hydrogen as a reductant during the iron ore extraction process rather than using fossil coke as usual, then the EAF (electric arc furnace) can be deployed to manufacturing steel using DRI (direct reduced iron) or scrap by replacing conventional basic oxygen furnace. Currently, the rated production capacity of the Raahe factory is 2.6 million tons of crude steel. (SSAB 2024) If adopting this HYBRIT route, which means hydrogen breakthrough ironmaking technology, is deployed to satisfy the nominal production capacity in Raahe, then 2.6 million tons of crude steel should be manufactured. The hydrogen demand for 100% hydrogen-based DRI process as reductant is around 50-60 kg for one-ton crude steel (Somers 2022). The detailed hydrogen demand for 2.6 million tons of crude steel production and required electricity is calculated following. It is worthwhile to point out that the capacity factor of SMRs is claimed to be 95%, which means the actual energy output is 95% of the total energy production when SMRs operate at rated power for the whole year (Mignacca and Locatelli 2020) and the capacity factor of the electrolyzer is assumed to be 95% in this thesis as well due to consistent operation and matched power.

$$\mathrm{H_D} = \mathrm{C} \times \mathrm{V} \times \mathrm{E_D} \tag{6}$$

Where H_D- Hydrogen demand for SSAB (TWh)

C- Hydrogen consumption coefficient for direct reduction iron (kg/ton)

V- Rated production volume (million tons)

E_D-Energy density of hydrogen (MWh/ton)

$$H_D = (50 \sim 60\text{kg/ton}) \times 2.6 \text{ million tons} \times 33.33\text{MWh/ton} \approx 4.3 \sim 5.2\text{TWh}$$

4.3-5.2TWh renewable hydrogen should be produced per year at most to satisfy the rated production volume. P2X Solutions has already built Finland's first industrial-scale green hydrogen and synthetic methane production unit in Harjavalta with a clean electricity supply from Fortum, currently, the production of green hydrogen is ramping up (P2X Solution 2025) and the chosen electrolyzer is a 20MW pressurized alkaline electrolyzer that comes from the German Sunfire GmbH company. This thesis takes this company as a reference technology practically to have a look at the energy needed for green hydrogen which can be produced by low-carbon electricity provided by SMRs. The efficiency of Sunfire-HyLink Alkaline is $64\%_{\text{LHV,AC}}$, which is calculated based on the low heat value of hydrogen and means 64% of electricity input will be converted into hydrogen, Sunfire-HyLink SOEC has higher efficiency, around $88\%_{\text{LHV,AC}}$, However, this kind of electrolyzer operates based on solid oxide electrolyzer cell (SOEC) technology and needs low-pressure steam (>150°C). The electricity needed for hydrogen demand is calculated according to equation 7 for both electrolyzers (Sunfire 2025).

$$E_{D1} = H_D \div E_E \tag{7}$$

Where E_{D1}-Electricity demand for hydrogen generation through electrolysis (TWh)

H_D-Hydrogen demand for SSAB (TWh)

E_E-Conversion efficiency of electrolyzer (%)

$$E_{D11} = (4.3\sim5.2\text{TWh}) \div 64\% \approx 6.72\sim8.1\text{TWh}$$

$$E_{D12} = (4.3\sim5.2\text{TWh}) \div 88\% \approx 4.89\sim5.9\text{TWh}$$

The electricity consumption E_{D12} decreases significantly if Sunfire-HyLink SOEC is chosen due to higher efficiency compared to that of Alkaline electrolyzer E_{D11}. Required electrolyzer capacity C_E can be calculated by equation 8 for both kinds of electrolyzers.

$$C_E = E_{D1} \div 8760 \text{ hors} \div CF_1 \tag{8}$$

Where C_E-Required capacity of electrolyzer for SSAB Raahe (MW)

E_{D1}-Electricity demand of electrolyzer (TWh)

CF_1-Capacity factor of the electrolyzer

$$C_{E1} = (6.72\sim8.1\text{TWh}) \div 8760 \text{ hors} \div 95\% \approx 807\sim973\text{MW}$$

$$C_{E2} = (4.89\sim5.2\text{TWh}) \div 8760 \text{ hors} \div 95\% \approx 588\sim625\text{MW}$$

The alkaline electrolyzer will require an 807-973 MW capacity while Sunfire Hy-Link SOEC with 88% efficiency needs around only 588-625 MW capacity assuming the capacity factor is 95% powered by SMRs.

4.1.2 Electricity consumption of EAF and other processes

For the H-DRI-EAF route with renewable hydrogen, 3.5-3.95MWh electricity is consumed of which electrolyzer accounts for 75% of consumption (Somers 2022) so that 25% of that electricity consumption is consumed by EAF and other processes, and the electricity consumption $\mathrm{E_{D2}}$ can be calculated below.

$$\mathrm{E_{D2}} = 3.5 \sim 3.95\ \mathrm{MWh/ton} \times 25\% \times 2.6\ \text{million tons} \approx 2.28 \sim 2.57\mathrm{TWh}$$

4.1.3 Heat demand for H-DRI-EAF route

SSAB gives an estimated biogas demand for Raahe transition, and this biogas energy needed will be utilized to reheat slab for rolling and casting, reheat of refractories, lime kilns, and power plant, the sum demand for biogas is 1.4 TWh by 2040, the reference temperature range for casting and rolling is from 600-800 °C as shown in figure 9 (Lilja 2020), although it also includes power plant consumption of biogas and other heat-needed processes, this available data is used to calculate possible thermal power demand maximumly following.

$$\mathrm{TP_{D1}} = \mathrm{T_D} \div 8760\ \text{hours} \tag{11}$$

Where $\mathrm{TP_{D1}}$-Thermal power demand for replacing biogas (MW)

$\mathrm{T_D}$-Thermal demand of biogas by 2040 (MWh)

$$\mathrm{TP_{D1}} = 1.4\mathrm{TWh} \div 8760\ \text{hours} \approx 160\mathrm{MW}$$

Then, thermal power demand for casting, rolling, and processing $\mathrm{TP_{D1}}$ can be satisfied with 160MW at most, and the required temperature is between 600-800°C, if this available data covers all the heat demand of related processes for the Raahe factory. As for the heat demand of pre-heating pellets and hydrogen, pellets need to be pre-heated into 800°C before being charged into the shaft furnace, where a direct reduction process happens, and 436KWh/ton steel electricity is needed by electric heater with 85% efficiency while pre-heating hydrogen to 500 °C needs 160KWh/ton steel using electric heater with 60% efficiency (Bhaskar et al. 2020) so that the original heat demand is around 370 KWh per ton steel for pellets preheating and 962 GWh is consumed annually for 2.6 million tons production volume without considering efficiency of electric heater. Meanwhile, 96 KWh/ton of steel is needed for pre-heating hydrogen, and around 250 GWh of heat demand annually for a rated production volume. The total heat demand is 1212 GWh per year for pre-heating pellets and hydrogen, and the thermal power demand $\mathrm{TP}_{\mathrm{D2}}$ is around 138MW.

$$\mathrm{TP}_{\mathrm{D2}} = 1.212\mathrm{TWh} \div 8760 \text{ hours} \approx 138\mathrm{MW}$$

The specific energy consumption (SEC) of the H-DR process as a function of the scrap charged into the EAF is shown in Figure 10, and the energy consumption of the direct reduction plant or shaft furnace is quite small due to heat recovery and the operation of shaft furnace is 800°C in the reference when pellets and hydrogen have been preheated, this part of heat demand is around 0.1MWh/ ton liquid steel by estimation based on this figure (Vogl et al. 2018).

$$\mathrm{TP}_{\mathrm{D3}} = 0.26\mathrm{TWh} \div 8760 \text{ hours} \approx 30\mathrm{MW}$$

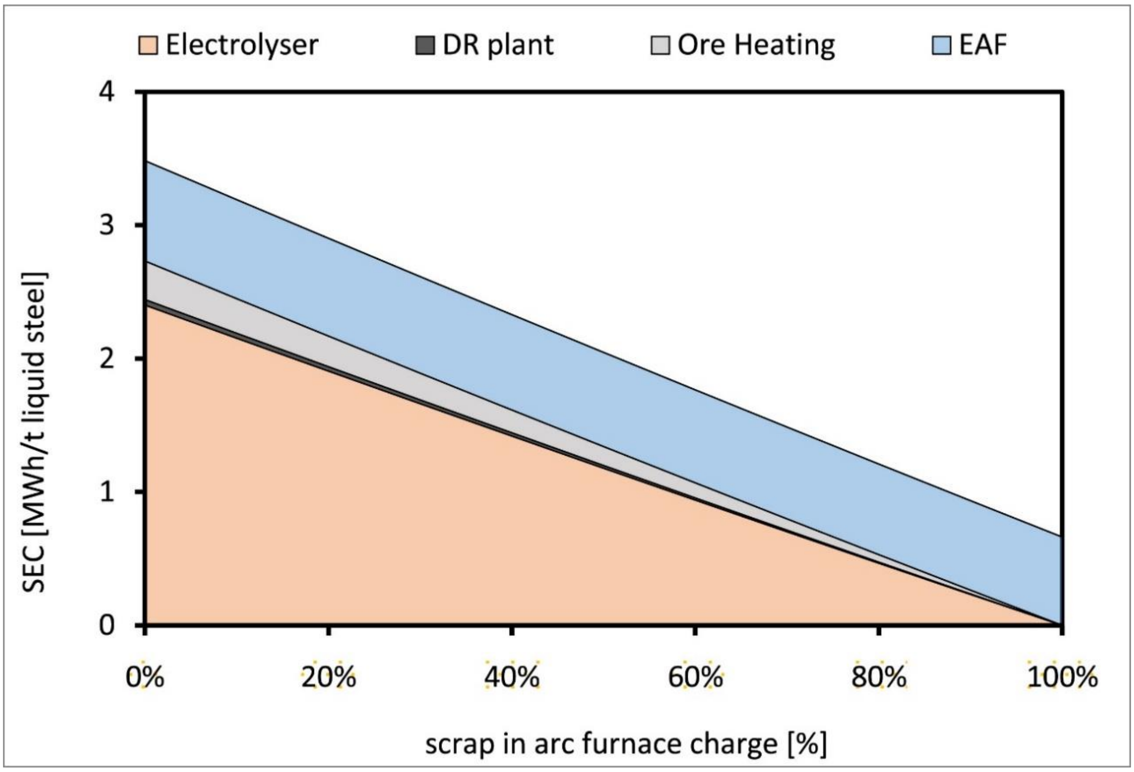

Figure 10. Specific energy consumption (SEC) of the H-DRI process as a function of the scrap charged into the EAF (Vogl et al. 2018)

The annual heat demand is 0.26TWh annually by multiplying 2.6 million tons of production while the required thermal power demand $\mathrm{TP_{D3}}$ is around 30MW for the direct reduction process. If SOEC is chosen, different system integrations might have various thermal power demands for SOEC operation. This thesis gives two operation modes, the first one is waste heat of SMRs will be utilized in the water evaporation process and electric heating is still needed to heat the steam and air to the operational temperature at around 800°C, then the thermal power needed for SOEC is 200KW external heat for 1 MW SOEC with at least 130 °C steam should be provided (Zhao et al. 2021). If this strategy is utilized, then the thermal power demand for Sunfire SOEC $\mathrm{TP_{D4}}$ from Sunfire company will be calculated below.

$$\mathrm{TP_{D4}} = \mathrm{TP_{El}} \times \mathrm{C_{E2}} \tag{12}$$

Where $\mathrm{TP_{D4}}$-Thermal power demand of SOEC (MW)

$\mathrm{TP_{El}}$-Thermal power demand coefficiency of SOEC electrolyzer (KW/MW)

$\mathrm{C_{E2}}$-Capacity of Sunfire SOEC electrolyzer (MW)

$$\mathrm{TP_{D4}} = 200\mathrm{KW/MW} \times 588{\sim}625\mathrm{MW} = 117.6{\sim}125\mathrm{MW}$$

The second one is utilizing high-temperature waste heat from SMRs directly to heat the steam to 800°C If the electrolyzer operates at 800°C and the high-temperature gas-cooled reactor (HTGR) is used for heating and electricity, approximately 75% of the required energy comes from electricity and remaining 25% is for process steam heating (Milewski et al. 2021). Based on this data, the required heat and thermal power $\mathrm{TP_{D41}}$ can be calculated following.

$$\mathrm{TP_{D41}} = \mathrm{E_{D12}} \div 75\% \times 25\% \div 8760 \text{ hours} \tag{13}$$

$$\mathrm{TP_{D41}} = (4.89{\sim}5.9\mathrm{TWh}) \div 75\% \times 25\% \div 8760 \text{ hours} \approx 186{\sim}224.5\mathrm{MW}$$

Both routes have the same magnitude of thermal power demand, and $\mathrm{TP_{D41}}$ is adopted in the further calculation because the temperature requirement for other processes is also high, and it is feasible to provide 800°C temperature for several types of SMRs.

Meanwhile, the possibility of decarbonizing district heating exists, the carbon dioxide emissions of district heating in Raahe in 2023 is 4 860 tons CO2 with an emission coefficient of 22.1 kgCO2/MWh and the total energy supplied is 219.7 GWh of which 90.3% comes from heat recovery or heat pump production so that the fossil fuel consumption is 16.5 GWh (Finnish Energy, 2024b, 2025). The reference temperature for district heating is 72-115°C (Joonas 2024). Because the heat demand is quite less compared with other processes, especially for fossil fuel consumption, and the temperature is not high, this part of heat demand is not included in the calculation later.

4.1.4 Total electricity consumption and heat demand

The total electricity consumption $\mathrm{E_{C1}}$ is around 9-10.67TWh if choosing the alkaline electrolyzer while the total electricity consumption is around $\mathrm{E_{C2}}$ $7.17\sim8.48\mathrm{TWh}$ electricity if Sunfire SOEC electrolyzer is chosen, which shows less electricity consumption due to higher electrolyzer efficiency

$$\mathrm{E_{C1}} = \mathrm{E_{D11}} + \mathrm{E_{D21}} = (6.72{\sim}8.1\mathrm{TWh}) + (2.28\ {\sim}2.57\mathrm{TWh}) = 9{\sim}10.67\mathrm{TWh}$$

$$\mathrm{E_{C2}} = \mathrm{E_{D12}} + \mathrm{E_{D21}} = (4.89{\sim}5.9\mathrm{TWh}) + (2.28\ {\sim}2.57\mathrm{TWh}) = 7.17{\sim}8.47\mathrm{TWh}$$

As for the total thermal power demand TPD If SOEC is chosen, it will be calculated below, while if selecting an alkaline electrolyzer, then the thermal power demand is less because normally alkaline electrolyzer doesn't need external heat (Firtina-Ertis 2022).

$$\mathrm{TPD} = \mathrm{TP_{D1}} + \mathrm{TP_{D2}} + \mathrm{TP_{D3}} + \mathrm{TP_{D41}}$$

$$\mathrm{TPD} = 160\mathrm{MW} + 138\mathrm{MW} + 30\mathrm{MW} + (186{\sim}224.5\mathrm{MW}) = 514{\sim}552.5\mathrm{MW}$$

In addition, another method for decarbonizing the steel sector is molten oxide electrolysis (MOE) technology which will achieve commercialization by 2026 as Bosten Metal company's schedule, then this technology might be a game-changer which only produces oxygen as a by-production and utilizes renewable electricity. Also, this direct approach simplifies steelmaking processes like cutting off iron ore sintering, pelletizing and replacing BF-BOF route, etc. conventional processes (Boston Metal 2025). The electricity consumption for MOE technology is around 4 MWh/ton of steel (Somers 2022)

The chemical reaction of MOE is shown below (Kim et al. 2010) and the electricity required is calculated which is comparable with the electricity and heat consumption of H-DRI-EAF route before, however, this technology needs a high electricity consumption as well, which is in the same order with using alkaline electrolyzer.

$$4\mathrm{Fe}^{3+} + 6\mathrm{O}^{2-} = 4\mathrm{Fe} + 3\mathrm{O}_{2(g)}$$

$$\mathrm{E_{MOE}} = \mathrm{C_{MOE}} \times \mathrm{V} \tag{14}$$

Where $\mathrm{E_{MOE}}$-Electricity consumption using MOE technology (TWh)

$\mathrm{C_{MOE}}$-Consumption coefficient (MWh/ton)

V-Rated production volume (million tons)

$$\mathrm{E_{MOE}} = 4\ \mathrm{MWh/ton} \times 2.6\ \text{million tons} = 10.4\mathrm{TWh}$$

Based on the total electricity and thermal power demand, the required power of SMRs is calculated below considering the capacity factor of SMRs.

$$\mathrm{P_D} = \mathrm{E_{C1}} \div 8760\ \text{hours} \div \mathrm{CF} \tag{15}$$

where $\mathrm{P_D}$-Power demand of SMRs

$\mathrm{E_{C1}}$-Electricity consumption using an alkaline electrolyzer

CF-Capacity factor of SMRs

$$\mathrm{P_D} = (9{\sim}10.67\mathrm{TWh}) \div 8760\ \text{hours} \div 95\% \approx 1081{\sim}1282\mathrm{MW}$$

The power demand of SMRs if utilizing SOEC, same calculation can be done and around 862-1018MW SMRs are needed. To satisfy required highest temperature requirement of around 950 °C in the shaft furnace first, only DF300 and GTHTR300 reactors meet the requirement as shown in Figure 7, and their output temperatures are 1000 °C and 950 °C respectively with 600 MW thermal output. If rated 300MW electricity will be generated, then left at most 300MW will be waste heat. Then 2 this kind of reactor can cover the total thermal power demand TP_D even considering the capacity factor. However, two of these kinds of SMR can't meet the demand of projected electricity consumption, because both kinds of reactors only have 300 MW electric power output, to satisfy the around 862 MW power demand or more than 1TW capacity in the future no matter which type of electrolyzer will be chosen. At least three to more than four this kind of 300 MW reactor should be deployed together with enormously excessive waste heat, and the same result can be seen for MOE technology due to similar electricity consumption.

4.2 Sizing SMRs for Outokumpu

This thesis will find the potential of utilizing SMRs for the industrial heat and electricity satisfaction of Outokumpu Tornio integrate which is under green transition and is the largest electricity single user of Finland (Motiva 2020) with 95% of electricity consumed coming from low-carbon sources in 2023 and Outokumpu has signed electricity supply agreements to increase low-carbon electricity consumption, like wind power (Outokumpu 2024a). From 2019-2023, the electricity consumption of Outokumpu in Finland varies from the lowest 2 545 427 MWh in 2023 to the highest 3 063 408 MWh in 2021, with the average electricity consumption being 2 839 068 MWh (Outukumpu 2024).

Another company is Outokumpu in Tornio, Finland, which primarily manufactures stainless steel and ferrochrome with raw materials coming from the mine in Kemi. To decarbonize the emissions of Outokumpu and transit towards sustainable steelmaking, in 2023, Outokumpu founded an EvoEnergy unit to explore the low carbon investments, including its energy generation, carbon capture, and hydrogen economy. Meanwhile, SMRs are considered for low-carbon electricity, and the possible location is near the factory in Tornio. As for the Kemi chrome mine owned by Outokumpu, it is about to be carbon neutrality by 2025 through carbon-free electricity, biofuel utilization, and replacing natural gas and propane with biogas for heating together with electrification of mining machinery. (Outokumpu 2024a) The latest progress is the revolution of the heating system of fresh air shafts at the mine by transferring propane-based heating to electric heating, which will replace 17.2GWh propane consumption and 4,000 tons of carbon dioxide emissions per year (Tornion Voima Oy 2025). Now, a preliminary study for the feasibility of SMRs has been started, technologies solutions, environmental impact and economic profitability and so on aspects will be evaluated, the further investment decisions will be made later (Outokumpu 2024c). It is also worthwhile pointing out that Outokumpu has begun to cooperate with Q Power to explore the feasibility of synthetic methane which can be utilized to replace fossil fuels, like LNG (liquified natural gas), together with CCU (carbon capture and utilization) technology (Outokumpu 2024d). Another case study is conducted below for Outokumpu to dig out the potential of SMR utilization in the future transition.

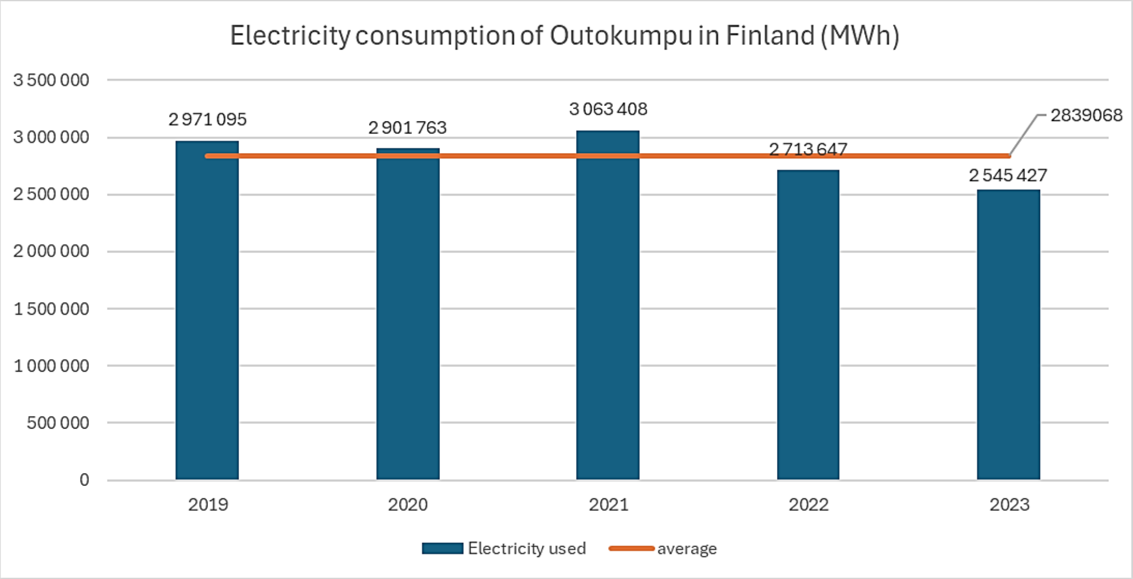

Figure 11. Electricity consumption of Outokumpu in Finland (Outukumpu 2024)

When it comes to the heat demand of Outokumpu, Tornion Voima Oy owns a CHP (combined heat and power) plant in Tornio to produce combined heat and electricity for Outokumpu Tornio and district heating for the Tornio region. In 2023, the production and fuel consumption of Tornion Voima Oy is illustrated in Figure 15 where orange means fuel consumption and dark blue means production (Tornion Voima Oy 2024a). The total district heating provided by Tornion Energia is 138.1GWh of which 136.8 GWh is purchased from outside which is generated by Tornion Voima Oy and 1.3 GWh is produced by fuels consumption (Finnish Energy 2024c), Tornion Voima Oy nearly provides all the district heating needed by the Tornio region. As for the temperature needed for Outokumpu utilization and district heating, the electric boiler built already in

Röyttä, Tornio can provide a reference temperature. In 2024, Tornion Voima Oy built a 40 MW electric boiler on the Outokumpu factory site, where produced processes steam can be utilized by the steel plan, also the district heat generated will be applied to the district heating network in Tornio and Outokumpu plan. The temperature of the steam generated by the electric boiler is up to 170 °C and produced steam can be divided into 5 and 8-bar pressures by reduction station for utilization later (Tornion Voima Oy 2024b). From the Tornion Voima Oy point of view, total heat demand is the sum of district heating demand and process steam heat demand for Outokumpu, which equals 453.1 GWh and around 170 °C is enough for process steam and district heating requirements.

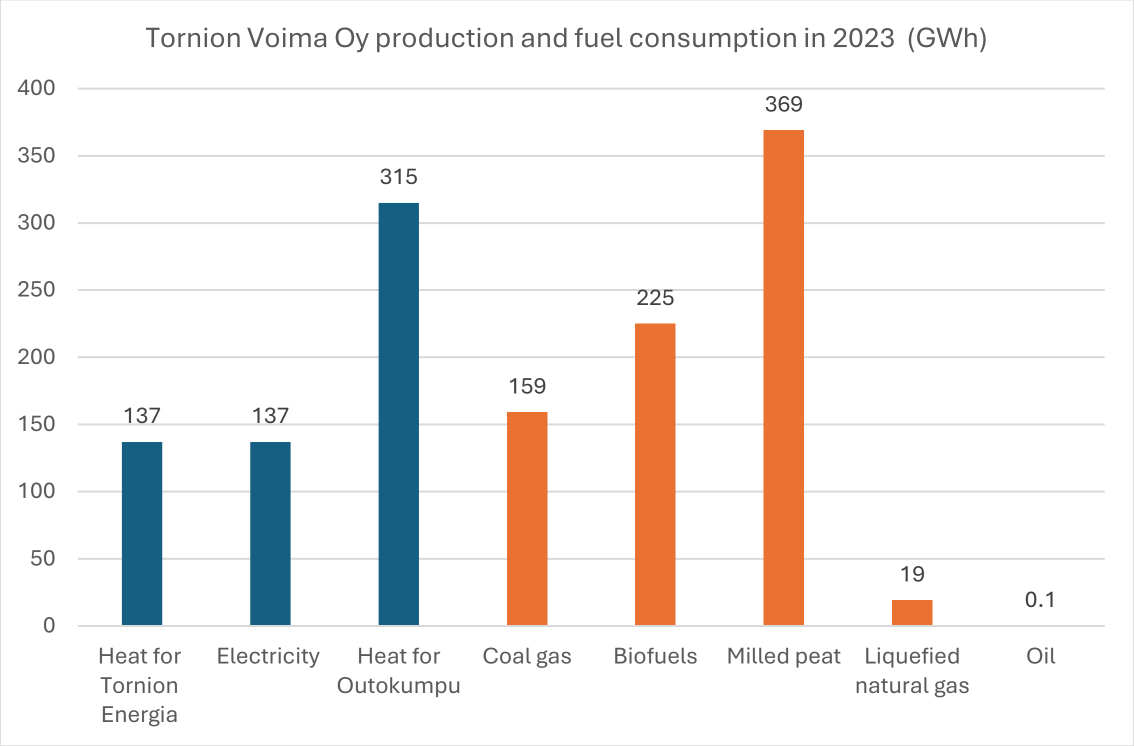

Figure 12. Tornion Voima Oy productions and fuel consumption in 2023 (Tornion Voima Oy 2024a)

However, Outokumpu does consume other kinds of fossil fuels except the process steam provided by Tornion Voima Oy. In 2019, the energy consumption of Tornio integrate was about 4.9 TWh of which 2.9TWh electricity, 0.9TWh natural gas, 0.6 TWh CO gas which is formed during ferrochrome production, and 0.4TWh heat consumption. The energy consumption doesn't account for the energy demand in the Kemi chrome mine which is owned by Outokumpu (Motiva 2020). During the ferrochrome production, fossil coal/coke is charged into a ferrochrome furnace as a reductant to produce ferrochrome, the chemical reaction is illustrated in Figure 16, and the carbon monoxide gas will be reused as an energy source, etc. purposes, while CO2 will be emitted due to coke/coal usage.

To specify the temperature requirement of manufacturing stainless steel and ferrochrome in Tornio Outokumpu by burning natural gas or recycled CO gas, and tap the potential of utilizing SMRs, detailed processing is illustrated in Figure 17, which highlights the process needing heating. In the ferrochrome works, the sintering process operates at a temperature of 1400 °C while the FeCr smelter operation temperature is around 1600 °C or even higher using submerged electrical arc furnaces. (Niemelä and Kauppi 2007), this temperature can be a reference temperature in a steel melting shop, for example, the operational temperature of melting ferrochrome, ferrochrome converter, and AOD (argon oxygen decarburization) converter. The annealing temperature is around 750-1200 °C normally (Outokumpu 2025) and the walking beam furnace for the hot rolling mill normally operates at 1250 °C but can reach 1450 °C in some cases (Calderys 2025). Based on the SMRs' range of sizes and temperature for heat application, the required temperature seems too high to be satisfied by SMRs, the highest temperature is around 1000 °C provided by the DF300 reactor shown in Figure 7, and this kind of reactor plans to test reactor by 2026, and the component is testing in 2023 (Dual Fliud 2025).

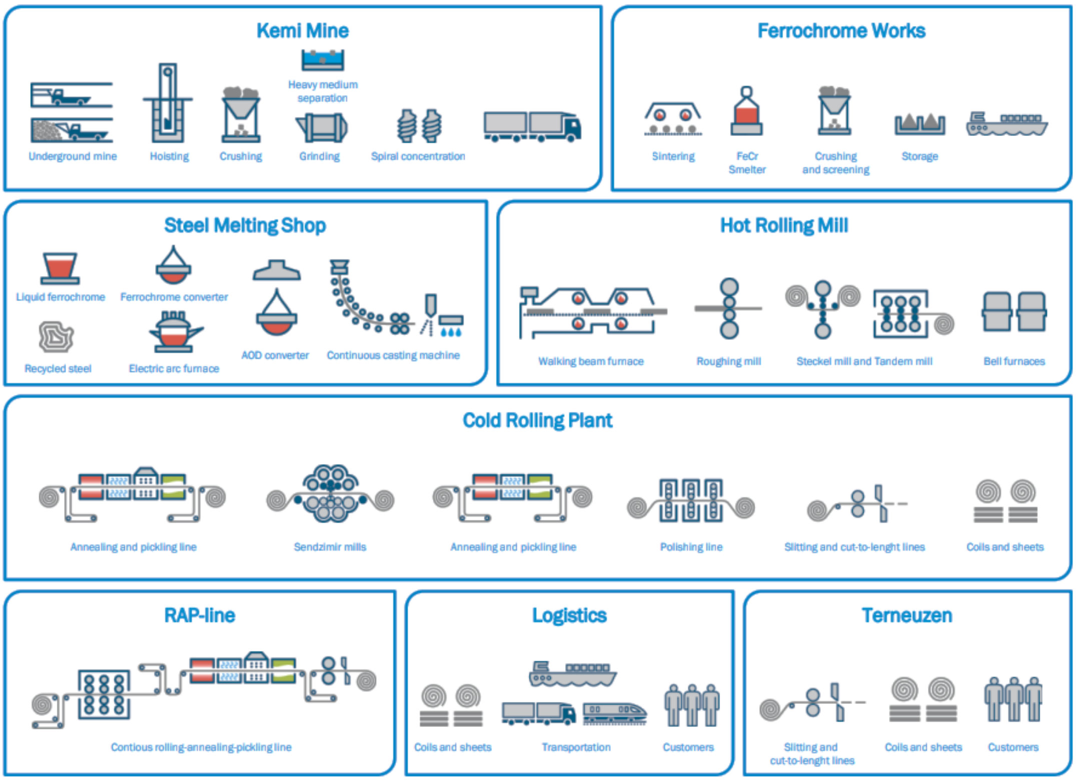

Figure 13. Manufacture process of stainless steel in Outokumpu Finland (Wass 2018)

The possible role of SMRs is to provide low carbon electricity no matter for industrial usage of Outokumpu or hydrogen production by electrolysis, and the wasted heat generated can be utilized for producing process steam, district heating, possible required heat for high-temperature electrolysis process, and the pelletizing plant of bio-coke in the future. As for satisfying the heat demand of Outokumpu during the manufacturing process by SMRs, it seems unrealistic or has very little potential due to the high temperatures required and the current solution of Outokumpu for decarbonization is synthesizing methane, which needs renewable hydrogen and captured carbon, to replace fossil fuel as mentioned above with cooperation with Q Power company, synthetic methane can also be liquified which is likewise fully interchangeable with liquified natural gas (LNG) and transported by existing infrastructure. Following energy consumption calculation will be done for synthetizing 0.9 TWh methane if all the natural gas consumption will be replaced while the CO gas consumption is out of calculation because this internal usage of CO will improve the system efficiency and is assumed still to be used in the future.

4.2.1 Electricity consumption of renewable hydrogen for synthetic methane

Under the current transition route of Tornio Outokumpu, synthetic methane will be produced by using clean hydrogen and carbon capture utilization technology to replace fossil fuel consumption like natural gas in Tornio which can be achieved by cooperating with Q Power Company. Figure 14 shows the path to achieve the decarbonization target of Outokumpu and the possible utilization of SMRs during the transition process, namely providing low-carbon electricity for industrial utilization or clean hydrogen production by electrolysis, the waste heat from SMRs can be applied for district heating or biocoke production plant in the future, although Tornion Voima Oy has already built the electric boiler to generate steam for Tornio steel works and Tornio region district heating network.

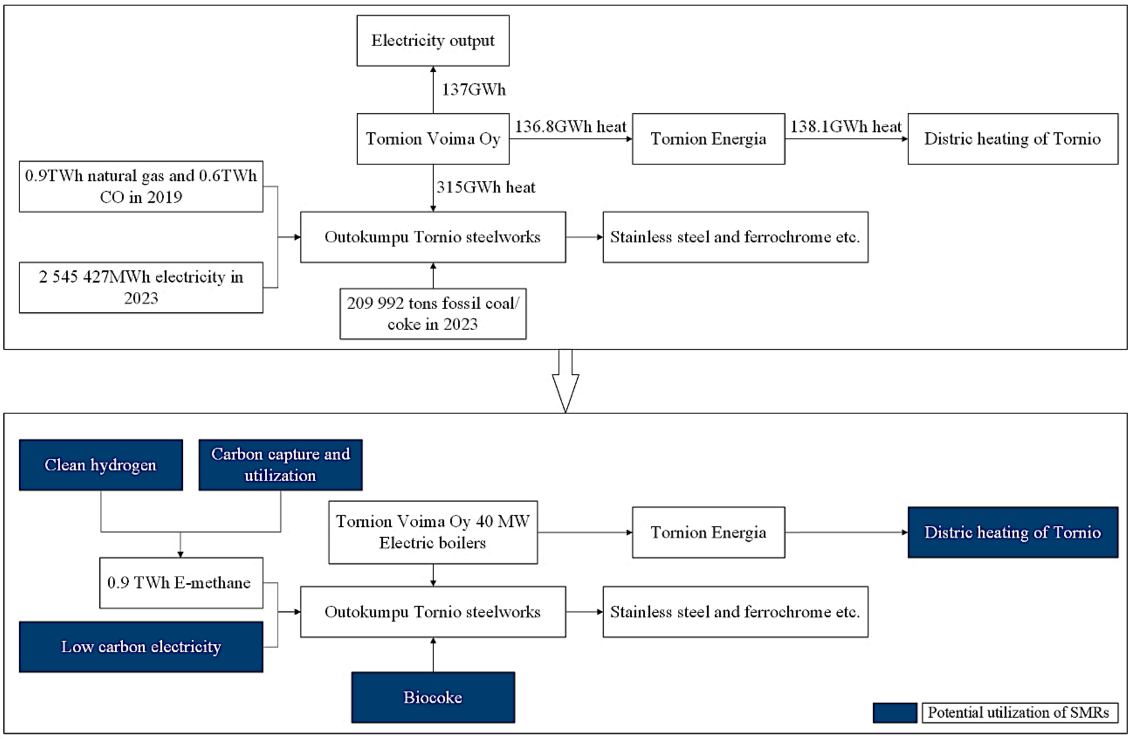

Figure 14. Potential utilization of SMRs during the transition of Outokumpu

Q Power company utilizes a biocatalytic methanation process with 82% plant efficiency, which means 82% of hydrogen energy input will be converted into output of methane, while if the electricity consumption is considered, the efficiency will be 81%, which indicates that the share of electrical consumption is quite low for this kind of bioreactors or this technology. The modular designs enable easy capacity increasing, and the TRL (technology readiness level) of the integrated scheme (hydrogen from electrolysis and carbon capture technology) is assessed to be 8, which means the system is completed and qualified, after commissioning of this kind of bioreactors in Harjavalta, the TRL will be 9, which means actual system proven in operational environment. The operation temperature of this process is only 50-70 °C and no need for heating, and the operation is near ambient pressure. The chemical reaction for this process is shown in equation 15 (Q Power 2024). What SMRs can provide for this specific biological catalysis methanation process is only providing low carbon electricity due to no need for heating and low operation temperature.

$$\mathrm{CO_2 + 4H_2 = CH_4 + 2H_2O} \tag{16}$$

If a total of 0.9 TWh of methane is needed, then around 1.1 TWh of clean hydrogen is needed based on the conversion efficiency and calculation of equation 16. As for hydrogen production, currently, Norwegian Hydrogen announced the planning of a green hydrogen project in Tornio, the initial capacity is around 50-100MW with an expandable capacity of 600-1 000MW and this project will start in 2026 (H2 Cluster Finland 2025). Although they didn’t reveal the exact method used to produce green hydrogen and the purpose of hydrogen utilization (Norwegian Hydrogen 2024).There are also hydrogen projects which are under development near Tornio, like Kemi and Simo with different possible applications, like green ammonia production.

$$\mathrm{HD_{Outo} = Me_D \div CE} \tag{17}$$

Where $\mathrm{HD_{Outo}}$-Hydrogen demand of Outokumpu in Tornio (TWh)

$\mathrm{Me_D}$-Synthetic methane demand (TWh)

CE-Conversion efficiency of bioreactors (%)

$$\mathrm{HD_{Outo}} = 0.9\mathrm{TWh} \div 82\% \approx 1.1\ \mathrm{TWh}$$

If the same type of pressurized alkaline electrolyzer, namely Sunfire-HyLink Alkaline, is chosen as the case study of SSAB Raahe, the efficiency 64% will be used for calculation again, which means 64% alternating current power input will be converted into hydrogen. To produce 1.1TWh clean hydrogen, then electricity consumption $\mathrm{E_{Outo}}$ is around 1.72

TWh calculated by equation 7. The required electrolyzer capacity $\mathrm{C_{Outo}}$ is 207MW calculated by equation 18 below.

$$\mathrm{E_{Outo}} = 1.1\mathrm{TWh} \div 64\% \approx 1.72\mathrm{TWh}$$

$$\mathrm{C_{Outo}} = \mathrm{E_{Outo}} \div 8760\ \mathrm{hors} \div \mathrm{CF_1} \tag{18}$$

Where $\mathrm{C_{Outo}}$-Capacity of electrolyzer for Outokumpu (MW)

$\mathrm{E_{Outo}}$-Electricity demand of Sunfire Hy-Link Alkaline electrolyzer (TWh)

$\mathrm{CF_1}$-Capacity factor of the electrolyzer

$$\mathrm{C_{Outo}} = 1.72\mathrm{TWh} \div 8760\ \mathrm{hors} \div 95\% \approx 207\mathrm{MW}$$

However, if Sunfire-HyLink SOEC electrolyzer is chosen, which features 88% efficiency and operates at around 800 °C with more than 150 °C low-pressure steam needed. The same calculation can be done by equation 7 and 18 for SOEC. To generate 1.1TWh hydrogen, 1.25TWh electricity can meet this demand and around 150MW electrolyzer should be utilized to satisfy clean hydrogen production.

4.2.2 Heat demand of transition for Outokumpu Tornio

When it comes to the heat demand for steam generation, the same calculation as the case study of SSAB Raahe can be done for SOEC, although the exact required thermal power is influenced by many factors, like the heat sources, exact system design and internal hear recovery, etc. element. For 1 MW SOEC electrolysis power input, around 200KW external heat is required if using waste heat of SMRs for water vaporization is adopted, then 30 MW external thermal power for 150MW SOEC is needed here. If using SMRs directly heat the required steam to 800°C, then thermal power demand $\mathrm{TP_{Outo1}}$ is around 65MW, the same calculation is based on equation 13 and is listed below.

$$\mathrm{TP_{Outo1}} = \mathrm{E_{Outo}} \div 75\% \times 25\% \div 8760\ \text{hours}$$

$$\mathrm{TP_{Outo1}} = 1.72\mathrm{TWh} \div 75\% \times 25\% \div 8760\ \text{hours} \approx 65\mathrm{MW}$$

The heat demand of Tornio Outokumpu and district heating of Tornio region is 453.1GWh with 170 °C as the reference temperature total of which 315GWh is for Outokumpu factory and 138.1 GWh is for district heating in 2023. Required thermal power demand is around 36MW and 24MW respectively based on the calculation below. Finland always starts district heating when the average monthly temperature is below 12°C in autumn and ends it when the average monthly temperature is above 10°C in spring (Aalto et al. 2016). The heating season generally is from October to April if take the average monthly temperature of Oulu as a reference for Tornio based on the heating season definition with 213 days and 5751 hours in 2024 (Finnish Meteorological Institute 2024).

$$\mathrm{TP_{Outo2}} = \mathrm{HD_1} \div 8760\ \text{hours} \tag{19}$$

Where $\mathrm{TP_{Outo2}}$-Thermal power demand of Tornio Outokumpu for process steam (MW)

$\mathrm{HD_1}$-Process steam heat demand of Tornio Outokumpu (GWh)

$$\mathrm{TP_{Outo2}} = 315\mathrm{GWh} \div 8760\ \text{hours} \approx 36\mathrm{MW}$$

$$\mathrm{TP_{Tornio}} = \mathrm{HD_2} \div 5751\ \text{hours} \tag{20}$$

Where $\mathrm{TP_{Tornio}}$-Thermal power demand of Tornio district heating (MW)

$\mathrm{HD_2}$-District heating demand of Tornio (GWh)

$$\mathrm{TP_{Tornio}} = 138.1\mathrm{GWh} \div 5751\ \text{hours} \approx 24\mathrm{MW}$$

When it comes to the carbon capture utilization for Tornio steel works, currently, this is no commercial operation carbon capture facility in Finland, however, many BECCU/CCU and BECCS projects will be developed in Finland by 2030 (Bioenergia ry 2024). The possible technology utilized for carbon capture commercially and practically on the industry scale is the liquid amine process. A simplified process of the amine absorption process is depicted in Figure 19, and the flue gas in this figure is from a heat recovery steam generator (HRSG) where the flue gas of natural gas combustion transfers heat to water to generate steam, the lean amine solution absorbs CO2 at low temperature and release pure CO2 when amines are heated in stripper (Strojny et al. 2023).

This technology is taken as a reference in this case study, because Metsä and technology company Andritz have started an investigation to capture wood-based carbon dioxide in Rauma, Finland (Metsä 2024), and Andritz company can use this liquid amine process technology. The liquid amine process provided by Andritz, which requires 3-4 bar and 110-130 °C steam for desorption, and the exact energy consumption of this process is not revealed by Andritz because it depends on the CO_2 concentration in the flue gas, the required amount of CO_2 to be captured, and other site-specific conditions. (Andritz 2025).

This process needs 3.1GJ/t CO2 (0.86MWh/t CO2) during the solvent regeneration process in the stripper column, which means the thermal demand for regenerating the solvent, while the compression and purification units process needs 18.4MW electricity (Strojny et al. 2023). If 35,000 tons of methane will be synthesized, then 110,000 tons CO2 should be captured for synthetic reaction per year (Ren-Gas 2024), 0.9TWh methane equals 60 000 tons methane if energy density 15KWh/ ton is used (Q Power n.d.) so that around 188,000 tons of CO2 should be absorbed annually to produce 0.9 TWh of synthetic methane. The electricity demand and heat demand are calculated below.

$$\mathrm{TP_{Outo3}} = \mathrm{CE_{CC}} \times \mathrm{V_{CO2}} \div 8760 \text{ hours} \tag{21}$$

Where $\mathrm{TP_{Outo3}}$-Thermal power demand of carbon capture technology (MW)

$\mathrm{CE_{CC}}$-Energy coefficient of carbon capture (MWh/t CO2)

$\mathrm{V_{CO2}}$-Volume of absorbed CO2 (tons)

$$\mathrm{TP_{Outo3}} = 0.86\mathrm{MWh} \text{ / ton CO2} \times 188\ 000 \text{ tons CO2} \div 8760 \text{ hours} \approx 18\mathrm{MW}$$

4.2.3 Total electricity consumption and thermal power demand

Total thermal power demand $\mathrm{TD_{all}}$ is 143 MW thermal power demand when choosing SOEC as a renewable hydrogen production measure, which is calculated below, with a temperature requirement under 200 °C generally except 800°C is needed if using waste heat of SMRs directly for SOEC. However, if choosing an alkaline electrolyzer, then the total thermal demand will be lower due to no external heat needed for an alkaline electrolyzer. Same situation for using SMRs for the water vaporization process in the SOEC system, because the required thermal power is lower as mentioned in Raahe's case study. In addition, total electricity demand $\mathrm{ED_{Outo,all}}$ in the future will be around 4.56 TWh which is the sum of electricity demand for hydrogen production by alkaline electrolyzer and average electricity consumption within the recent five years, so the required electric power is 548MW calculated by equation 22. The same calculation for SOEC, then around 4.09 TWh electricity consumption annually in the future, and 491MW power should be provided.

$$\mathrm{TD_{all}} = \mathrm{TP_{Outo1}} + \mathrm{TP_{Outo2}} + \mathrm{TP_{Tornio}} + \mathrm{TP_{Outo3}} = 65 + 36 + 24 + 18 = 143\mathrm{MW}$$

$$\mathrm{ED_{Outo,all}} = \mathrm{E_{Outo}} + \mathrm{E_{Outo,average}} = 1.72\mathrm{TWh} + 2.84\mathrm{TWh} = 4.56\mathrm{TWh}$$

$$\mathrm{PD_{Outo}} = \mathrm{ED_{Outo,all}} \div 8760\ \mathrm{hours} \div \mathrm{CF} \tag{22}$$

where $\mathrm{PD_{Outo}}$- Power demand of SMRs (MW)

$\mathrm{ED_{Outo,all}}$- Electricity consumption using alkaline electrolyzer (TWh)

CF- Capacity factor of SMRs (%)

$$\mathrm{PD_{Outo}} = 4.56\mathrm{TWh} \div 8760\ \mathrm{hours} \div 95\% \approx 548\mathrm{MW}$$

If using high-temperature waste heat from SMRs directly for SOEC, then the outlet temperature of SMRs should be around or higher than 800°C. One DF300 or GTHTR300 can provide all the thermal demand even considering the 95% capacity factor because the thermal power is 300MW if operating at 300MW electricity output, which is significantly higher than demand, but it is not enough to satisfy possible electricity consumption in the future due to only 300MW electric power. The same situation can be seen if not using high-temperature waste heat directly for SOEC which needs less thermal power demand while electricity remains the same. In comparison, if using an alkaline electrolyzer, the required electric power will be higher and the thermal demand will be lower than using SOCE so that the total thermal demand is extremely low annually because only process steam and district heating of Tornio need thermal energy from SMRs in the transition path while SMRs' temperature range is not enough to meet the over 1000°C demand for ferrochrome or stainless steel manufacture processes.

BWRX-300 can be another choice based on trading off the low carbon electricity generation and thermal power output if no need for around 800°C temperature steam for SOEC, which depends on the exact system design and how to use waste heat from SMRs, although significant excesses heat will be generated as well. This reactor features 300MW electricity output and 870MW thermal capacity with 288 °C and 95% capacity factors designed. One BWRX-300 reactor can cover half of the electricity consumption annually if using an alkaline electrolyzer or more than half for the SOEC option. If coving all the electricity consumption, then at least two 300MW reactors with excessive heat generation.

4.3 Sizing SMRs for Kokkola Industry Park

Kokkola Industrial Park (KIP) is the largest inorganic chemical industry in northern Europe, located in Kokkola, Finland and there are 16 industrial companies in KIP. Although companies in KIP utilize large amounts of different fuels and energy in various formats that are not all produced and distributed by Kokkolan Energia, it also is reasonable to have a look at the energy production of Kokkolan Energia for KIP, because Kokkolan Energia provides and distributes district heat, process steam and electricity for Kokkola municipality and KIP, the energy Kokkolan Energia provided can be satisfied by SMRs and left part can be satisfied by companies themselves. In the meantime, there seem no public records of total energy consumption in KIP now (Joonas 2024). However, Kokkola municipality consumes 1.83TWh electricity in 2023 of which 1.484 TWh of electricity comes from industry consumption (Finnish energy 2024b). In 2019, Boliden

Kokkola zinc mill consumed 1.2 TWh of electricity as mentioned before (Motiva 2020), which indicates most of the electricity will be consumed by Boliden Kokkola.

In 2023, Kokkolan Energia sold 466 GWh of industrial heat (steam and district heat) and 320 GWh of district heating. The fuel consumption is 592GWh, with 64 149 tons of CO2 emissions in the production process, also it purchases 342.3 GWh of electricity and 424 GWh of industry heat (Kokkolan Energia Oy 2023). Although the heat purchased from external sources can be replaced by SMRs, it is better to purchase the industrial waste heat rather than generate it individually so that it improves energy efficiency. For example, Boliden plants in KIP sell 440 GWh of steam and district heating per year (Motiva 2020) and provide more than 40% of the energy used for district heating, produced by Kokkolan Energia for Kokkola city. The waste heat from Boliden Zinc first goes through the power plant to generate electricity, then goes to the district heating network (Boliden 2023). In 2023, the total supply of district heating produced by Kokkolan Energia is 370.2GWh of which 320.4 GWh is for sale and 49.8 GWh heat losses (Finnish Energy, 2024b).

From the energy balance point of view, the demand side is 342.3GWh purchased electricity, 370.2 GWh district heating, and 466 GWh industrial heat needed while the supply side is purchased 424GWh industrial waste heat and 592GWh fuel consumption. Then the total heat demand except the recovered waste heat $\mathrm{HD}_{\mathrm{Kokkola}}$ is 412.2 GWh which can be replaced by SMRs and the required power of SMRs for heat demand is around 50 MW calculated by the following equation. In the meantime, the 342.3 GWh electricity purchased by Kokkolan Energia also can be provided by SMRs, and the required electric power is 41MW. In terms of the temperature for district heating and process steam. District heating temperature varies between 72-115°C based on the outside temperature and the process steam, the temperature is approximately 175, 225, and 280 °C with 4.5, 40, and 70 bar respectively (Joonas 2024).

$$\mathrm{HD}_{\mathrm{Kokkola}} = 466 + 370.2 - 424 = 412.2\mathrm{GWh}$$

$$\mathrm{TP}_{\mathrm{Kokkola}} = \mathrm{HD}_{\mathrm{Kokkola}} \div 8760 \text{ hours} \div \mathrm{CF} \tag{23}$$

Where $\mathrm{TP}_{\mathrm{Kokkola}}$-Thermal power demand of SMRs (MW)

$\mathrm{HD}_{\mathrm{Kokkola}}$-Heat demand of Kokkola industry park except recovered waste heat (GWh)

CF-Capacity factor of SMRs

$$\mathrm{TP}_{\mathrm{Kokkola}} = 412.2\mathrm{GWh} \div 8760 \text{ hours} \div 95\% \approx 50 \text{ MW}$$

$$\mathrm{EP}_{\mathrm{Kokkola}} = \mathrm{ED}_{\mathrm{Kokkola}} \div 8760 \text{ hours} \div \mathrm{CF} \tag{24}$$

Where $\mathrm{EP}_{\mathrm{Kokkola}}$-Electric power demand of SMRs (MW)

$\mathrm{ED}_{\mathrm{Kokkola}}$-Electricity demand of Kokkola Industry Park (GWh)

CF-Capacity factor of SMRs

$$\mathrm{EP}_{\mathrm{Kokkola}} = 342.3 \div 8760 \text{ hours} \div 95\% \approx 41\mathrm{MW}$$

Although Kokkolan Energia is planning to build two 60MW electric boiler plants and one district heating battery to decarbonize industrial steam production and district heating, the final investment decision will be made by early 2025 (Kokkolan Energia 2024), having a look at SMRs also provides a possibility for other industrial parks or other purposes. Based on calculation results, 41 MW electricity output and 50 MW thermal output should be satisfied for Kokkolan Energia generally. Based on the output temperature shown in Figure 7, BWRX-300, NUWARD, and Rolls-Royce all have a higher thermal power output, which a little exceeds the required thermal output although these types of SMRs attract more attention and PWR-20 seems more suitable for KIP.

PWR-20 was proposed by the Last Energy company in the USA with 20MWe and 80 MWth, the outlet coolant temperature is 331 Celsius degrees which meets the temperature requirement of process steam. The fuel type is UO2 pellet with less than 4.95% enrichment. The current development for this type of SMR is on track for signing an agreement for 57 units of deployment across four countries (IAEA 2024b). The capacity factor is 95% uptime with 300 Celsius degrees continuous operation for 72 months of fuel cycle (Last Energy 2025). To satisfy the 50 MW heat demand, one PWR-20 is enough to meet the heat demand although electricity demand is not satisfied, while if satisfy 41 MW electric power, at least two PWR-20 reactors are needed. If two PWR-20 SMRs are chosen as energy sources, the 592 GWh fuel consumption is phased out with 64 149 tons of CO2 emissions deduction annually in the production process, and the electricity demand will be satisfied as well, although excessive heat will be generated.

5 DISCUSSION

The number of SMRs varies from 2 to more than 13 in 2050 for the Dutch energy system in the future based on different scenarios analysis and assumptions. The SMRs will be allocated only in the industry cluster in Netherlands for power and industrial heat satisfaction. For example, industrial energy demand of Zeeland region seems to be met by 2 SMRs under consideration of the report. 80% heat demand from refineries or chemical sectors can be met by 4 - 10 SMRs according to different scenarios in the future. However, this study doesn't consider exact SMRs types and only uses a generic SMRs featuring 150 MW electricity output and 250MW heat output for analyzing, meanwhile, the heat output temperature of SMRs is assumed to be 300°C and this model only covers the industrial heat demand of 200 - 400°C temperature range.(Zandt et al. 2024) The same trend can be seen in this scenarios-based analysis, more electricity demand than industrial heat demand in the future and SMRs will be utilized for satisfying most part of industrial heat while less proportion of electricity supplement for different scenarios.

The potential of SMRs for chemical industry is also researched by European Chemical Industry Council, electricity demand and steam consumption of crackers for petrochemicals are shown while the energy consumption for Chlor Alkali sectors is quantified as well, however, this study didn't give the corresponding needed SMRs to satisfy the expected energy demand (European Chemical Industry Council 2024). Except for the chemical industry, the combination of data center and SMRs are becoming an emerging option for increasing electricity demand of artificial intelligence (AI), Internet of thing (IoT) etc. sectors' dramatic development, and SMRs provide stable and uninterrupted electricity for these related energy demand. For example, Google and Kairos Power have planned to build 7 SMRs with up to 500 MW electricity, in the meantime, Amazon invested in X-Energy and committed to support the initial 4 units of Xe-100 reactors (Chernicoff and Vincent 2024). Compared with research above, this thesis gives the exact types and number of SMRs for energy demand of metallurgical industries in Finland by case studies, and the hydrogen utilization is considered in SSAB Raahe case. Besides, the challenges of implementing SMRs are provided as well.

There are still some limitations about case studies in this thesis. Based on the transition route of the SSAB Raahe factory in Finland, this thesis projects that total electricity consumption varies from the lowest 7.17TWh to the highest 10.67TWh depending on the two kinds of electrolyzer and corresponding efficiency. 588-625 MW SOEC or 807-973 MW alkaline electrolyzer will be required for green hydrogen production. Compared with 1 GW electrolyzer needed for hydrogen production for Raahe factory (Vakkilainen et al. 2024), the results of this thesis seem a little lower for SOEC, primarily because of higher efficiency of SOEC, and the capacity factor is estimated to be 95%. The required capacity for alkaline electrolyzer is quite close to 1GW. Meanwhile, the hydrogen demand for one-ton steel will have an impact on the hydrogen production and electricity consumption indirectly, also the results of this thesis doesn't sum the current electricity consumption because this result is calculated on the hydrogen-based DRI-EAF route, which will replace the current electricity consumption totally by assumption, although more detailed needs to be figured out in the future.

If heat demand is prioritized to be met for SSAB Raahe, then two DF300 or GTHTR300 can be chosen to cover the demand, but the electricity supply is not enough for the projected electricity consumption. However, if projected electricity consumption is prioritized to be met, three to four DF300 or GTHTR300 should be installed, while significantly excess waste heat is generated as well, which indicates that the heat demand or thermal power is quite lower than the electricity demand for SSAB Raahe. It is worthwhile pointing out that other types of SMRs are alternatives and different solutions for SSAB Raahe exist based on different focuses and choices. This thesis just gives examples of SMRs that can cover the thermal power demand and required temperature for the whole transition route.

It is a little difficult for SMRs to provide heat for such industries like Tornio steel works of Outokumpu due to the higher required temperature or SSAB Raahe which has much less thermal power demand than electric power demand in the future, but SMRs can provide a huge amount of clean electricity for the Outokumpu and SSAB transition in Finland while the waste heat can be utilized partially for different applications, although excessive waste heat will be generated locally. As a comparison, the temperature range of SMRs is suitable for the forestry industry or chemical industry, like the paper industry shown in Figure 7. As for the case study of KIP, this thesis mainly focuses on the industrial heat demand, although district heating demand is also included in the KIP case study. One PWR-20 small modular reactors are needed to meet the heat demand of KIP although the electricity demand is not met, and KIP still needs to purchase electricity. Compared with the Kokkolan Energia plan to build two 60MW electricity steam boilers, the result of the calculation for heat demand is 50 MW which is less than the total 120 MW electric boilers. The results of this thesis don't consider several impact elements, for example, the heat losses of waste heat recovery and distribution of industrial heat, heat demand fluctuation no matter for district heating or industrial heat including the process steam and district heating for industry, especially the consumption peak, and thermal storage so that the planned capacity of two 60MW electricity steam boilers is higher than result of this case study. If 120MW thermal output is needed, then 2 PWR-20 are needed. Besides, this case is studied only from the Kokkolan Energia point of view, not for the whole Kokkola Industry Park due to lack of public data for the whole energy consumption of this industry park.

In the future, the possibility of deploying SMRs for the forestry industry can be investigated, as energy supply also for energy-intensive biogenetic carbon capture utilization and storage. also it is worthwhile to point out that the forestry industry still needs the industrial heat demand provided by fossil fuel consumption in Finland if all the fossil fuel consumption in the forestry industry is estimated to be used as industrial heat as mentioned before, although around 92% of the fuels used in the forestry industry has been renewable energy in 2023 and left part should be compensated in some way for decarbonization. Lastly, the potential of SMRs for specific chemical companies should be researched later, because this thesis doesn't give a case study for chemical companies, and the waste heat could be utilized more efficiently than steel or ferrochrome industries here due to more suitable temperatures range, meanwhile, the possible hydrogen production using waste heat of SMRs by thermochemical route is another choice in the future for better waste heat utilization.

6 CONCLUSIONS

In 2023, the current fossil fuel consumption of the Finnish technology industry is around 13.5 TWh, forestry industry consumes around 49.6 TWh fuels of which about 4 TWh comes from fossil fuels and most of the fuel consumption is renewable fuel. The decarbonization potential of hydrogen utilization for the technology industry in Finland is at most 6 Mt CO2 eq. based on the roadmap of industry sector. For the chemical industry, the potential of electrification and changing the feedstock source will eliminate nearly all the scope 1 emission while hydrogen utilization is not as significant as in the technology industry. When it comes to the forestry industry, the potential of electrification or hydrogen utilization for decarbonization is low, because the main measure is phasing out fossil fuel by biofuel and CCUS for the forestry industry.

When it comes to the sizing and quantity of SMRs to satisfy the energy demand of Finnish industry, one micro-reactor PWR-20 is enough to meet the industrial heat and district heating demand together with the waste heat recovery for Kokkola Industrial Park and Kokkola municipality theoretically based on the data of Kokkolan. When it comes to SSAB Raahe, three to four DF300 or GTHTR300 can cover the electric power and thermal power demand of SSAB Raahe. As for Outokumpu, at least two 300MW reactors are needed with excessive heat generation, such as DF300, GTHTR300, or PWRX-300. One PWR-20 is enough for Kokkolan Energia.

The limitations or challenges of deploying SMRs are mainly economics, legislation, and social impacts. The costs of SMRs are still significantly high and increasing, together with a long construction time, although proponents argue that the positive learning curve, modularity design, co-site economy, etc. elements can decrease the costs and construction duration in the future, and some of these advantages are still controversial. Finnish public has six times higher acceptance than opposition about nuclear, while the acceptance of closer location of SMRs is not high. Finnish authorities have been renewing the legislation of nuclear power to accommodate SMRs, separating decision-in-principle, site and technological evaluation might be the prospective way for licensing SMRs in the future without compromising safety. This thesis gives an overall review of Finnish industries energy consumption and potential of SMRs for three case studies, in the future, the potential of SMRs can be assessed further for chemical sector or others.

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