VTT Technical Research Centre of Finland

EcoSMR, Finnish Ecosystem for Small Modular Reactors – Final Report

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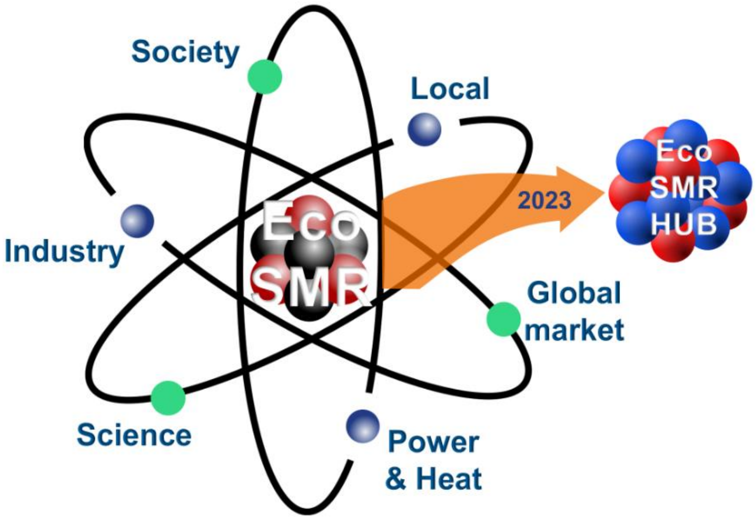

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Summary

EcoSMR was a Business Finland funded co-innovation project with two research partners and ten company partners. The aim of EcoSMR project was to enable Finnish companies to participate in emerging small modular reactor markets through supply chain development and developing competences in certain topics. EcoSMR research partners were VTT and LUT University. Company partners were AFRY, Clenercon, EnviroCase, Fortum, Helen, Platom, Refinec, Rockplan, TVO and Vantaan Energia.

The research work in EcoSMR was conducted under three main topics: licensing, heating reactor prospects and business model and ecosystem development. In addition, active dissemination work was conducted through organizing several webinars and seminars and writing articles in magazines and newspapers. In licensing, a suggestion on the basis for new regulation framework was proposed, EPZ determination was reviewed, prediction of licensing costs was examined and the applicability of safety analysis tools for SMRs were studied. In heating reactor prospects, different kind of analysis were conducted related to competitiveness, load following capabilities, integration to district heating network, market potential and carbon footprint. Additionally, pre-design of a heat exchanger for Finnish district heating reactor was drawn up. The research work on business models and ecosystem development focused on revisioning the quality assurance procedures of the global supply chains, fleet ownership and operation models on small modular reactors and co-ownership models of SMRs.

EcoSMR project created an SMR community in Finland and brought it to the consciousness of international SMR actors. The project facilitated discussion between Finnish SMR actors and between Finnish and foreign actors. The work will continue under EcoSMR Hub. The Hub aims to bring together Finnish SMR actors and keep the discussions and supply chain development, which was started under EcoSMR, ongoing.

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Contents

Abbreviations

AEP	Advanced Energy Project
BWR	Boiling Water Reactor
CAPEX	Investment Cost
CDF	Core Damage Frequency
CHP	Combined Heat and Power
CNSC	Canadian Nuclear Safety Commission
CRP	Coordinated Research Project
DC	District Cooling
DH	District Heating
DHR	District Heating Reactor
DHRS	Decay Heat Removal System
DIP	Decision in Principle
DOE	Department of Energy
ECCS	Emergency Core Cooling System
EIA	Environmental Impact Assessment
ELC HI	High average electricity market price
ELC LO	Low average electricity market price
EPR	Emergency Preparedness and Response
EP&R	Emergency Preparedness and Response
EPZ	Emergency Planning Zone
FMI	Finnish Meteorological Institute
FOAK	First of a Kind
FSAR	Final Safety Analysis Report
HaaS	Heat as a Service
HALEU	High-Assay Low-Enriched Uranium
HOB	Heat Only Boiler
HP	Heat Pump
HTGR	High Temperature Gas cooled Reactor
IAEA	International Atomic Energy Agency
LCA	Life Cycle Assessment
LDR	Low temperature District heating and desalination Reactor
LOCA	Loss of Coolant Accident
LUTHER	LUT Heat Experimental Reactor
LWR	Light Water Reactor
MCFR	Molten Chloride Fast Reactor
MEAE	Ministry of Economic Affairs and Employment
MED	Multiple Effect Distillation
MSF	Multi-Stage Flash
MSR	Molten Salt Reactor
NEA	Nuclear Energy Agency
NGR	Next Generation Reactor
NPP	Nuclear Power Plant
NRC	Nuclear Regulatory Commission
OPEX	Operational cost
PAZ	Precautionary Action Zone
PRA	Probabilistic Risk Assessment
PRW	Pressurised Water Reactor
PRZ	Pressuriser
PSA	Probabilistic Safety Assessment

RCS	Reactor Coolant System
RO	Reverse Osmosis
RPV	Reactor Pressure Vessel
RRV	Reactor Recirculation Valve
RVV	Reactor Vent Valve
SA	Severe Accident
SFR	Sodium cooled Fast Reactor
SME	Small and Medium-sized Enterprises
SMR	Small Modular Reactor
SNF	Spent Fuel
STUK	Radiation and Nuclear Safety Authority
TM	Technical Meeting
TRISO	Triple Coated Isotropic (TRISO) particles
TRL	Technology Readiness Level
UPZ	Urgent protective actions Planning Zone
USNC	Ultra Safe Nuclear Corporation

1. Introduction

Nuclear reactors have been used for power production in the world since the 1950s. The first reactors were small, but since then have been growing in power output during the history of nuclear power. The logic behind this development is economics of scale. This has been reasonable since the capital costs of nuclear power plants form a significant share of the whole cost of the plant, but are not very sensitive to the size of the plant. On the other hand, Small Modular Reactors (SMR) are small (often < 300 MWe) nuclear reactors. Instead of economics of scale, SMRs aim to utilize modularity and standardization of power plant components. The logic behind this is to significantly reduce the overall capital costs. The aim in many designs is to produce the power plant components in factories that can be readily transported to the plant site, assembled efficiently and connected to the grid. In some cases a whole reactor unit can be manufactured in a factory and transported to the plant site to be used as a stand alone "nuclear battery". The target applications of different SMR designs range from conventional power production to many other applications such as e.g. process heat, district heating and desalination. One significant feature describing many of the SMR designs are passive safety features which include for example utilization of natural circulation in the primary circuit.

The EcoSMR project is a Business Finland funded co-innovation project whose purpose is to conduct preliminary studies on certain topics concerning SMRs and build know-how and competences for Finnish actors in the SMR field. The research in the project is concentrated on light water reactor technologies. Specific research topics include licensing, heat use of small reactors, case studies, business models and ecosystem creation. The project began in August 2020 and was originally supposed to end in two years, but was extended by five months until the end of 2022 because of challenges caused by COVID.

Project partners comprise of two research institutions and ten companies and are presented in Figure 1-1. Research partners are VTT and LUT University. Additionally, three companies Fortum, Refinec and TVO have their own company projects. Other partners in the project include AFRY, Clenercon, Envirocase, Helen, Platom, Rockplan and Vantaan Energia.

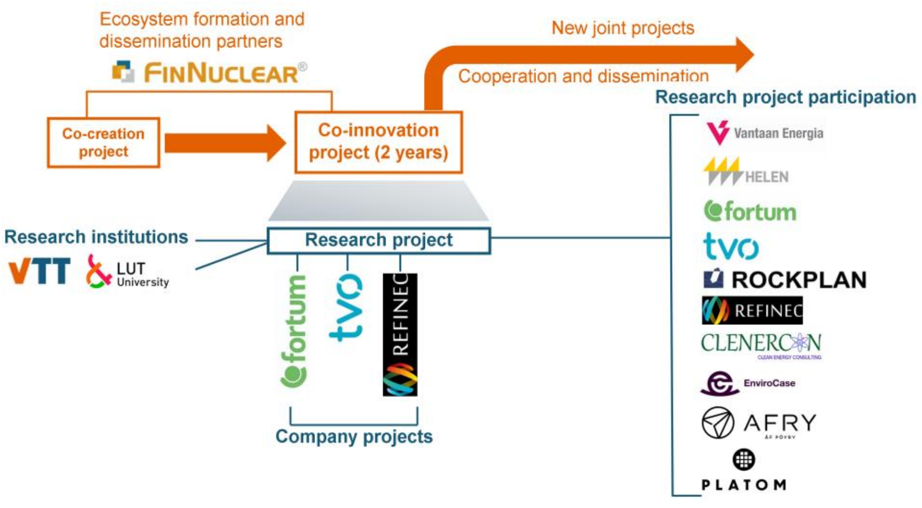

Figure 1-1. EcoSMR partners.

In some of the research cases LDR (Low temperature District heating and desalination Reactor) has been used as an example reactor. LDR is a heating reactor developed in a parallel project funded entirely by VTT.

Research work in the public EcoSMR project has been carried out by VTT and LUT university. This report summarises the main results of that work and outlines a way forward. A short introduction to the work of the company projects is also given in chapter 8. The report is organized in such a way that each chapter begins with a short summary of the work and results achieved under the topic(s) covered in the chapter followed by a more detailed presentation on the work. Work packages on licensing, heat use of SMRs, ecosystems and dissemination have a dedicated chapter. Work packages on case studies and business models are summarised under one chapter. Other work conducted in the project is reported in its own chapter. An appendix in the end of the report presents all publications produced during the project.

2. Goals and motivation

The main goal of the EcoSMR project was to enable Finnish companies to participate in the emerging SMR markets through consulting work, supply chain participation and expertise on SMR integration for novel applications. The main motivation of the project was the potential of SMRs to become the future of nuclear energy in electricity and heat production. In order to utilize this potential, cross-cutting and efficient research and collaboration is needed. EcoSMR's aim was to network Finnish companies with international actors and to develop know-how on specific fields such as e.g. licensing and heating reactor prospects.

More specific goals of the project include developing knowledge and expertise in SMR licensing related issues. These issues include streamlined licensing, SMR emergency planning zone (EPZ) determination and licensing cost estimation. Understanding the specific needs and development targets in analysis tools for SMR licensing was also a goal.

Under the topic of district heating reactors, the main goal was to investigate potential for district heating reactors in Finland. Related subgoals were understanding design requirements for Finnish heating reactor, calculation tools development for district heating networks, surveying technical, economic and regulatory demands and analysing load follow capabilities of heating reactors.

Other important goals were to define service and business opportunities and models for economical and efficient use of SMRs and built an ecosystem of networks for the industry. The motivation of this kind of networking and ecosystem was to facilitate efficient collaboration and communication and business model examination.

3. Licensing, regulations and design criteria

3.1 Summary

This chapter summarises the work done on licensing issues in the EcoSMR project. Some of the key issues in SMR licensing are related to regulations, cost and siting. Current regulations enable SMR licensing, but they do not consider the SMR specific characteristics such as serial production and geographical deployment of SMRs. Current legislation assumes one license applicant who is responsible of everything including technology and site. In the EcoSMR project, a new approach is suggested. This approach separates site license and technology license and recognises the possibility of multiple license holders who can benefit from the earlier licensed technology or site.

Ability to predict licensing costs is essential in order to make SMR deployment economically feasible. Two different approaches for such predictions have been examined, namely top-down and bottom-up approaches. Both approaches were found to involve challenges related to insufficient data on share of licensing costs in available references (top-down approach) or high dependency of cost estimate on SMR design (bottom-up approach).

Size of emergency planning zone (EPZ) is one of the key factors in SMR siting. EPZ size is particularly important for heating reactors. A review on EPZ determination was conducted during the project. Based on the review some recommendations were suggested. One is that for a rigorous and definitive basis for EPZ, a full scale PSA should be conducted. Another is to follow closely related projects in UK, USA and Canada. Some preliminary calculations were also conducted. In one study a simple scaling exercise comparing Olkiluoto 3 to LDR-50 was performed. As a result, the PAZ (Precautionary Action Zone) and UPZ (Urgent protective actions Planning Zone) for LDR were calculated as 130 m and 520 m compared to the values given in the Finnish YVL guide 5 km and 20 km.

Expertise for licensing and safety analysis in Finland was examined. The calculation tools currently under development were found to provide a good basis for safety analysis of SMRs especially for light water reactor based technology. For next-generation technology, more resources and development may be needed. Attention must be paid also to maintaining current expertise through education of new experts.

3.2 Streamlined licensing process

3.2.1 Proposal for a new licensing mode

Although it would, in principle, be possible to apply the regulatory processes currently in effect in Finland for the licensing of SMRs, the current processes do not justly consider the new construction, deployment and operating models envisioned for economically feasible SMR projects. To make such projects feasible, the regulatory processes should be adapted to justly consider the serial production and wide geographical deployment possibilities of SMRs.

The regulatory processes operate on two levels. The government decision making consisting of the decision in principle, the construction license, the operating license and the license for decommissioning are managed by the Ministry of Economic Affairs and Employment (MEAE). This level is usually referred as “licensing”. The Radiation and Nuclear Safety Authority STUK performs the technical regulatory control, which is usually referred as “oversight”. The work in EcoSMR has focused on the licensing, while the work to rationalize the regulatory oversight is underway elsewhere, such as the KELPO project run by the Finnish nuclear power companies.

The current licensing process in Finland is illustrated in Figure 3-1. The current legislation assumes that there is one applicant per project that is responsible for everything, including site, technology, operations and safety. The current decision-making path in Figure 3-1 is thus well suited for individual large projects that are run by one applicant. The project can include multiple reactors and/or multiple sites, but other applicants cannot leverage approved sites or technologies directly. New projects need a new assessment by STUK every time. As the delivery contract for a plant has to be done before the detailed regulatory review of the plant for the construction license, there is not yet knowledge of how the stated regulatory requirements are actually to be implemented in the plant. This results in major uncertainties in the cost and the schedule of the project.

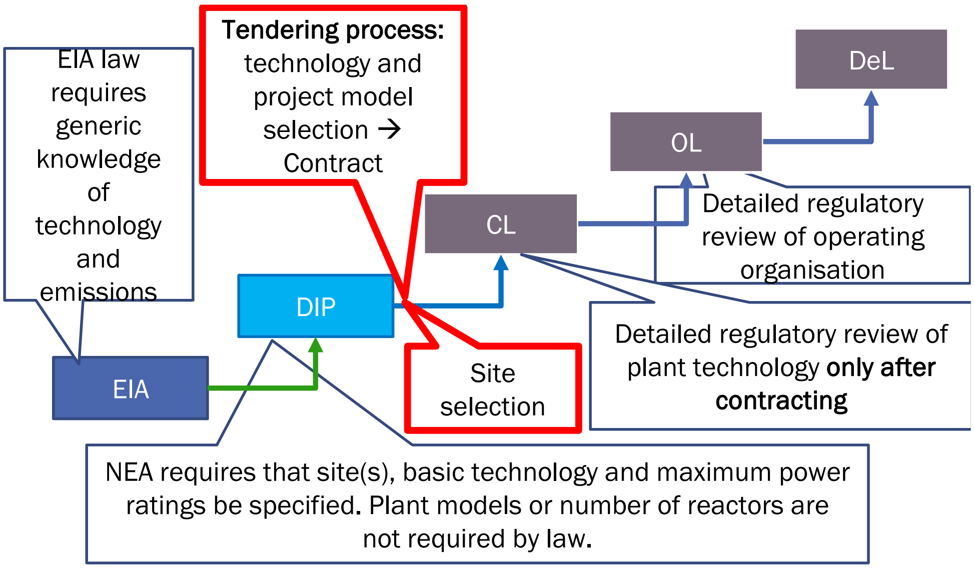

Figure 3-1. The current licensing process in Finland.

A proposal as a more streamlined licensing process to address the above-mentioned problems was develod as illustrated in Figure 3-2. The proposal separates the technology and the site so that each can be approved independent of projects to the depth that would be done for the construction license. This model also does not assume a single applicant that is responsible for both, the technology and the site. The applicant for the technology approval could be the plant vendor with the best knowledge of its technology who directly interfaces with STUK. The remaining assessment for the construction license phase in this model would then be to ensure the compatibility of the technology and the site. Under this model, an applicant can then leverage approved reactor designs and licensed sites, which would significantly reduce project uncertainty.

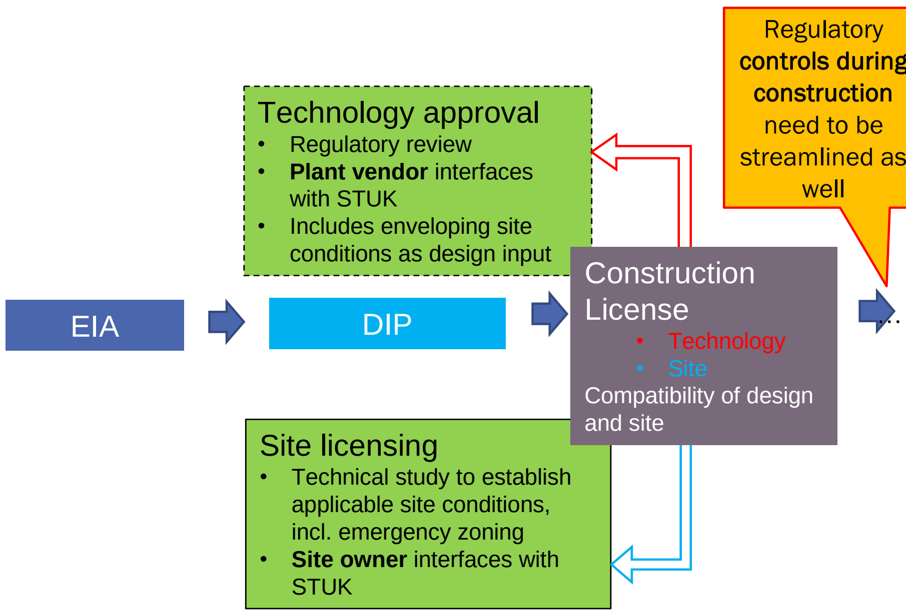

Figure 3-2. Proposed streamlined licensing process.

The proposed model implies that it must be possible to reallocate responsibility to capable parties. Table 3-1 provides an idea of how this could be realized. It should be noted that the holder of each authorization needs to have a certain level of technology competence, for example, to act as an "Intelligent Customer" capable of establishing a "Design Authority" as outlined in [IAEA, 2003].

Table 3-1. Reallocation of responsibilities in the frame of the proposed licensing model.

	Old license holders	**New holders or respective authorisations**
Technology	Plant owner • Outsources to Vendor	Vendor/IPR holder, via Design Certification
Site	Plant owner	Site owner – can be Owner of Plant owner, or transfer site to Plant owner for the project
Operations	Plant owner	Plant owner • May outsource to a Service provider
Liability	Plant owner	Plant owner
Waste management	Plant owner (financial) • may outsource activities to a daughter company	Plant owner (financial) • May outsource activities to a Service provider

[IAEA, 2003] Maintaining the Design Integrity of Nuclear Installations throughout their Operating Life, INSAG-19, IAEA, Vienna, 2003.

3.2.2 Licensing cost of SMR

SMR licensing costs and challenges in their estimation were studied under task 1.1 in the EcoSMR project. Licensing costs are generally not very sensitive to reactor size. SMRs aim to utilize standardization which means that the licensing costs of reactors under the same regulations are shared by the number of built SMRs. This number is generally not known when building the first reactor(s). To make SMRs economically viable, it is important that the licensing costs are predictable. Two approaches for estimating the costs were introduced in this task. The whole study is presented in reference [Helminen, 2023].

The approaches examined were i) Top-down and ii) Bottom-up approach. In the first approach, the overall nuclear power plant cost is broken down to different categories, licensing being one of them. In the second approach, the licensing costs are generated for suitable entities like for example structures or components. The survey referenced here concentrated more on the top-down approach because more references were available for that approach.

Some challenges were identified concerning both studied approaches. In the top-down approach, available references do not usually identify the share of licensing work in the overall costs. Also, the available values are given for large nuclear power plants and their comparability to SMRs is questionable. In the bottom-up approach, cost estimates are highly dependable on plant design. For a more sophisticated licensing cost estimate, a more comprehensive study would be required.

[Helminen, 2023] Helminen, A., Tulkki, V., “Licensing costs of SMR and challenges in their estimation”, VTT-R- 00221-23.

3.3 SMR siting and emergency preparedness

A central question in SMR deployment is the emergency planning zone (EPZ), whose size determines, to a large extent, where such plants can be located. This is important particularly for heat applications, as heat should not be transferred over long distances. A review was compiled about current international

(IAEA, national regulators) developments in appropriate EP&R (emergency preparedness and response) for SMRs [Ilvonen, 2021]. For a rigorous and definitive basis, it is proposed to study the EPZ sizing problem numerically by full-scope PSA (level 3: offsite consequences, like the probability distribution of dose at given distances) for choosing well-justified sizes of EPZ zones. That is a laborious, 'brute-force' approach, which can be done for one plant type at a time. However, results for several plant types may allow to derive more universal recommendations. The importance of PSA/PRA is that it incorporates the frequencies of various accident sequences and thus also their resulting radioactive releases.

The review work started with a general literature survey on the SMR EPZ problem, but is also based on work in the IAEA CRPs (coordinated research projects) I31029 'Determining the technical basis for EPZ for SMR deployment' (2018-2021) and J15002 'Effective use of dose projection tools' (2020-2022). A TECDOC based on the former CRP is expected to appear in 2023. Some information / insight also comes from participation in various IAEA Technical Meetings (TM), particularly the Feb 2017 TM on NGR EPZs, and the Sep 2020 TM on NGR and EPR (NGR = next generation reactor). Other relevant meetings were the Apr 2019 TM on Advances in EPR arrangements, and the Dec 2019 Regional workshop on EPR for SMRs.

In Finland, a reform of nuclear regulation (legislation and regulatory guides) is expected in the coming years. For assessing the possibility of SMRs in Finland, the licensing process, licensing requirements and related safety issues should be studied in more detail. This includes particularly passive safety systems and further evaluation of potential offsite consequences, all the way down to doses and health effects. It is recommended to follow closely the related developments in the UK, Canada and the USA, where the US NRC is already well advanced in considering the licensing and siting of SMR plants. Only by timely actions in Finland may we ensure not lagging behind other EU countries, like Sweden, Estonia or Poland.

As practical applications of the proposed EPZ right-sizing process, some simple case studies for NuScale (50 MW electric version) and the VTT-designed LDR-50 'Low-temperature District heating and desalination Reactor' (50 MW thermal) were performed using the VTT-developed ARANO code for atmospheric dispersion and offsite dose assessment. All the results are very preliminary in nature and for definitive results, much more data and project resources would be needed. Also, in addition to hypothetical plant releases, we should consider the transports of spent fuel (SNF), which may take place through more densely populated areas than usual before, if the SMR plants are in city area, and thus possibly introduce more initiating events for accidents and cause higher population doses, should a release happen. To study transport routes, knowledge of the total inventory transported at one time is the starting point.

For NuScale, a MELCOR model has been developed at VTT by Sevón (2021) based on publicly available data. NuScale FSAR (2020) can be found on the NRC website, and its Part 2, Tier 2, Rev. 5, Ch. 19 (PRA and SA evaluation) considers in 19.1.4 PRA for power operation of a single module, for internal events. Largest contribution (22.3 %) to Core Damage Frequency CDF comes from an RCS LOCA inside containment: One RVV (reactor vent valve) opens from PRZ (top of RPV) to containment. The ECCS fails, as the other two RVVs open, but RRVs (reactor recirculation valves) do not, and the RCS coolant inventory is lost. Normal DHRS (to pool) is assumed unavailable. MELCOR simulation of this sequence predicted a Cs-137 release of 1.3 GBq (among other nuclides) to the outside atmosphere, as compared with the 100 TBq limit, which has been used for severe accidents in Finland. Even with unfavourable weather conditions (stability F, wind 2 m/s) the total effective dose in one week remains lower than 0.2 mSv even at 100 m distance, to be compared with the usual evacuation limit of 20 mSv / 1 week.

For the LDR-50, there is currently no plant model for any SA code, and actually MELCOR use would not be allowed for new reactor design by license conditions. For this reason, an approach with variations possibility was chosen. The reactor inventory, based on Serpent calculations, for most of the 84 ARANO nuclides was received as given data. In ARANO, the nuclides are divided into nine groups of similar chemistry etc. and for subsequent combinations, the whole inventory of each group was released separately and doses vs. distance from that (completely hypothetical) release were calculated by ARANO.

The doses were chosen as the 95 % fractile from a long-term weather data. Then it is possible to express various cases (with some assumed groupwise actual release fractions) as a linear combination of the whole-inventory-of-group dose results.

Furthermore, a very simple scaling exercise was performed: In usual assessments, it was found that the typical dependence of dose D on distance r was of the form $D = 1/r^a$, where the exponent a is somewhere between 1 and 2. Using the value a = 1.22 (from the fit to a certain assessment's results), and the fact that Olkiluoto 3 (4300 MWth) was licensed with PAZ 5 km and UPZ 20 km, we get by pure scaling for LDR-50 the corresponding radii as 130 m and 520 m.

[Ilvonen, 2021] Ilvonen, M., ”Review of SMR siting and emergency preparedness”, VTT-R-01612-20.

3.4 Expertise for licensing and safety analyses of small reactors

Increasing interest in SMR technology has raised questions about the applicability of computational tools and methods developed for large LWRs for the licensing analyses of emerging reactor concepts. This question is complicated by the wide range of technologies under the SMR umbrella, as well as the scope of analyses required for the licensing process.

The capabilities of current state-of-the art methods were evaluated by comparing the calculation codes used at VTT with identified challenges related to novel reactor concepts [Leppänen, 2022]. The topics covered core neutronics, thermal hydraulics, fuel behaviour, severe accidents, PRA, final disposal and specific challenges related to molten salt reactors. The emphasis was put to tasks closest to the reactor core, because it was assumed that similarities to conventional LWRs increase when moving further away from what differentiates these technologies in the first place.

It was concluded that the computational tools currently under development provide a good basis for SMR safety analyses, in particular for LWR-type concepts, provided that the progress follows the expected path, and that new methods can be sufficiently validated by comparison to experimental data. Expanding from LWR-type SMRs to next-generation technologies, however, may require significant additional resources in the development of new methodologies. In addition to state-of-the-art calculation tools, maintaining the high level of competence requires that sufficient efforts are devoted to the education of new experts.

[Leppänen, 2022] Leppänen, J., “Overview of calculation tools used for SMR safety analyses.” VTT-R-01008-22, VTT Technical Research Centre of Finland, 2022.

4. Heat use of small reactors

4.1 Summary

EcoSMR project studied district heat SMR from following perspectives.

- **Investment analysis** – a techno-economic analysis of how profitable heat SMRs would be as a part of district heat grids. The analysis focus on the value of production, competing technologies, and uncertainties.

- **Integrating a nuclear heat plant to a district heating network –** Identifying boundary conditions of integrating heat only reactor to a district heating grid, focusing on temperature levels and variability of demand in the grid.
- **Analysis of load following capabilities of nuclear heat plants** – VTT's Apros model of LDR-50 was expanded based on the results from integration task, and we simulated load following capabilities of LDR-50. Few particularly difficult load following cases were selected assuming a small district heating grids where the SMR would provide most of the heat and have to be the main unit following the load.
- **Market potential of a Finnish district heating reactor** – Task covers a review of Finnish district heating grids and an estimate of market potential and heat SMRs in Finnish district heating grids, a review of export potential to the Baltic countries and Poland, and a literature study of additional export potential in desalination.
- **Pre-design of a heat exchanger for Finnish district heating reactor** – Based on lessons learned, and to be able to consider the manufacturability and potential manufacturing companies, we designed a preliminary heat exchanger for a proposed 50 MWth Finnish DH reactor operating with natural circulation.
- **Carbon footprint of district heating reactors** – This task was done in collaboration with Aalto university. In the Advanced Energy Project course, a group of master students analysed the carbon impact of district heating reactor by studying both LCA emissions of building the unit and substituted emissions when replacing fossil fuels when operating.

All tasks advanced the knowledge of a specific topic and overall understanding of the heat use of SMRs. However, none of the tasks were able to provide final conclusive answers, mainly because many assumptions are case and site specific.

4.2 Investment analysis

Investment analysis tries to evaluate the potential return on an investment and decide how likely it is a good opportunity. Main components of heat SMR investment analysis include the costs of licensing, building, and operating, costs of integrating to grid, potential revenue from generation, and the risks and uncertainties associated. To make it more complicated, all or most of these depend on the location.

Capital costs associated to investment of heat SMR were particularly uncertain when the EcoSMR project started and we decided that we do not try to acquire real values, but instead study ranges that could be profitable and acceptable. This approach would require an update in further studies as there is nowadays significantly more information available.

The potential revenue from generation is an important shift of focus from production cost to the value of production. However, it requires a modelling of a district heating system and we did analysis for the Capital regions of Finland, Estonia, Latvia, and Lithuania in EcoSMR project. The basic workflow of these analysis is presented in Figure 4-1.

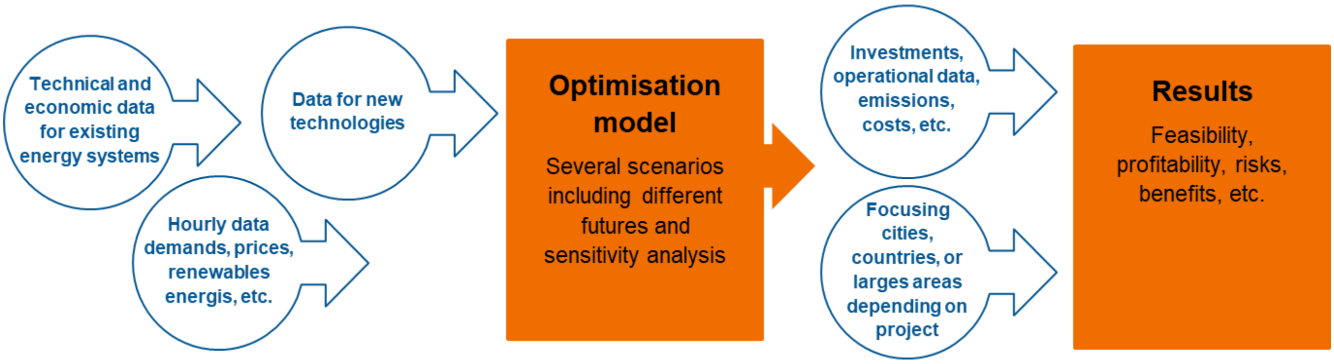

Figure 4-1 Analysis framework of the investment studies.

The city level district heating network typically consists of a range of thermal fuel units, CHPs and heat only boilers, heat pumps, and storages. These units are used to generate electricity, district heating, and in some cases, also district cooling, Figure 4-2. For each case study, we also defined certain investment options. Figure 4-2 shows typical options to generate low carbon heat.

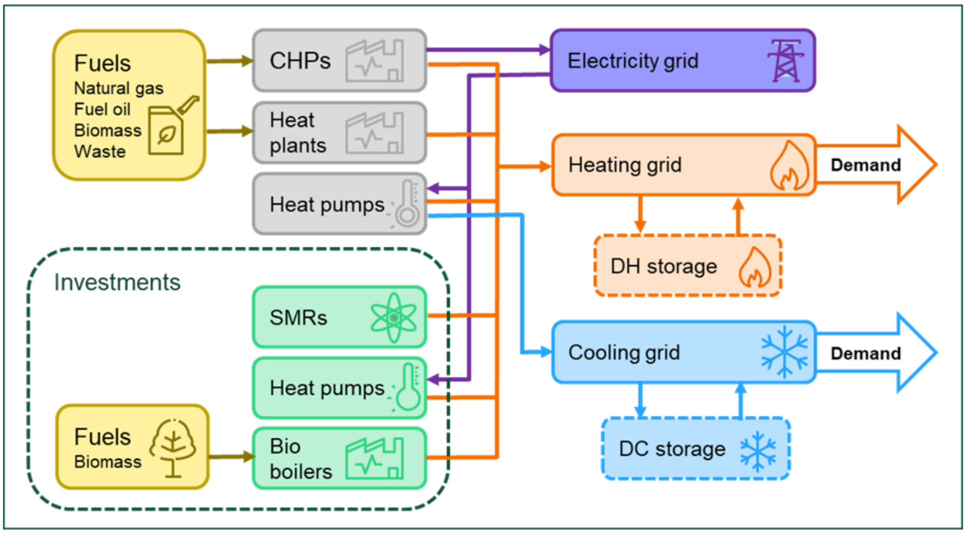

Figure 4-2. Schematic figure of modelled city-level energy systems.

Biomass boiler is a well established technology limited mostly by availability of sustainable fuel, amount of truch traffic near the plant, and the price of fuel. With these limitations, it is very easy to scale up, but there is notable uncertainty in the availability and price of fuel because biomass can be used in many low carbon products, such as transport bioliquids.

Heat pumps should be divided into three groups: building level heat pumps, large heat pumps from good heat sources such as waste water or data centres, and large heat pumps from ambient heat sources such as sea water or air. In our analysis, we assume that building level heat pumps reduce the demand of district heating by x %, but do not study them directly. In addition, in our analysis, we assume that large heat pumps from good heat sources will be the primary option for centralized solution, but the potential of good heat sources is limited.

Against this background, we modelled a range of scenarios studying SMRs and heat pumps from ambient heat sources as options to replace fossil fuels. In the modelled scenarios, SMR cases were cheaper than heat pumps from ambient heat sources, see Figure 4-3 [Pursiheimo, 2022].

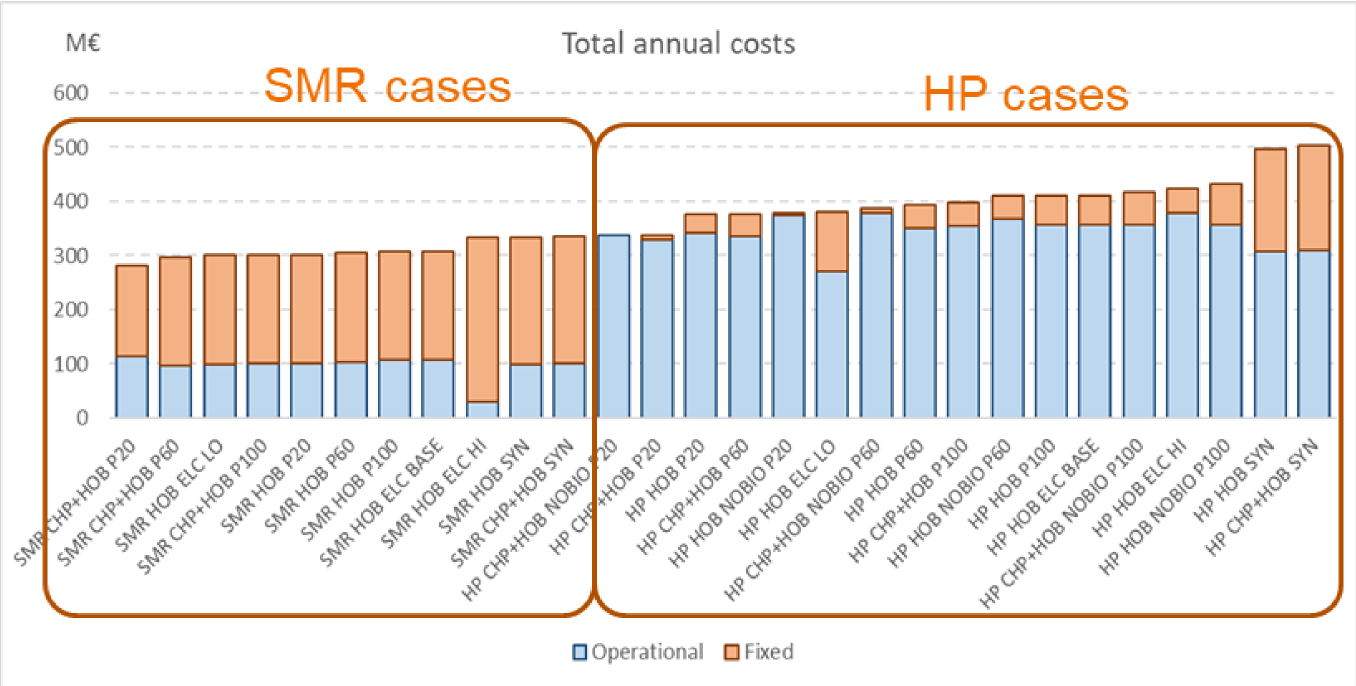

Figure 4-3. A summary of cost results from studied SMR and HP cases.

Risks and uncertainties are also an important consideration in the investment analysis of nuclear power. These can include regulatory risks, technological risks, and risks related to public perception and acceptance of nuclear power. It is important to carefully consider and quantify these risks in order to make an informed decision about the potential return on an investment in nuclear power.

The largest systemic uncertainties on heat only SMR and CHP SMR investment profitability in the Finnish capital region were electricity price, electricity grid fees including taxes, and the price of biomass and natural gas, see Figure 4-4 [Lindroos, 2019]. The first three of these can change the order of most profitable investment options, whereas the increasing natural gas price makes any option more profitable compared to existing large natural gas fired units in Helsinki.

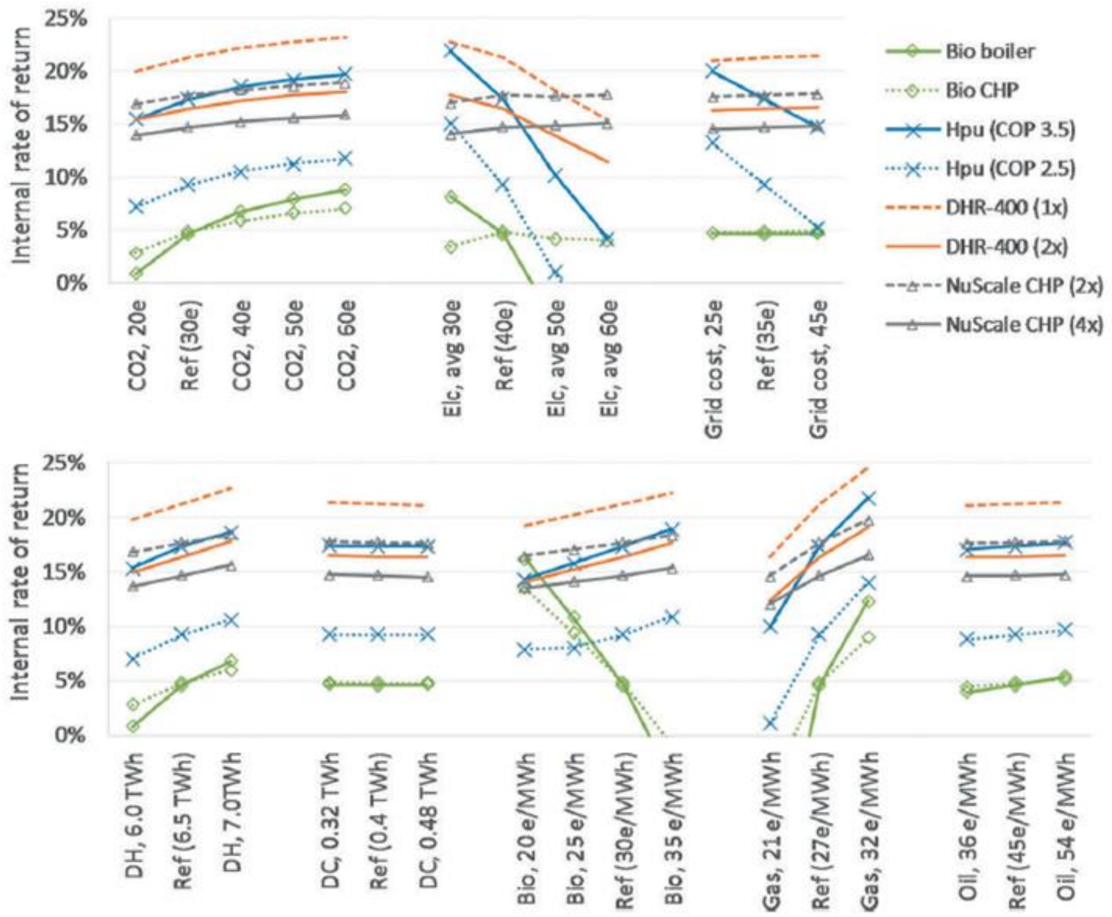

Figure 4-4. A summary of analyzed systemic uncertainties.

When a similar analysis was repeated for Baltic countries, we varied the amount of installed capacity, fuel prices, and assumed investment costs, see Figure 4-5 [Lindroos, 2022]. Amount of installed capacity was defined as a multiplier of the summer demand, for easier comparison as the size of the DH grids vary. Investment profitability varied between Baltic capitals due to existing units in the system. Vilnius has already invested in waste incineration and biomass units, and additional investments to SMRs was not profitable. Tallinn and Riga are still relying on fossil fuel based generation and SMR investments were significantly more profitable.

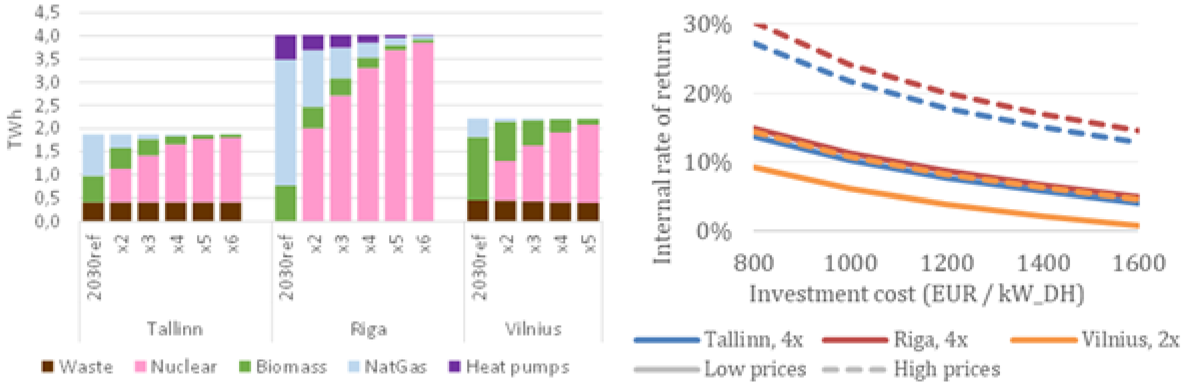

Figure 4-5. District heat generation in Baltic capitals as a function of invested heat SMR capacity (left) and calculated profitability of 4x cases for Tallinn and Riga, and 2x case for Vilnius (right).

[Lindroos, 2019] Lindroos, T.J., Pursiheimo, E., Sahlberg, V., and Tulkki, V. 2018. A techno-economic assessment of NuScale and DHR-400 reactors in a district heating and cooling grid. March 2019, Energy sources. Part B Economics, planning and policy 14(1):1-12.

[Lindroos, 2022] Lindroos, T.J., Putkonen, N., Niemi, A., Alblouwy, F., and Suikkanen, H. 2022. Prospects of electricity and heat-only SMRs in the Baltic Region. November 2022. Conference: Nuclear Science and Technology Symposium - SYP2022 At: Helsinki, Finland.

[Pursiheimo, 2022] Pursiheimo, E. Lindroos, T.J. Sundell, D. Rämä, M., and Tulkki, V. (2022). "Optimal Investment Analysis for Heat Pumps and Nuclear Heat in Decarbonised Helsinki Metropolitan District Heating System", Energy Storage and Saving, 1, 80-92, https://doi.org/10.1016/j.enss.2022.03.001.

4.3 Integrating a nuclear heat plant to a district heating network

In this task we focused on grid integration from the operation perspective (temperature levels, supplied power) and did not analyse integration costs, which is something to improve in further work.

Open source production data of Helen and temperature measurements of FMI show that there is almost a linear dependency between district heating demand and outdoor temperature when below ~12 degrees (Figure 4-6). Data also shows that there is certain baseload demand due to hot water demand, and hourly demand varies ±300 MW depending on weekday, hour, and other factors. These can be analysed further to build regression models for specific grids.

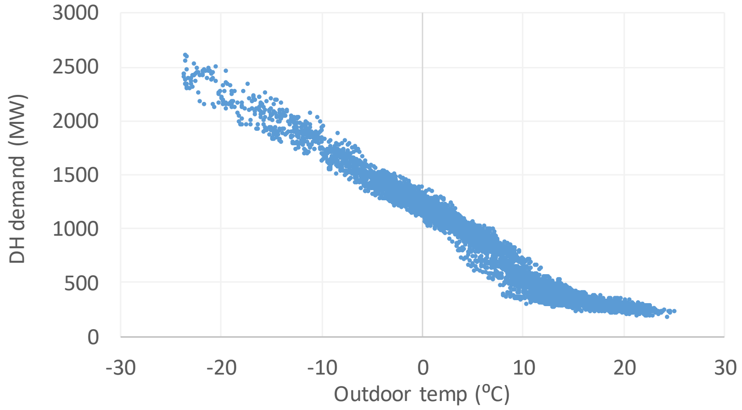

Figure 4-6. District heating demand in Helsinki in 2015 as a function of outdoor temperature.

District heat supply and return temperatures vary from grid to grid and single units can feed different temperature than other units. Therefore, there is no real generic answer on temperature levels, but Finnish Energy provides overall guidelines that can be used as assumptions (Figure 4-7).

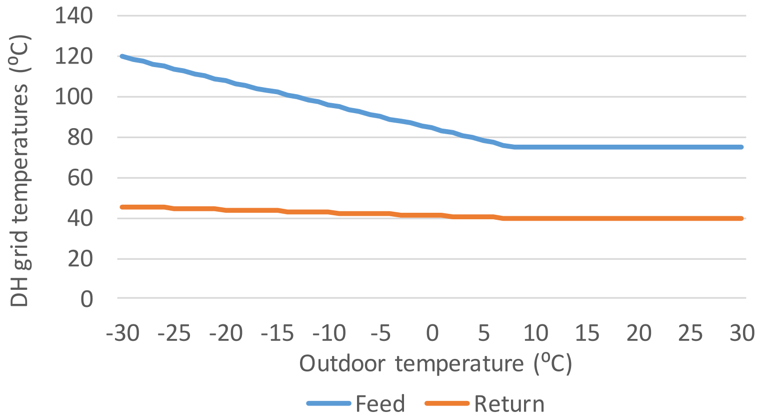

Figure 4-7. Generic assumptions on district heating feed and return temperatures as a function of outdoor temperature. These can vary significantly from grid to grid and single units can follow different curves in the same grid.

Based on historical temperature data from 2016 and 2019, the number of hours when district heat feed temperature is higher than set border condition decreases quickly as a function of temperature (Table 4-1). Hours when feed temperature would have been above 100 degrees in 2016-2019 was only 112 hours per year.

Table 4-1. Calculated number of hours when district heat feed temperature is higher than set border condition, e.g. 90 degrees.

DH feed temp	2016	2017	2018	2019
>90 deg	750	320	970	460
>95 deg	410	110	350	150
>100 deg	210	60	120	60
>110 deg	40	0	0	0

Even during the hours of high demand, heat SMR can supply heat, but it needs to be upgraded with other units in the grid, e.g. a biomass boiler. Calculating the share of heat that a specific unit with a given output temperature can provide shows that this is not a limiting factor for the heat SMR. The estimate in Table 4-2 is calculated from the energy needed to update the water from return temperature to either outlet temperature or the final feed temperature if higher than SMR outlet temperature.

Any unit with 100 degree output would have been able to provide more than 99% of the energy when forgetting the capacity limitations, which is much higher than economically viable capacities in investment analysis.

Table 4-2. A calculated share of energy that is distributed below set border condition, e.g. 90 degrees. This equals an estimate that how large share of the DH heat and heat SMR with specific output temperature could provide.

Nuclear DH Output temp		2016	2017	2018	2019
90 deg	**%**	97.30%	99.20%	97.80%	99.00%
95 deg	**%**	98.70%	99.70%	99.30%	99.70%
100 deg	**TWh**	99.40%	99.90%	99.80%	99.90%
110 deg	**TWh**	99.97%	100.00%	100.00%	100.00%

4.4 Analysis of load following capabilities of nuclear heat plants

District heat (DH) demand and supply temperature vary strongly depending on the outdoor temperature, which means that some load following would be required from the nuclear heat plant especially in small DH networks. The aim of this task was to study the load following capabilities and thermal-hydraulic limitations of nuclear heat reactors. VTT's reactor design LDR-50 was used as a case study in the analysis [Komu, 2022]. The analyses were done with the process simulation software Apros.

The LDR-50 reactor module is connected to the DH network via secondary circuit. The Apros model included the primary circuit and the secondary circuit with boundary conditions. The model was extended to comprise the whole secondary circuit all the way to the district heating network. Now, return and supply temperatures of the district heating network act as a boundary condition for the model. Reactor power can be given to the model in a table form or calculated with point kinetics.

Historical district heating data from Helsinki was utilized to get boundary conditions to the Apros model: return and supply temperatures, and power. Three different types of difficult load following cases each with a duration of one week were selected to test the limitations of the design. The results indicate that the reactor survives the challenging load following cases without difficulties and the thermal-hydraulic design poses no limitations to the operation. In the future, the calculations can be used as boundary conditions for core calculations or repeated coupled calculations with a neutronics code to find the limitations of the neutronics design.

[Komu, 2022] Komu, R., el.al. (2022), "District Heating Reactor LDR-50: Thermal-Hydraulic Analysis of Difficult Load Following Cases", The 13th International Topical Meeting on Nuclear Reactor Thermal-Hydraulics, Operation and Safety (NUTHOS 13) Hsinchu, Taiwan, September 5-10, 2022.

4.5 Market potential of a Finnish district heating reactor

Annual district heat (DH) production in Finland totaled 35.1 TWh in 2021 with the production profile as shown in Figure 4-8. As can be seen in the figure, over 37 % was produced by fossil fuels and peat, while 45.1 % was covered by bio-based fuels. Thus, although been in decline during the past years, the specific emissions were still 102.5 gCO_2/kWh. [Energiateollisuus, 2021] Considering the ambitious emission reduction goals [Valtioneuvosto, 2019] and the current production profile, there would seem to be a clear demand for technologies that can replace, in the short term, the fossil fuels, and in the longer term, most other combustion-based production in the Finnish DH networks. Nuclear energy, with its lifecycle greenhouse gas emissions comparable to wind, solar and hydro power [UNECO, 2021], represents one possible technology that could be used for producing dispatchable heat for district heating.

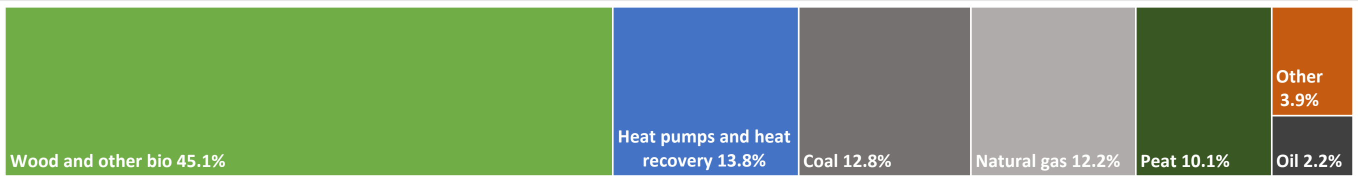

Figure 4-8. District heat production by fuels in Finland in 2021.

The prospects for district heating reactors of domestic design in Finland were investigated and are presented in the following. Moreover, the export potential to the Baltic countries and Poland are discussed as well as an alternative use case for the reactor in water desalination. Both LUT and VTT have been developing DH reactor concepts and an important design aspect has been to enable domestic manufacturing of the components to as large extent as possible. Thus, the Section 4.5 end with a description of the work that was done for pre-designing the primary heat exchanger, a major component of a DH reactor, that has potential for being cost effective and possible to manufacture in Finland.

4.5.1 Prospects for district heating reactors in Finland

The supply temperature to the DH network depends on the outside temperature and ranges between 65 to 115 °C, with the maximum design temperature of 120 °C. This means that the temperature that a DH reactor needs to be capable to produce is significantly lower to what is needed for efficient electricity production with nuclear reactors. This also results in significantly lower operating pressure and, subsequently, in less demanding requirements for pressure-bearing components, such as the reactor pressure vessel (RPV), making it possible to manufacture them with reduced wall thicknesses compared to RPVs of electricity producing light water reactors.

The high seasonal variation in the heating demand presents a challenge for the economics of a district heating reactor and its sizing. A generic DH duration curve is presented in Figure 4-9, which shows the hours of the year sorted in descending order based on the DH load. Although, such a curve is region dependent, the qualitative shape of the curve is representative and shows that the peak load during the coldest hours in winter is roughly ten times the load during warm summer hours. If designed sufficiently small, a single or a few DH reactors could provide the base load all year round in very large networks. More likely, however, considering a smaller network with also other heat sources, a DH reactor would cover the need up to some fraction of the peak load (e.g., 40 %) and then adjust its output such that it can operate a reasonable part, such as 9 months, of the year. Thus, the reactor should be designed to be capable of performing load following.

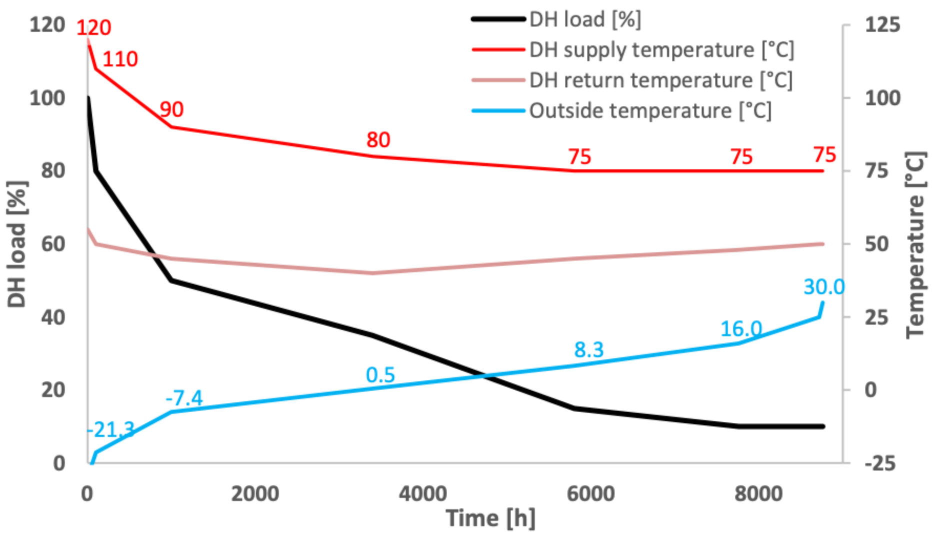

Figure 4-9. A generic DH duration curve and the dependence of the supply and return temperatures on the outside temperature.

The regional DH statistics in Finland [Energiateollisuus, 2019] were analyzed to also identify, on one hand, the suitable reactor size in MW_{th}, and on the other hand, the potential locations and the number of reactors that could theoretically fit into the Finnish DH networks. The production of district heat in different regions in Finland is shown in Figure 4-10 and the total production capacity and the estimated peak demand for the same regions is shown in Figure 4-11. The capital region has a significantly higher production and capacity than other regions in Finland and has been excluded from the graphs. After the capital area, a group of six cities can be distinguished with a production of over 1000 GWh after which there are several regions with a production up to a few hundred GWh. Major part of the production is covered by fossil and bio-based fuels.

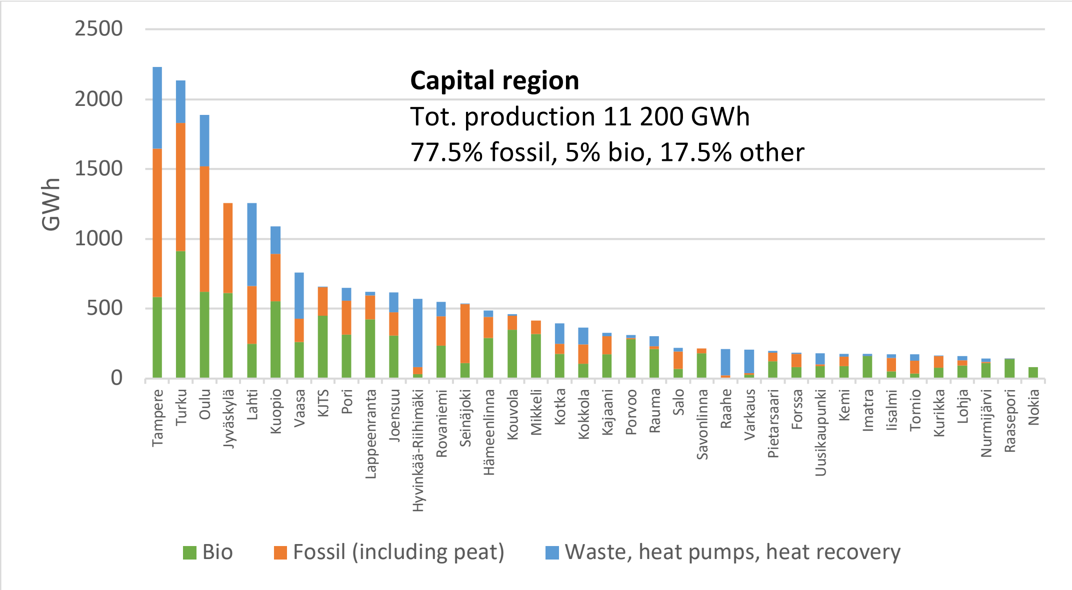

Figure 4-10. Produced district heat in different regions in Finland in 2019.

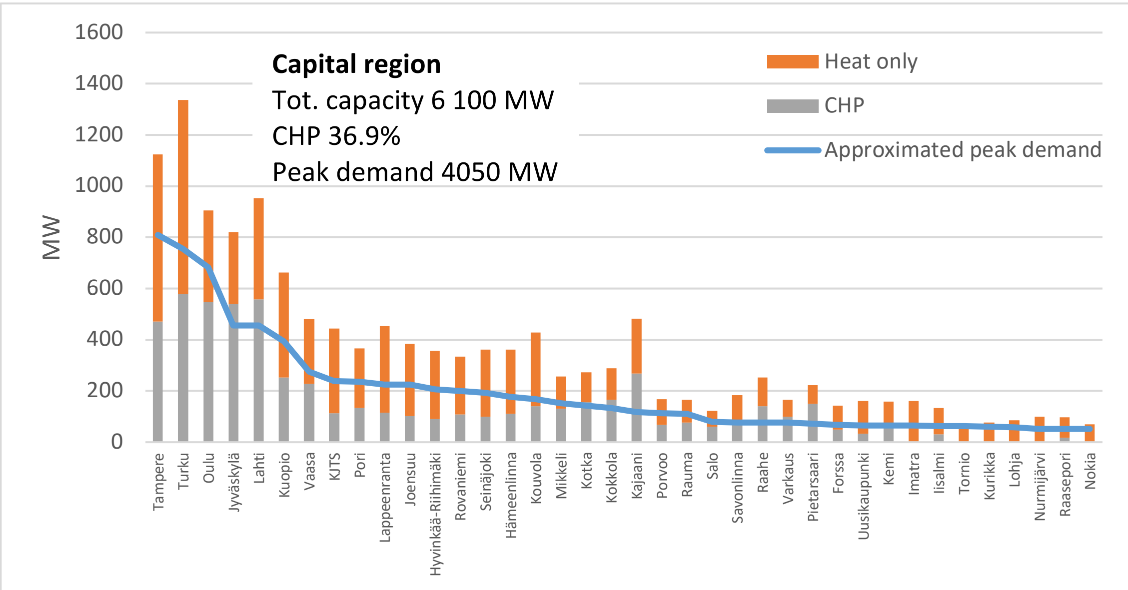

Figure 4-11. District heat production capacity and estimated peak demand in different regions in Finland in 2019.

Capital region, with its considerable DH demand could likely accommodate reactor units in the hundred-megawatt scale. However, considering the significantly smaller demand in other regions of Finland, the suitable size would more likely be some tens of thermal megawatts. Also, to start benefitting from series production would likely take tens of units. An analysis of potential number of reactors in different regions in Finland was conducted based on the regional statistics. It was assumed that the fossil and bio-based fuels would be replaced, and that the reactor should have a roughly 9-month annual operation time. A reactor sized at 24 MW_{th} was considered for this analysis to consider a good number of potential regions while still having a somewhat reasonable unit size. The results are shown in Table 4-3. Theoretically there could be room for almost hundred heating reactors of 24 MW_{th} distributed to 19 cities or regions in Finland. Considering a larger reactor, say 50 MWth, would mean roughly 50 reactors but would also drop 7 potential cities from the list of potential regions.

Table 4-3. Theoretical number of small DH reactors that could be accommodated in DH networks of different regions in Finland considering replacing fossil and bio-based fuels.

Region	Number of reactors	Region	Number of reactors
Capital region	46	Tampere	7
Turku	8	Oulu	7
Jyväskylä	6	Lahti	3
Kuopio	3	Vaasa	1
Kerava, Järvenpää, Tuusula, Sipoo	3	Pori	2
Lappeenranta	2	Joensuu	1
Rovaniemi	2	Seinäjoki	2
Hämeenlinna	1	Kouvola	1
Mikkeli	1	Porvoo	1
Rauma	1	**Total**	**98**

Along with the serial production model, most SMR designs aim for economic feasibility via passive and simplified safety systems made possible by the smaller power output of the reactor. The modest operating parameters of a DH reactor combined with even an order of magnitude smaller thermal power compared to typical electricity producing SMR designs could potentially make implementing safety functions in a DH reactor even simpler. The radioactive inventory of a reactor is proportional to its thermal power and in a small DH reactor thus significantly smaller than even in typical electricity producing SMRs. These features should help in justifying siting such reactors safely near populated areas, which is a necessity for the intended use in providing heat to DH networks. Furthermore, the above-mentioned features should help in reducing the costs as the technology must be competitive with alternative heat sources.

4.5.2 Export potential to the Baltic countries and Poland

The Baltic countries and Poland were identified as obvious candidates for exporting the Finnish DH reactor technology. The current state of DH in these countries was investigated especially regarding the current DH production/consumption, its geographical variation and energy source distribution to assess the potential for the deployment of small reactors.

Some district heating related key figures in these countries are given in Table 4-4. Even combined, the district heat production in the Baltic countries is much below the production in Finland, while Poland has almost twice the production of Finland. The heating networks in the Baltic countries originate from the Soviet era, although parts have been replaced with modern pre-insulated piping. Still, the average heat losses are large compared to the average heat loss in Finnish DH networks (8.6% in 2021). The heating degree days representing the annual need for heating decrease towards south. The values represent an average between 2017-2021 and the corresponding heating degree days in Finland are 5367. This may present challenges considering the annual operating time and thus the economics of a DH reactor in these countries.

Table 4-4. Key figures of district heating in the Baltic countries and Poland. [Statistics Estonia, 2022; MEAC, 2016; IEA, 2019; LŠTA, 2018; Official statistics of Latvia, 2022; Statistics Lithuania, 2022; IEA, 2021; Eurostat, 2022; Blumberga et al., 2018; Forum.

District heat	Estonia	Latvia	Lithuania	Poland
Production (TWh)	4.5 (2017)	7.51 (2020)	8.98 (2018)	74.2 (2018)
Network length (km)	1 455 (2017)	2 000	2 885 (2019)	20 139
CHP share (%)	50 (2017)	71 (2018)	39 (2019)	66 (2018)
Grid heat loss average (%)	21	11.8	15,3	11.8
Heating degree days	4 176	3 806	3 807	3172

DH production by fuel in the Baltic countries and Poland is presented in Figure 4-12. While still significant parts of DH produced by natural gas, the Baltic countries, especially Lithuania, have invested significantly to bio-based fuels to replace fossil fuels as the energy source for DH. This is not the case in Poland, where over 70% of the production is still based on coal.

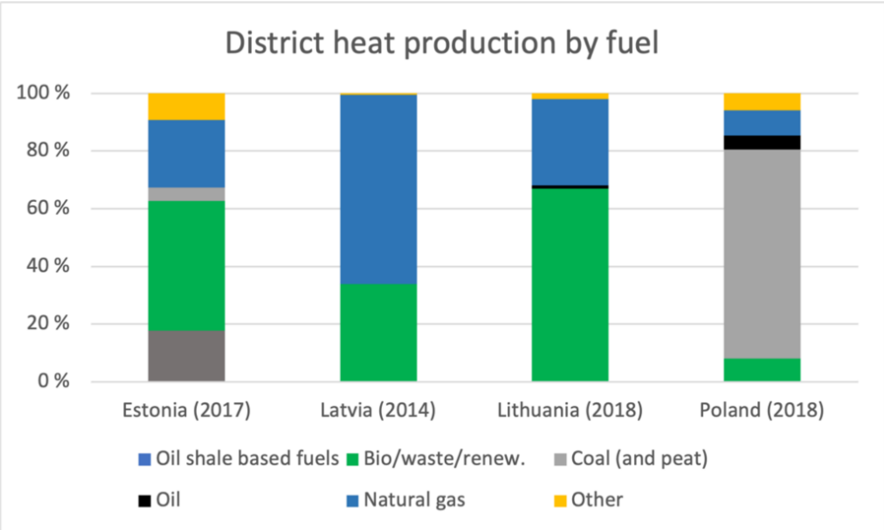

Figure 4-12. DH production profiles by fuel in the Baltic countries and Poland. [IEA Estonia, 2019; Official Statistics of Latvia, 2022; Forum Energii, 2019].

Based on Table 4-4, it can be concluded that the Baltic countries form a relatively small potential market for DH reactors. A more detailed breakdown identifying the largest regions for district heat consumption in Table 4-5 reveal that the capital regions of these countries, with district heat consumption comparable to larger and mid-sized cities in Finland, are the most likely locations considering DH reactor deployment.

Table 4-5. DH consumption in regions with the largest consumption in the Baltic countries. [Statistics Estonia, 2022; [Official Statistics of Latvia, 2022; Statistics Lithuania, 2022].

Estonia (2019)*			**Latvia (2021)**			**Lithuania (2020)****		
Region	**DH cons. (GWh)**	**Population**	**Region**	**DH cons. (GWh)**	**Population**	**Region**	**DH cons. (GWh)**	**Population**
Harju Tallinn	1 664 1 186	601 544 436 090	Riga	3 236	610 210	Vilnus	1 443	825 231
Ida-Viru	538	135 249	Pierīga	1 151	381 352	Kaunas	987	564 593
Tartu	373	153 147	Latgale	911	249 951	Klaipėda	561	320 876

* A rough estimation based on total heat consumption in the regions and assuming that the share of DH is 39.7%
** A very rough estimation based on total heat consumption in households in Lithuania distributed to regions proportional to population.

The largest regions in DH consumption in Poland are shown in Table 4-6. The regions included in Table 4-6 all have an annual consumption over 4 000 GWh but in almost all 16 provinces in Poland the consumption is over 1 000 GWh. Although these are larger regions with the more detailed distribution inside the provinces remaining to be clarified, it is evident that small DH reactors could easily fit into the heating networks in several areas in Poland.

Table 4-6. DH consumption in the regions with the largest consumption in Poland. [Urząd Regulacji Energetyki, 2020].

Region	DH cons. (GWh)	Population	Region	DH cons. (GWh)	Population
Mazowieckie	13 268	5 425 000	Wielkopolskie	4 832	3 496 500
Śląskie	9 310	4 492 300	Pomorskie	4207	2 346 700
Dolnośląskie	4 945	2 891 400	Małopolskie	4086	3 410 400
Łódzkie	4 917	2 438 000	…	…	…

As a summary, a few small DH reactors could likely be exported to the Baltics, mainly in the capital regions, while Poland represents a significant potential market considering its current DH consumption and production profile still heavily reliant on coal. Technically, the design temperatures of the Finnish DH networks (120 °C) should be sufficient also in these countries, although supply temperatures up to 130 and 135 °C are reported for Latvia and Poland, respectively [Grzegórska et al., 2021]. However, there is a general trend in moving towards lower supply temperatures as distribution networks are modernized. The maximum supply temperature of 115 °C mentioned for Estonia, for example, is well in line with that used in Finland [Volkova et al., 2020].

4.5.3 Additional export potential in desalination

In addition to district heating, another potential area of application identified for small low-temperature reactors is water desalination. In 2020, the global installed desalination capacity was 97.2 million m^3/day [Eke et al., 2020]. The need for desalination is significant in parts of the world suffering from low precipitation and/or high population density. Middle-East and North Africa alone have almost 50% of the current desalination capacity. In addition to significant demand of fresh water, its current production by desalination is heavily reliant on fossil fuel -based energy.

Although, several desalination techniques exist, the multi-stage flash (MSF) and multiple effect distillation (MED) thermal processes and the reverse osmosis (RO) membrane process are the dominant desalination techniques employed [Eke et al., 2020]. The energy consumption and typical temperature requirements for these processes are given in Table 4-7. Although RO is the technique currently most used, the two thermal techniques would be the options that could be coupled with a heat-only reactor producing low temperature heat as illustrated in Figure 4-13. This type of setup would then require some electricity from an external source in addition to heat. As can be seen in Table 4-7, the temperature requirements of these processes are very similar to what is used in district heating. Although the efficiency of the MSF process could be increased by increasing the temperature, it also increases the accumulation of salt to surfaces (i.e., scaling) which sets an upper limit to the used temperature. The MED process is similar to MSF but utilizes even lower temperatures. Typical unit sizes for MED and MSF range from 10 000 to 30 000 m^3/day.

Table 4-7. Energy demand and temperature requirements for the three most common desalination techniques. [Ghaffour et al., 2013].

Process	Thermal energy (kWh/m^3)	Electrical energy (kWh/m^3)	Typical feed temperature (°C)
MSF	7.5…12	2.5…4	90…120
MED	4…7	1.5…2	60…75
RO	-	0.5…4	ambient

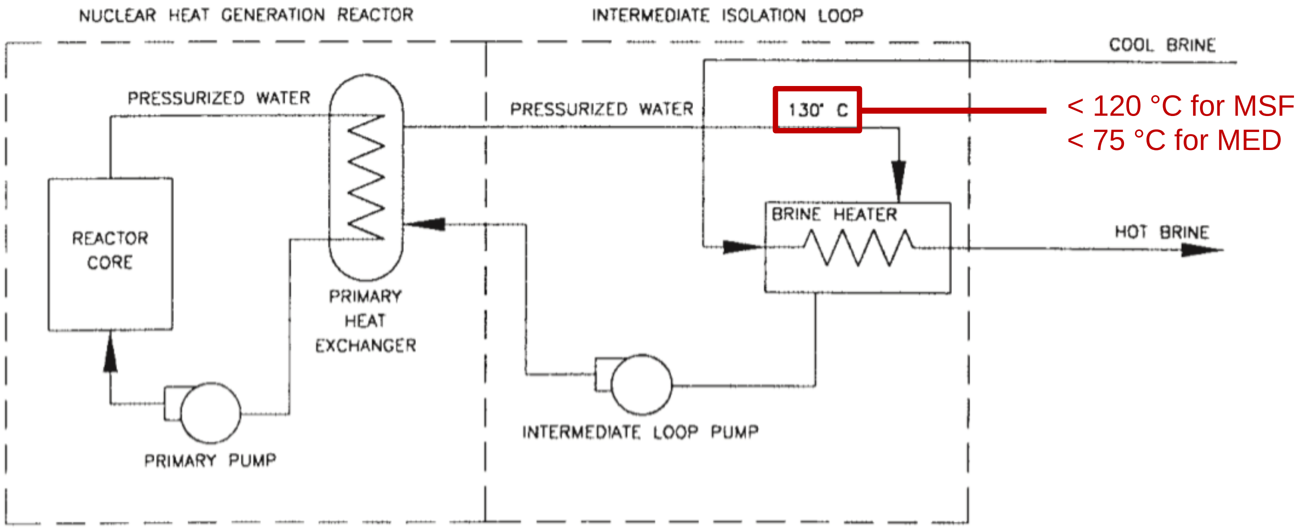

Figure 4-13. A thermal desalination process coupled with a heat-only reactor. [IAEA, 2000].

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4.6 Pre-design of a heat exchanger for Finnish district heating reactor

To be able to consider the manufacturability and potential companies that could manufacture parts for the Finnish DH reactor there should be at least some realistic preliminary designs for the components. For this reason, work was done to come up with a preliminary design of the primary heat exchanger for the proposed 50 MW_{th} Finnish DH reactor operating with natural circulation [Saari, 2023].

The primary circuit heat exchanger is a major component critical to the performance of the reactor system; a preliminary design and optimization was thus carried out to evaluate the feasibility of the natural circulation concept and obtain information on the general characteristics of a good design.

As the reactor design considered produces a constant heat rate of 50 MW, the heat transfer rate of the heat exchangers will remain unchanged as well. The operating point will set on such primary (hot) side temperature, that at a given secondary-circuit water inlet flow rate and temperature, this amount of heat is transferred. With the seasonal variation of the district heating water supply and return temperatures, the design must ensure that necessary temperature levels are met, while the maximum primary-side pressure and temperature are not exceeded at any operating point. To achieve this goal, a shunt connection to reduce the temperature variations at the secondary circuit (and thus primary circuit as well) was considered (Figure 4-14).

In the process of optimization, three operating points were considered, as listed in Table 4-8. The DH return water temperature cannot be affected; it is typically lowest at mid-load situations at near 0 °C ambient temperature, increasing towards the lowest and highest loads. The secondary circuit inlet temperature $T_{2ndr\text{-}in}$ to the reactor heat exchangers will exceed this by the DH heat exchanger ΔT, and secondary circuit outlet temperature $T_{2ndr\text{-}out}$ can be set by controlling the mass flow rate pumped through the secondary circuit. The DH supply temperature can then be set to an appropriate value for a given load point by the bypass shunt.

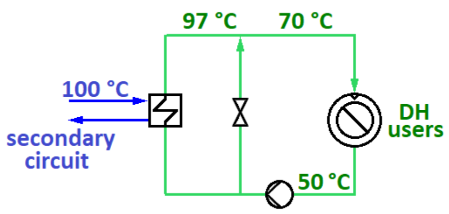

Figure 4-14. District heat network connection to control DH supply temperature while maintaining secondary-circuit temperature.

Table 4-8. District heating water and secondary circuit water temperatures at the three considered operating points.

	Peak	Mid	Min
$T_{2ndr\text{-}in}$ [°C]	58	43	58
$T_{2ndr\text{-}out}$ [°C]	123	~100	~100
$T_{DH,sup}$ [°C]	120	80	75
$T_{DH,ret}$ [°C]	55	40	50

The objective function in the preliminary optimization was set at minimizing the size of the reactor pressure vessel. This requires efficient use of the annular space between the rises and the reactor pressure vessel wall. A counter-current tubular heat exchanger design with the primary (hot) water entering the tubes at the top of the downcomer, and secondary (cold) fluid entering the shell side from the bottom of the shell was considered. Initially several designs were considered, including an angular, boxy shell of welded plates (option 0 in Figure 4-15), longitudinally-finned double-tube configuration without shell and primary water in the inner tube (option 1), a conventional round-shell configuration (option 2), and an elongated shell (option 3). Of these, the flat shell plates of option 0 would need to be excessively thick to accommodate even the modest pressures while the tubes at the corners would likely have poor shell-side flow and add little effective heat transfer. Option 1 proved to yield an inefficient heat transfer performance and use of space. Conventional segmentally-baffled shell-and-tube configuration (option 2), and a slightly elongated variant thereof (3) were thus selected for further study and design optimization.

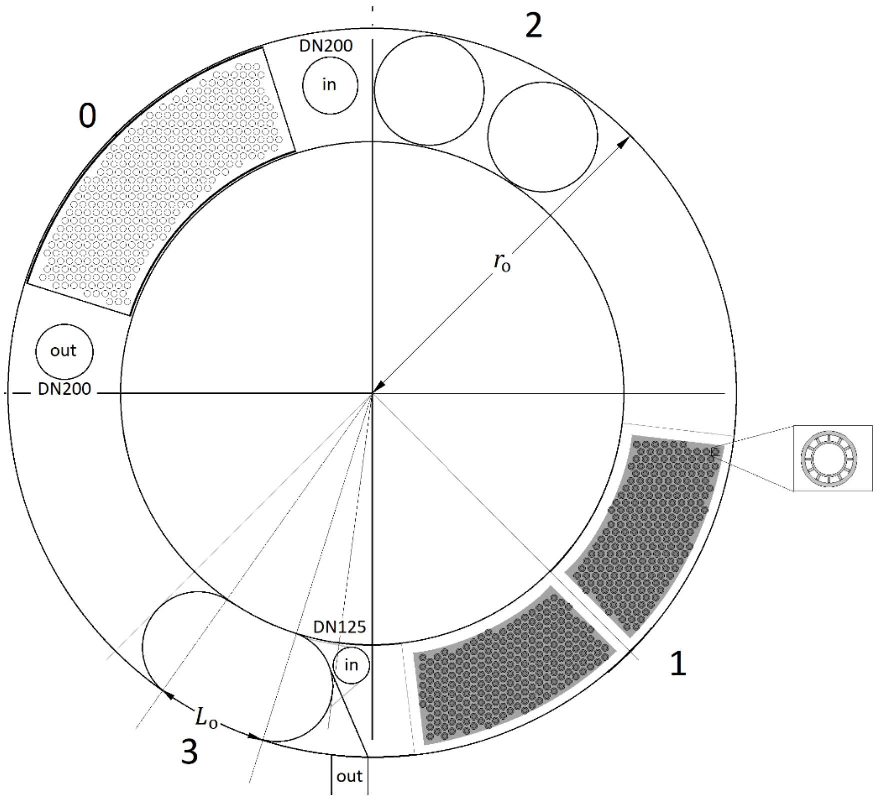

Figure 4-15. Design options considered for the heat exchanger.

The design optimization of options 2 and 3 was carried out using differential evolution. The objective function was minimizing the downcomer outer radius r_o (i.e., the radius to the pressure vessel inner surface). The optimization was repeated for different pressure vessel total heights H_{tot} from 5 to 9 m at 1 m intervals, assuming the maximum length of the heat exchanger at H_{tot} - 2 m. Table 4-9 lists the decision variables, constraints, and some main results obtained for the shortest 5 m pressure vessel height; the pressure vessel radius at different heights is shown in Figure 4-16. The 3 load points of Table 4-9 were evaluated, and a candidate solution was rejected if on any one load point a constraint was violated.

Table 4-9. Optimization results for 5.0 m pressure vessel.

		Constraint	Case 2	Case 3
Decision variables	Baffle cut *BC* [%]	0.2 < *BC* < 0.4	20.6	26.2
	Radius to pressure vessel inner surface r_o [m]	1.15 < r_o < 1.60	1.35	1.34
	Tube outer diameter d_o [mm]	*	10.0	10.0
	Baffle spacing S_{bf} / shell diameter $D_{sh,in}$ [-]	$0.2 < \frac{S_{bf}}{D_{sh,in}} < 1.0$	0.379	0.655
	Tube length L_t [m]	2.0 < L_t < [H_{tot}-2.0]	3.00	3.00
Dimensions	Tube pitch [mm]	1.25 d_o	12.5	12.5
	Tubes per shell [-]		471	973
	Baffle plates per shell [-]		19	7
	Shells in downcomer [-]		17	8
	Shell thickness [mm]		10	25
Flows and heat transfer	Average overall heat transfer coefficient [W/m²K]		2428	2477
	Primary water inlet temperature [°C]	*T* < 148	134-148	134-148
	Primary water (tube-side) velocity [m/s]		0.49-0.51	0.49-0.52
	Primary water pressure drop, tube+core [mbar]		14.3+2.4	14.6+2.3
	Secondary water (shell-side) velocity [m/s]	w < 1.5	0.98-1.47	0.91-1.37
	Secondary water pressure drop [bar]	Δ*p* < 1.0	0.28	0.49

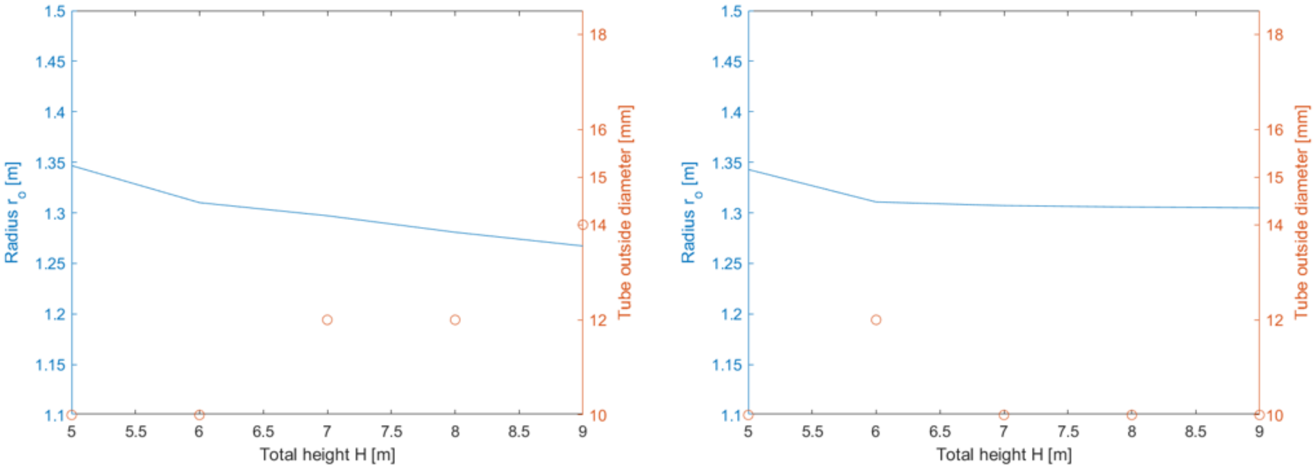

Figure 4-16. District heat network connection to control DH supply temperature while maintaining secondary-circuit temperature.

The results indicate that the use of space was not substantially inferior for Case 2, and the round shell has the advantage of much lighter configuration for a given pressure design. Being a widely used configuration, option 2 represents also a low-risk design with advantages of well-established sizing procedures and heat transfer correlations for shell-side calculation, as well as ease of manufacturing, in comparison to the other less conventional options. In Case 2, the total amount of shells that could fit the annular downcomer proved to be 17; reducing this by 1 would increase the radius somewhat, but the benefit of having 8 pairs of shells, each fed by a single secondary water pipe, would likely outweigh the slight increase in size.

[Saari, 2023] Saari, J., Suikkanen, H., Mendoza-Martinez, C., Hyvärinen, J., (2023), Optimization of natural circulation district heating reactor primary heat exchangers. Energies, 16, 2739, https://doi.org/10.3390/en16062739.

4.7 Carbon footprint of district heating reactors

Group of students from Aalto University studied the carbon footprint of district heating SMRs as part of an advanced energy project coursework [AEP, 2022]. The goal was to estimate the CO_2 emission reduction potential of nuclear district heating plants. The scenario involved varying number of VTT's LDR-50 reactor units in the district heating network of Helsinki.

The carbon emissions were estimated by means of life cycle assessment (LCA), taking into consideration the construction of the reactor units and the nuclear fuel cycle. A python program based on Mixed integer simulation was written to model the behaviour of the district heating network under different boundary conditions. Three scenarios were simulated:

1. Base (from 2018 district heating data)
2. 250 MW SMR
3. 700 MW SMR and No Natural Gas Plants.

The scenarios with nuclear heat resulted in some 30% reduction in CO_2 emissions compared to the baseline. Although this can be considered a significant improvement, the potential was clearly limited by the variation in seasonal demand. The SMRs were assumed to be used for baseload production only, which capped the total capacity to a level where significant production during the winter months was left for fossil fuels. Achieving larger reductions in emissions by introducing larger share of nuclear heat would have required either long-term heat storages or reactors capable of load-follow operation without compromising the economics.

The study pointed out the complexity of the district heating system, with multiple heat sources and considerable variation in demand. The conclusions made for one district heating system may not apply to another network with different capacity and means of production. In addition to Helsinki, similar studies should be performed for small networks in the future.

[AEP, 2022] A. Vankeirsbilck, B. Shrestha, A. Muralidharan, F. Khalid and N. Tanny. “Carbon Footprint of District Heating SMR” Aalto Energy Project Report, Aalto University, 2022.

5. Case studies and business models

5.1 Summary

To oversimplify it, after you have chosen the technology rest of the traditional nuclear power plant project is business as usual. There’s been no giant steps taken from the business perspective for a long time. Now SMRs are changing this business landscape. Or at least some of the SMRs and microreactors are since some of the SMRs located at the large end of the scale are quite like the traditional cases. The rest of the changes are more economical and political than technological or business.

What makes SMRs different are money, schedule, risk, location, replicability, market, customer and acceptability. Just about all top business aspects. One missing is the repayment period since we don’t know that yet and opinions fluctuate. One might say that this is an all-new ballgame but there are some basic structures that control the game and the referees like authorities will remain the same and probably good so considering the nature of the nuclear technology.

Whenever there is a substantial change in industry and technology the competition will accelerate. Usually, it will take more time for the “old money” to change course and invest heavily on the new ideas than for the “new money” grown up in the fast-moving business making quick decisions when opportunity knocks. When assessing this from the not so traditional SMRs point of view finding a middle way would probably be the best strategy. It takes time to mature the technology and develop business to realize business returns. Maybe too much so for an investor with focus on opportunity costs. However, reaction time and flexibility are important, and organizations strategy must support short time-to-decision.

If regulation enables smaller SMEs to break through their demand will grow exponentially and the supply side will become the bottle neck. Old rule “Well begun is half done” or in this case “well-designed”, becomes the guiding rule. This needs to be considered starting from the design phase of the FOAK and more so when the design is updated for the commercial serial production version. Here it is important to remember the nature of nuclear industry, licensing a nuclear power plant is an expensive and tedious process. You don’t want to make any significant changes in the design once it is approved and the critical parts need to be designed right the first time. However, optimizing the product for manufacturing, delivery, maintenance, refit and decommissioning is an iterative learning process where you work from finish to start.

From business point of view the shorter construction time, smaller investment and simplicity are important and reduce risk by making projects more predictable. However, turning one by one business into a fleet business is probably the biggest driver for many nuclear industry companies. The idea goes more to the direction of property or aviation business: if one fails it's just one of the fleet and the rest balances the books. Nuclear industry is however closer to the aviation since if one fails the rest must be inspected, fixed and probably grounded for some time. But building and operating a fleet usually makes business attractive.

5.2 Four business cases

Since there are no existing cases of SMRs in use in Europe the business cases presented here are fictitious and any similarities with potential real-life locations or actors are unintended.

Here we assume that legislation requires over 50% of the power plant to be owned by a license holder and the operator to be also a license holder. In Finland we currently have only two such companies, Fortum and TVO, but there are no legal barriers to incorporate a new limited liability company.

Case 1: Municipal District Heat (DH) only

When a municipal at the west coast of Finland was considering replacement for a district heating plant burning wood chips, coming to the end of its life cycle early 30's, the municipal energy company proposed to the local executives to consider a heat only SMR. Since there is not much experience about nuclear energy in most municipalities or current partners, a service contract was made with a consulting company to obtain needed expertise to support decision making both at the municipality and local companies as potential partners or customers.

After six months a plan was drafted to direct more detailed planning. Some non-definitive directives were agreed (Table 5-1). Final business model was chosen to be HaaS (Heat as a Service) and municipal energy utility to be a minority owner with only 5%. Five other municipal energy companies became owners with 5% share. The strategy here was to build similar NPPs also to these municipals by utilizing similar ownership structure.

Table 5-1. Directives for SMR planning in Case 1.

Customer	District heating customers
Ownership	The plant would be owned by: license holder (a large Finnish nuclear energy company, minimum 51%), municipal energy utilities (30%), other companies (19%)
Pricing	Ltd. company (also a mankala was considered)
Financing	Owners, Municipality finance (to be negotiated), market loan
Operating	A Finnish nuclear energy company (new or existing)
Supplier	New Finnish company

Case 2: Combined Heat and Power (CHP)

There are several cities in Finland that have large energy intensive industry nearby. This relationship has often been beneficial for both parties and even joint energy production solutions have taken place over the history. Nowadays the emission and environmental regulation is setting new boundary condition. Also, in the case of pulp and paper industry the value of raw material can be higher in other uses than burning for energy.

In this case somewhere in Finland we have a win-win situation between a medium sized city and a large industrial complex. The industrial process itself requires electricity but not so much heat. However, since the flow of materials changes excess heat is no more available and thus some external heat will be needed for heating the buildings. Directives in Case 2 are presented in Table 5-2.

Table 5-2. Directives for SMR planning in Case 2.

Customer	District heating, industry
Ownership	The plant would be owned by: license holder (a large Finnish nuclear energy company, minimum 51%), municipal utility company (20%), local industry (29%)
Pricing	Ltd. company
Financing	Municipal utility company, industrial company
Operating	A Finnish nuclear energy company (existing)
Supplier	Foreign company

Case 3: Power only

Though Finnish NPPs are expected to be operational for several decades there will be a tipping point in the future when it will be economically sound to replace those. There are several investment options for power production today and more so in the 2050’s but here we assume that the option selected would be one or more power only plants in the vicinity of 250-350 MWe. Also, the operating environment in EU will certainly change, but again we assume that only a Finnish license holder can operate in Finland.

This case is quite straightforward. Basically, there is no big difference in owning and operating an individual nuclear power plant, but the difference is in slightly smaller reactor size combined with serial plant procurement, and owning and operating a fleet. Directives for Case 3 are presented in Table 5-3.

Table 5-3. Directives for SMR planning in Case 3.

Customer	Owners
Ownership	An existing Finnish license holder
Pricing	Mankala or electricity exchange
Financing	Owners
Operating	A Finnish nuclear energy company (existing)
Supplier	Foreign company

Case 4: Process heat

A large industrial complex next to a medium sized city calculated that using the existing material streams for novel products made more sense business wise than burning those for heat. It was also possible to sell the excess heat not needed as process heat to the local district heating company. Since the temperature of steam needed for the process was quite high, they made the investment decision based on that.

Since there were no Finnish solution providers who could deliver, negotiations were started with a foreign company who had just started selling suitable micro reactor -based power plants. After discussions it was clear that there was no existing Finnish company that could build, own and operate the plant. Also a solution for the fuel management was needed. But since market potential was seen both in several industrial sites and in Europe partners decided to start evaluating a business case based on starting a new company that would apply for new operating license. This is now work in progress. Directives for Case 4 are presented in Table 5-4.

Table 5-4. Directives for SMR planning in Case 4.

Customer	Industrial complex / process heat (high temperature steam)
Ownership	New (Finnish) license holder
Pricing	Cost based pricing for own use, market-based pricing for district heat
Financing	New company raises funding, negotiations with the technology supplier ongoing
Operating	New (Finnish) nuclear energy company
Supplier	Foreign company

5.3 Timing and learning

When developing and launching new technology to the market timing and learning are as important as in any strategy planning. In the case of SMRs the number of known and unknown knowns and unknowns is so large that business risk is substantial whatever strategy you choose. From the customer side challenge is that SMRs is not just technology but part of a bigger picture, energy portfolio, property development and area/urban development. Step by step decisions to move forward based on existing knowledge and active foresight must be made. The big question is “when we know enough to take the next step?”

In Figure 5-1 this challenge is presented from the timing and learning point of view. We need to build the FOAK, first one, as quickly as possible after the technological solutions exist. In the complex system finding out how the plant performs, what are the real CAPEX and OPEX, uptime/downtime and unexpected events can not be simulated but need a real-life case. However, we can not wait for the results of the first “living lab” to proceed to plan and sell the “Second of a Kind”. Many countries aim for 2035 to be carbon neutral and several cities aim for 2030 to make their decisions about future energy solutions

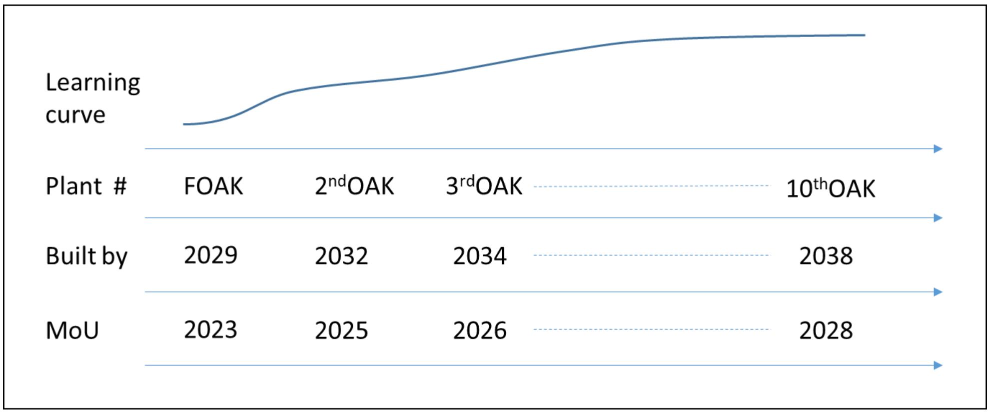

Figure 5-1. Step by step plan to demonstrate the building of SMR fleet.

Several potential cases need to be evaluated parallel and they need to start Environmental Impact Assessment (EIA) already when development of the first begins. If the first case advances as planned the development of the second will be faster and should begin in three years and the third two years from this. There is always a risk that something comes up that delays or halts the project but from the case and business development point of view there is no possibility to wait for the first ten years to play it safe and only after that start developing the next case. What we need to advance commercial activation is a clear, realistic and fact-based vision that sets the steps from here to the international business as usual.

To really understand the cases and requirements the location plays a significant role. Here local actors like municipality, power grid operator, district heat network operator and citizens participate the decision-making process. There are some basic requirements like ground properties, ground water basin, logistics etc. that are limiting factors but rarely obstruct construction but at single cases. A suitable location can usually be found somewhere in the target area. However, more generic but site related topics are public opinion, funding/financing, local energy options/solutions and their lifecycle, politics and vision of regional development.

At first the learning is fast. When FOAK is built all pieces are there and after that it just making and doing everything better. However, learning curve is different for all parties and new ones keep coming as we go. Some have no previous knowledge about NPPs, some are nuclear experts who quickly learn new type of an NPP. Municipalities and traditional energy companies are again different. So how do we secure that all parties will have the information, knowledge and understanding about SMRs needed to keep up with the roadmap all the way till the first SMRs exist in Finland? And not just to keep up but to actively join the ecosystem building that roadmap and knowledge and capacity? EcoSMR project and its continuation the EcoSMR HUB are initiatives that bring all parties together to create and share information but many more actions in education, industry and policies are needed if SMRs become a near future reality. Many most interesting round table discussions about business aspects were arranged in EcoSMR project. Hopefully this type of discussion evolves and expands in the EcoSMR HUB to attract more organizations and people around the table.

Politics and regulations set the boundary conditions, context, for the solutions. When new technology or new ways of using it emerges, it takes time for political views and regulations to adapt and change the modus operandi to tap into the opportunity. This transition delay is time of uncertainty both for the suppliers and customers and impacts their decision making. Of course, there is a difference between domestic and foreign suppliers, but they are all supplying “new nuclear” solutions. They need information about the market and local conditions, but they also need to supply right from the beginning right information to the market and locals to success. All companies need local partners and Finnish companies need foreign partners as subcontractors. Open dialogue and sharing a common goal are the tools needed to keep the train on the track, accelerate when possible and break if needed.

6. SMR ecosystems

6.1 Summary

During the start of the project Finland had only a handful of companies looking at the prospects of SMRs that initiated this project. These companies were mostly energy and consultancy companies with their eye on the potential prospects of the technologies. During the project meetings and dissemination events a larger share of Finnish companies started to identify business opportunities around SMR development, deployment and operation. By providing basic information about the SMR technology and business opportunities in webinars, seminars, conferences, ecosystem meetings and scientific publications the project has managed to increase the understanding of SMR technologies and business opportunities among Finnish companies. The attraction can be measured with observing the membership base of the follow-up project EcoSMR-Hub which will launch in the spring of 2023.

6.2 Nuclear Ecosystems in Finland

Business Ecosystems are a common way to adapt to emerging megatrends. Technological advancements, consumer behaviour changes, geopolitical changes, black swan events and many other factors may contribute to a profound change in business environments and business logics. Figure 6-1 illustrates how emerging business needs start to draw organizations together to think about potential solutions. The formed Sector-Specific Ecosystems may work internally or in collaboration, aiming to understand the megatrends and their potential implications to certain business areas. The ecosystems will form temporary Work Groups from member organizations or together with other interested ecosystem members. These working groups will further refine the common goals and evaluate in coordination which consortium composition would be the fest fit to provide the designed solution. In the best case the Customer is already in the beginning in the Temporary Working Group providing insights about the actual business environment and needs where the solution is designed. When the scope and consortium memberships are agreed a Project Proposal is delivered to the Customer organization for evaluation.

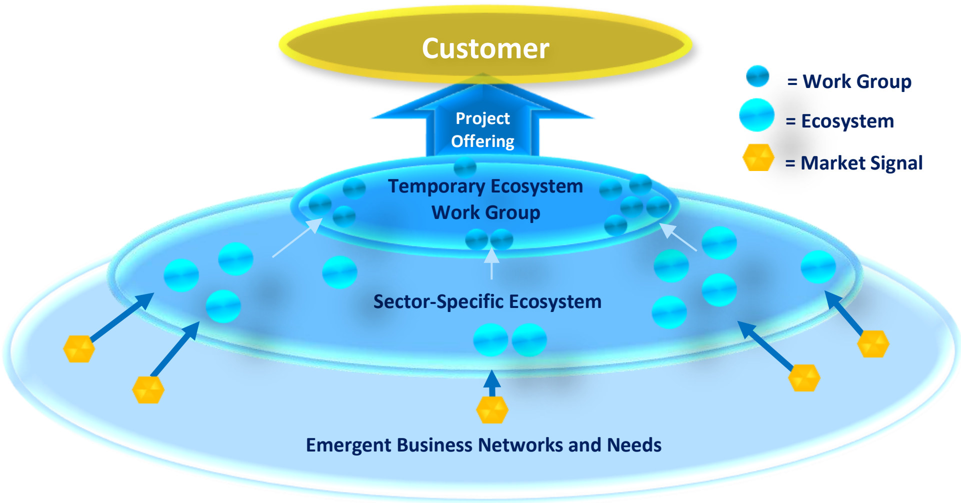

Figure 6-1. Project consortium evolution in Ecosystems.

Climate change and the emerging needs to rapidly deploy a large amount of controllable low-emission energy sources have evolved to be among the major megatrends organizations and individuals have concerns about. SMRs are at least in theory a technology basket that could be deployed in scale, fast, cost-effectively, safely and without major climate emissions. Major innovations in SMRs relate to the deployment methods, quality assurance improvements, passive safety mechanisms and new applications for nuclear energy use.

In time the ecosystems and their initiated projects mature and resolve issues emerging along the development roadmap. When multiple solutions around the megatrend challenges increase in technology readiness level (TRL) they start to form industrial ecosystems. In Figure 6-2 below is an example of an industrial ecosystem built around SMRs. The figure illustrates how coupling the provided stabile electrical and thermal energy streams with advanced industrial processes can generate multiple valuable outputs. By siting the reactors close to the beneficiary industry, the 2/3 of total nuclear energy currently lost in the cooling water release process can be utilized in energy intensive processes such as facility heating, chemical processing, desalination and even marine transport propulsion for large vessels. The coupled chemical processes may include hydrogen and nitrogen production with electrolysers and Haber-Bosch synthesis with further processing into synthetic fuels and fertilizers. The desalination processes produce mineral-dense waste stream called brine, which can be further extracted into useful elements.

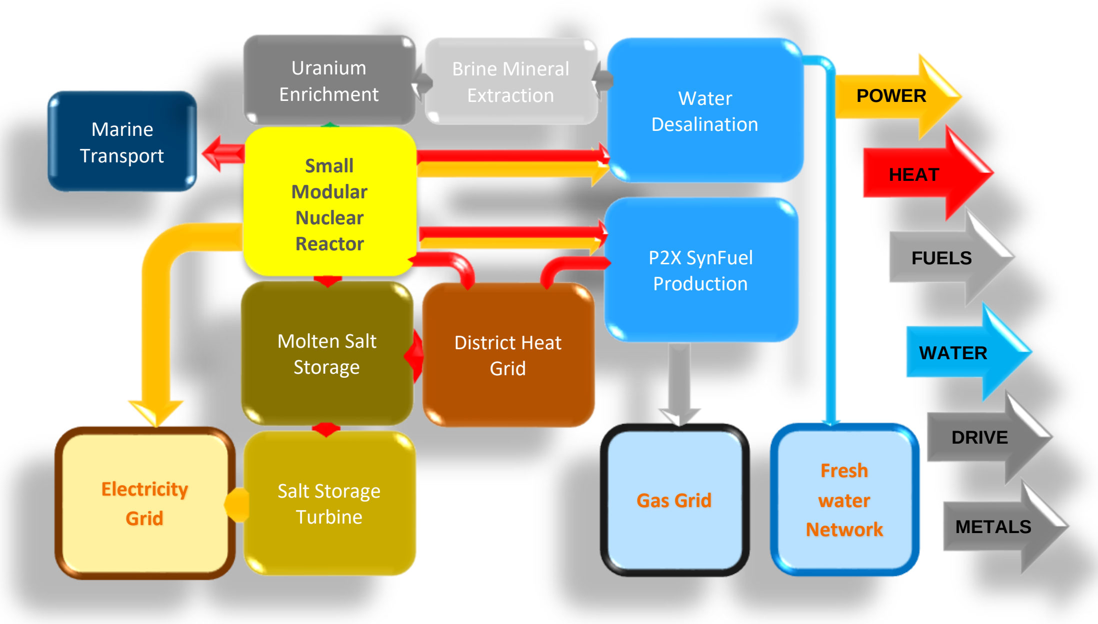

Figure 6-2. Example of a Nuclear Industrial Ecosystem

In the Finnish context the low-emission production of process and facility heating is a real challenge. Wind power and heat pumps, electric boilers, biomass boilers and hydrogen applications are methods to generate low-emission heat. These sources are not yet sufficient alone to provide all the demanded heat and their significant upscaling could provide price pressure over other relevant electrification solutions. Nuclear heat and combined heat and power (CHP) production could be an environmentally friendly and economically competitive method to satisfy evolving energy quality needs. For this reason alternative nuclear energy applications are becoming a field of interest among industrial actors in Finland.

Currently the Nuclear Energy Ecosystems in Finland are developing in several frontiers. From 2019 EcoSMR focusing on SMR technologies, EcoFusion focusing on Fusion Energy Technologies, EcoDeco focusing on Nuclear Decommissioning technologies and Finuels on Nuclear Lifecycle Services. These projects have brought together organizations with interests in the Nuclear Energy value chains operating in Finland. Interactions have been facilitated through information newsletters, webinars, industry meetings, seminars, ecosystem meetings and discussion groups. Figure 6-3 illustrates the evolution of Finnish Nuclear Energy Ecosystems. EcoSMR, dECOmm, FinnFusion and Finuels being the first Finnish Nuclear Energy Ecosystem projects in decades brought together organizations interested in the life-cycle management of nuclear energy installations. EcoSMR-Hub is the continuation of the EcoSMR-project. Lappeenranta-Lahti Technical University has also announced its 4^{th} Generation Testbed project collaboration with USNC. Fortum and Helen have announced their collaborative feasibility study of SMRs and Fortum also has feasibility collaboration with Swedish and Estonian partners. SMR-design and analysis tools are being developed at VTT to help with the safety verification of new plant designs. EcoSMR members have also expressed interest in nuclear hydrogen, nuclear robotics, modular construction and brownfield repurposing development projects that may lead to joint development efforts in the coming years.

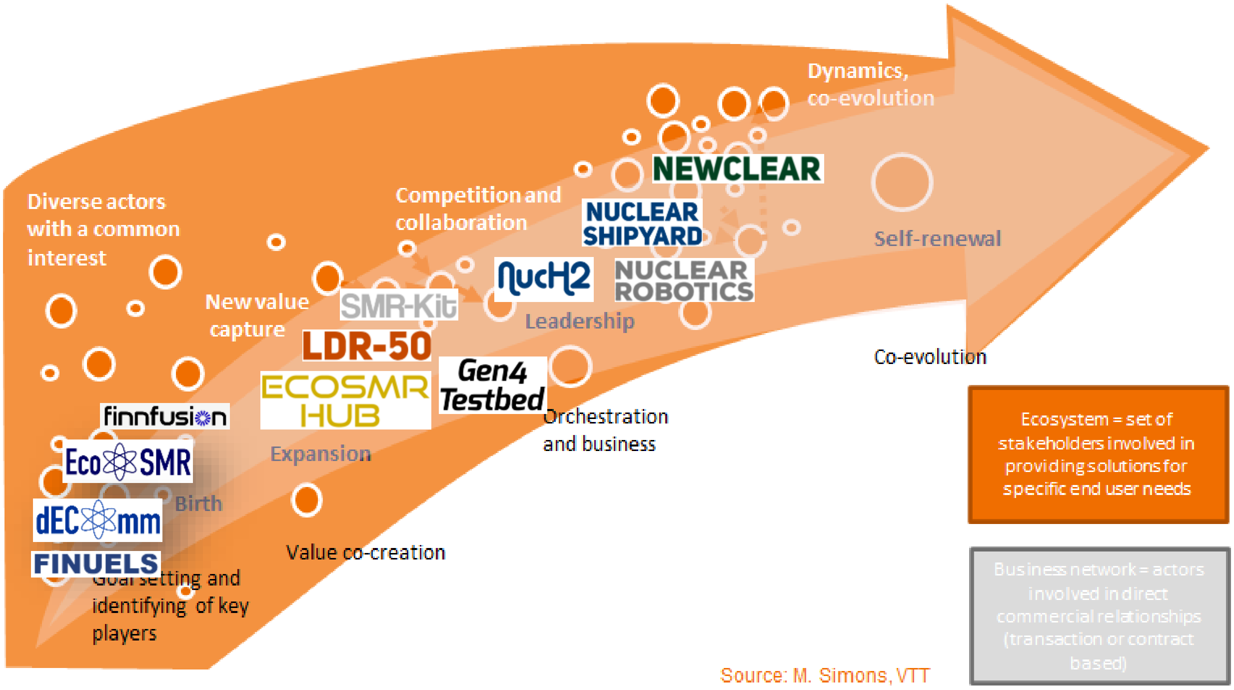

Figure 6-3. A Draft of a Nuclear Energy Ecosystem Roadmap in Finland.

Table 6-1. Industry Collaboration events organized during the project.

Date	Event Name	Event Summary
22.03.2021	Open Business Day 2021	SMR Business Seminar
24.11.2021	Investment modelling of district heating in Finland	Webinar
15.06.2021	Status of district heating reactor design in Finland	Webinar
02.02.2022	Supply chain for district heating in Finland	Webinar
23.03.2022	Licensing and regulatory policies in Finland	Webinar
3.-4.5.2022	Open Business Day	SMR Business Seminar
06.06.2022	Changes in Energy Market	Webinar
10.06.2022	SMR Hub discussions	Webinar
14.06.2022	LDR-50 Development Review	Webinar
31.08.2022	Ecosystem Meeting August	Webinar
28.09.2022	Ecosystem Meeting September	Webinar
28.10.2022	Ecosystem Meeting October	Webinar
23.11.2022	EcoSMR, dECOmm & SMRSiMa Joint Final Seminar	SMR Business Seminar

Table 6-2. Industry Collaboration events attended during the project.

Date	Name	Place	Event Summary
24.-25.5. 2022	NKS seminar	Stockholm	Nordic nuclear safety research seminar
30.5. - 3.6. 2022	FISA / EURADWASTE 2022	Lyon	European nuclear safety and waste management conference

7.-8.6. 2022	Nordic Nuclear Forum	Pikku Parlamentti, Helsinki	Conference on Nordic Nuclear Energy, most likely issues around SMR covered as well..
21.07. 2022	NEaNH GIF Task Force	Webinar	Introduction of nuclear district heating for the representatives of the GIF NEaNH members
5.-10.9. 2022	NUTHOS-13	Online	13th International Topical Meeting on Nuclear Reactor Thermal- Hydraulics Operation and Safety
7.-9.9. 2022	Management Systems Exhibition	Helsinki	Event to raise awareness and increase understanding of management systems as integrating all the vital objectives of nuclear facilities and activities.
19.-21.9. 2022	IAEA Technical Working Group on Gas cooled modular reactors	Wien, Austria	Technical working group mostly concentrated on CHP use of nuclear energy
21.-23.9. 2022	CET2022	Oskarshamn / Sweden	The conference will present new energy technologies and their system aspects at national, regional, and local level with emphasis on the convergence of SMR with renewables, hydrogen production and CO2 storage.
25.-26.10. 2022	Tampereen Energiamessut	Tampere, Finland	VTT marketing paying side event fee
1.-2.11. 2022	Suomalaisen Ydintekniikan Päivät	Paasitorni, Helsinki	Nuclear Energy Sciences Seminar
7.11. 2022	NIRO Nuclear District Heating	Webinar	Introduction of nuclear district heating for the representatives of the UK government

6.3 Ecosystem interview results

As a part of the ecosystem work all project members were interviewed once in 2019 and another time during 2022. Even a short gap between the interviews indicated rapid and radical changes in the prospects of SMR deployment among the interviewed organizations. The following sections summarizes the key results from the interviews.

Is nuclear energy still relevant?

The electricity market development was predicted to have higher volatility in the future, which would make more controllable and flexible energy technology solutions more competitive. In the beginning of the project in 2019 natural gas and biomass were seen as most credible competing forms of adjustable energy for small nuclear reactors in the next decades' electricity markets. The other energy markets such as district and industrial heating had become so expensive due to fuel and emission fees that Finnish industrial companies had financial challenges in their long-term stability already in 2019. The Russian attack to Ukraine and European energy deliveries in early 2022 made the situation worse. Europe became more dependent on more expensive liquid natural gas (LNG) since pipeline natural gas and biomass imports from Russia ceased. There is no clarity yet how long the chaotic energy market situation will last and what price range will the fuel prices settle into. Faster return of investment options with already good social acceptability are attracting capital in the high uncertain environment. Will the alternatively supported technologies ultimately solve the economy and environment related energy challenges? Meanwhile especially Central Europe should lower its heavy dependency on fossil fuels in heat, industry and district heat markets while there are not many available solutions how to do that safely in the necessary scale and time.

The industrial need for high temperature heat is slightly greater than for low temperature heat. Novel 4th generation nuclear energy reactors can provide solutions for direct high temperature heat applications. For electricity generation and low temperature heat generation traditional 3rd generation light water technologies can already provide a range of feasible solutions. The production of hydrogen and heat with nuclear power and the opportunities to decarbonize maritime shipping with nuclear propulsion are also subjects of interest for the Finnish industry. It is expected that the demand for electricity and low-emission fuels will increase dramatically over the coming decades. The total size of the district heat market is expected to remain about the same, i.e. energy efficiency and heat pumps will compensate for the increase in demand.

Industries or municipalities considering SMR development as an investment option should discuss potential collaboration with other users and stakeholders to share project risks and optimize the utilization of the nuclear energy production. Collaborative investments are especially encouraged when the current needs and long-term strategies of the different organizations are aligned. The suitable scale of the SMRs is identified regionally case-by-case according to the total forecasted demand and regional industrial development. The potential implementation of urban nuclear solutions must always be approved by the residents. From the plant sizing point of view, it is more important in the realm of SMRs that nearly identical batches of plants can be delivered and operated in multiple sites over time to realize the economies of scale through reactor fleet management models. Concluding this type of arrangements may very well require broad international collaboration.

In a healthy competition environment the quality and affordability of equipment and services will improve. Currently known pilot project suggestions in Europe could already provide a sufficient business rationale for production investments of new suppliers. This would require that the qualification processes of nuclear grade components can be further internationally harmonized. Currently on average 5% of equipment suppliers in the nuclear energy industry are lost every year, which may compromise the long-term cost and availability of necessary lifetime-extension components. Among the big industrial manufacturing players in Finland, many would be mature enough to develop necessary services in the SMR supply chains.

Most of the district heating network organizations - usually the regional energy companies - are quite narrow in size and they will unlikely establish new nuclear qualified operating branches in their near-future forecasts. Ready-made shelf solutions are more interesting, since few Finnish companies could alone invest into their own product development in the scale of nuclear energy production. Due to these budgetary constraints, new business and financing models and financing company collaboration models for SMR development are required. In Finland, the strength of cooperation is a competitive advantage in the nuclear energy sector. Maintaining the regular meetings and enabling free discussion and networking keeps up the good multidisciplinary dialogue. More development of the business ecosystem going forward would be needed. An external professional facilitator could be a refreshing and braver discussion leader in informal events.

Piloting SMRs in Finland

Small research plants could be useful in terms of smaller risk investment piloting, but at the same time may be very challenging to make them profitable if they include high cost nuclear liabilities. Research equipment and reactors can be smaller in size but especially the first commercial size nuclear energy pilots should consider the economic balance of long-term operations. In all pilot projects there is need to understand the total project costs also outside the nuclear energy production plant; such as network extensions, transformers, heat exchangers, conversion units, energy storages and safety features required for optimal investment case. Life-cycle impact and operation simulations of new SMR designs play an essential role in the efficient plant design optimization before practical user experience and usage data becomes available. It is also essential in piloting to prepare adequately on how to ensure sufficient financing and service delivery if the pilot project goes wrong or is delayed from the planned schedule. In nuclear heat applications the nearby siting close to the end-use may be a more market-limiting issue than the technological challenges.

Piloting SMRs designed for electricity production is most swiftly done in an existing licensed site. For heat application most of the feasible sites should be separately licensed for the specific use. Heat reactor pilot should be placed on an existing industrial site, where the district heating network is already connected. A traditional paper mill location, where production operations have been or are being run down, could offer a suitable plot of land and a great social acceptance for a replacement investment. Another good option for a pilot site would be a provincial center or capital region. In addition to emission reduction and economic calculations, the final investment location is influenced by the local willingness to start the project and the ability of companies interested to implement the project at the designated location. The bedrock siting would enable advantages such as crash barrier, plot savings, invisibility, diffusion barriers, potential for large water reservoirs for cooling and heat storage pools with a completely different volume than on the surface. The first plant type to be placed underground could receive significant competitive and visibility advantages. The potential technical and economic constraints of underground siting require further examination. With the collaboration between domestic operators, it would be possible to pilot smaller class heat plants together. It could be good to have specialized suppliers who can serve several operators with shared costs. A real discussion about the implementation of the pilot plants should start now if there is a serious goal to start practical construction preparations by no later than 2027. By 2027 there should strong commitments by the investors and municipalities to proceed, a ready environmental impact assessment (EIA) etc. It is necessary to be able to predict the payback period of plant investments with sufficient certainty. Cost of capital and waste management fees must also be considered.

Nuclear Energy Ecosystem activities help maintaining connections the most efficient way when there is a real business case. Due to people's backgrounds, common discussions usually lead to interesting technical or financial considerations, while the discussion about real cooperation between the business ecosystem members does not get sufficiently represented. In all Finnish organizations strongly related to energy there are very different types of actors. In terms of the structure of the ecosystem, it is worth thinking about blocks where the actors are at a certain profiles related to awareness and position on nuclear energy solutions. More actors from the forest and metal industries could be included into the ecosystem. Finland also has developable manufacturing technology for pressure vessel and primary circuit parts. For exporting suppliers the biggest difficulties are in the contractual liability issues. In this network a large range of small companies work together, for which the cooperation interfaces and communications must be maintained with excellence.

Nuclear energy politics

Industrial integration in large-scale energy planning is important to meet the necessary overall demand such as process or household heating which together energy-wise represent many times the size of electricity consumption. Promoting international energy collaboration is considered important, especially within Europe. When implementing complex solutions, local help is needed for cultural encounter and understanding of legislation and requirements. Legislation and social acceptability considering nuclear energy are the biggest challenges for SMR development in most of the international energy markets. Barriers to enter the nuclear energy sector in Finland are rather high due to the unique configuration of requirements and challenges and the country has its own way of working. On the other hand in Finland, there is a group of suitable size that knows each other and there are already positive experiences of cooperation from an earlier time. Authorities, academia, companies and civil society are capable of constructive dialogue in all levels. A network of partnerships, largely at the national level is required to jointly finance the first shared-risk implementation projects of the first SMRs. In the case of a modular solution, there should be a high certainty of expansion opportunities after the piloting phase. After siting the remaining challenges would be intermediate fuel storage and logistics in a populated area.

The high heat demand especially in the urban areas would require solutions to tackle challenges of social concern, safety and security hazards and competitive land use needs. In the overall solution, a centralized interim storage of the spent nuclear fuel is needed at the existing plant site or at a separate centralized storage site. It is necessary to accurately map SMR in relation to other heat productions, how it affects others, e.g. in terms of security of supply. Recent developments highlight the security of supply, reliability, the risks of geopolitics regarding to fuels and energy infrastructure; also the regulations and requirements for operations may become stricter due to geopolitical tensions.

Reaching a EU-wide consensus to support the stabilization of the investment environment for small modular nuclear reactor business models is uncertain. Thus, national programs and bilateral cooperation remain as more likely options for nuclear grade qualification harmonization. At the heart of the energy crisis, politicians are in a hurry to find solutions; thus support for nuclear power plant extensions in Europe is currently strong. During the energy crisis there could be enough political support to enable construction of new nuclear energy facilities. The investment environment is still so uncertain that practical investments into SMRs in Europe are still very limited. The low-emission production of district heat remains a large technical challenges for cities, as electricity can be procured and transmitted much more flexibly than high amounts of heat. Subsidy structures such as ones used with the wind power industry could successfully implemented increase the deployment rate of SMRs as well. These same lessons such as better instructed planning boundaries, clear and well-reasoned permitting, rapid processing speed of appeal rounds, etc. could also be used technology neutrally. The regulative demands and the enabled use of novel problem-solving techniques should evolve hand-in-hand. With regard to the research infrastructure, Finland has been successful in this, but the situation in terms of personnel and education should also be fixed.

Regulating SMRs

By 2022 it was identified that all of the novel materials, components and methods applied with SMRs need to be qualified for their durability and safety over the whole plant life-cycle. Choosing the materials for the components, dimensioning, life cycle simulations, obsolescence management, effects on plant safety, etc. are also big questions. As far as Finnish industry is concerned, the efficiency of the entire supply chain must be good in order to guarantee international competitiveness and cost efficiency. The delivery of a nuclear facility requires a lot of design manufacturing technology, dimensioning, planning, manufacturing, compliance verification, assembly, etc. Practical solutions around quality systems and qualification of components and services are essential steppingstones towards international harmonization of nuclear energy quality systems. These developments are necessary to enable SMR deployment economics and scalability. Another key issue enabling SMRs is the justification and calculation method to validate the required plant-specific Emergency Planning Zone (EPZ), which dictates the suitable siting locations and much of the plant’s CAPEX and OPEX costs. Will the EPZ requirement be based on calculations related to plant operational conditions, radionuclide inventory, security system maturity, nominal power or something else will be open until the Finnish nuclear energy legislation is complete. The qualification process for the use of novel project management and process control tools and approaches should also be considered during the law renewal process. It is necessary to be able to guarantee and prove safety redundantly for each system for the next 30–40 years without domestic reference objects.

7. Dissemination

7.1 Summary

The goal of the dissemination work package was to spread knowledge of the project and its results and facilitate the expansion of the SMR ecosystem. Dissemination was handled through conference presentations and articles, journal articles, research reports, long and short webinars and seminars. These activities effectively lifted EcoSMR in the general consciousness of SMR actors world wide. Interest in SMRs and the EcoSMR project grew substantially both in Finland and foreign countries during the project. Especially the different webinars and seminars were excellent in growing the ecosystem of SMR actors in Finland.

7.2 Webinars

7.2.1 EcoSMR Open Business Day 2021

Originally EcoSMR project was planning to organize yearly seminars, but because of the COVID pandemia, the first seminar had to be held virtually as a webinar. A half day webinar was organized on 22.3.2021. The webinar included a welcome session, keynote session and a session on companies' and politician's views. The program is presented in Table 7-1.

Table 7-1. EcoSMR Open Business Day 2021 program.

Session	Speaker	Title
Welcome session	**Antti Vasara**, President & CEO, VTT	Opening speach
	Silja Häkkinen, Senior Scientist, EcoSMR Project Manager, VTT	EcoSMR introduction
Keynote session	**Tiina Koljonen**, Team Leader, VTT	Transition to carbon neutral societies – how to define role of new technologies and innovations?
	Sophie Macfarlane-Smith, Head of Customer Business, Rolls-Royce Plc.	UK SMR – Reliable, Affordable, Investable
	Kalev Kallemets, CEO, Fermi Energia	Estonian 1GWe SMR deployment: need, challenges & solutions
	All	Panel discussion
EcoSMR partner companies and a politician's view	**Antti Rantakaulio**, Business Development Manager, SMR, Fortum Power and Heat Oy	Fortum – utility view on SMRs
	Phil Hodges, UK Nuclear Business Unit Head, AFRY	Accessing International Markets and Overcoming Local Challenges
	Atte Harjanne, Member of Parliament, Parliament of Finland, Green Parliamentary Group	Means over ends or a new atomic age? Political perspective to the future of SMR technology
	All	Panel discussion

In the Keynote session, Tiina Koljonen talked about new innovations and technologies, EU's climate neutrality plan by 2050 and how many countries have adopted even faster schedules. Sophie Macfarlene-Smith explained the potential of SMRs to supply low carbon electricity, heat, hydrogen etc. economically and reliably and presented Rolls Royce's plan for commercial SMR units by 2031. Kalev Kallemets talked about rising CO_2 prises reducing the share of electricity produced by shale oil in Estonia and how the public feedback on four studied SMR options has been surprisingly positive. However, many challenges still need to be solved. Panel discussion called for a quick need for actions and new solutions.

In the second main session, Antti Rantakaulio presented Fortum's current market portfolio that contains more than 35 TWh of nuclear generation and made an extensive overview of the current markets. He presented how climate change mitigation will change these markets, and how SMRs could be one way forward for Fortum and other companies. Phil Hodges talked about SMRs from project development point of view noting specific local challenges and overcoming them through collaboration with local stakeholders, industry, and regulators. Atte Harjanne discussed on political challenges ranging from underestimated scale of climate change problem to problematic concepts and policy designs. Atte suggested solving the main barriers by focusing on system level perspective and emission reductions through technology neutral mechanisms. In the panel, different obstacles and their solutions were discussed. It was also noted that regulations and standardization are common challenges for all actors. These challenges must be addressed to avoid a huge amount of overlapping work by different stakeholders.

The webinar attracted 234 participants from 16 countries in Europe, Asia and North America. Some polls were done during the webinar that are presented in Figure 7-1. Many of the participants were working on SMR related topics and most had at least some advance understanding on what they are. The most popular application for SMRs was seen to be combined heat and power. The main purpose of SMRs as seen by the participants answering the poll was fight against climate change. The most popular role for SMRs in the organizations of the participants was business opportunity.

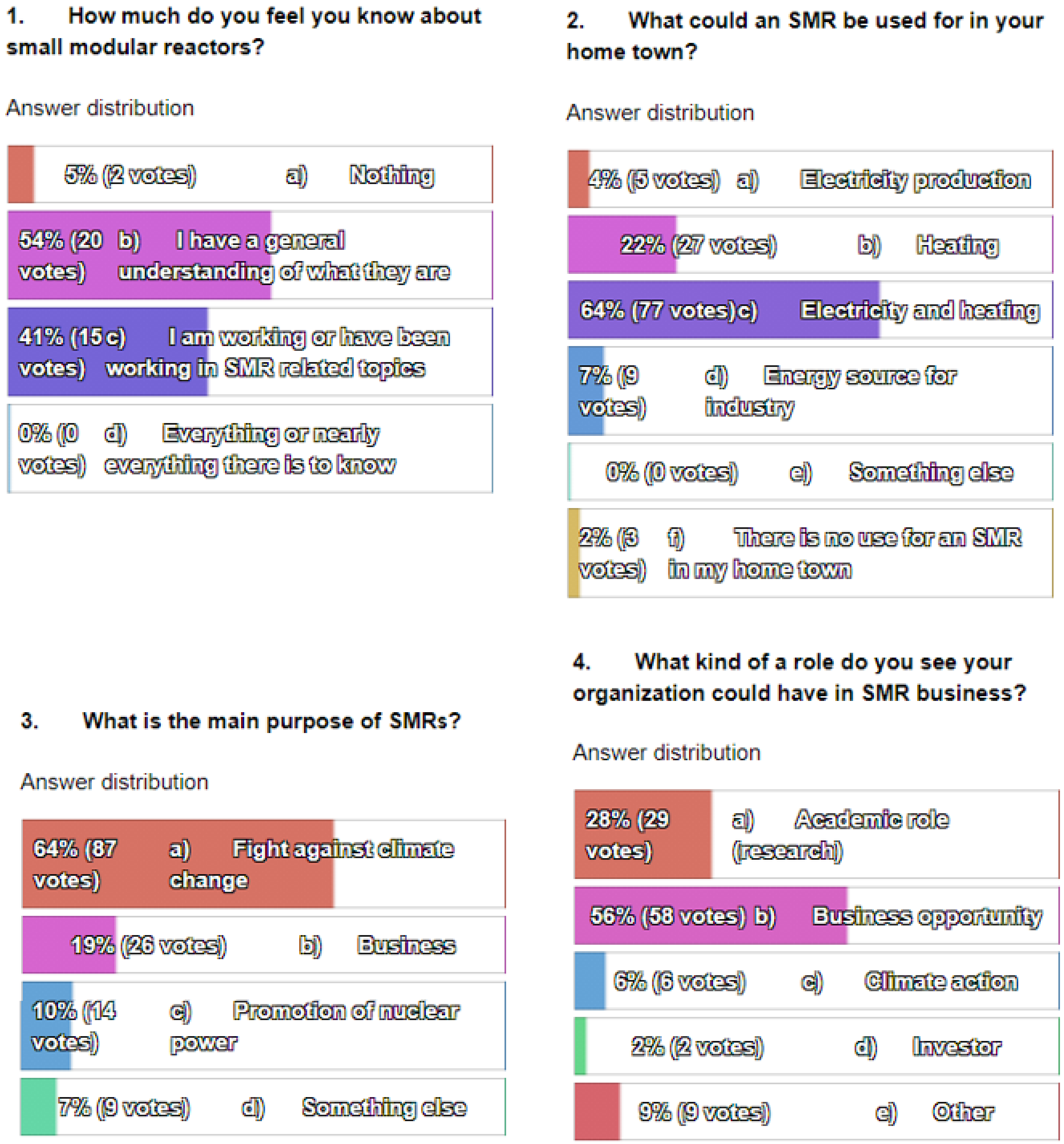

Figure 7-1. Polls done during the EcoSMR Open Business Day 2021 webinar.

7.2.2 Short webinars

During the project, four open one hour webinars on different SMR related topics were organized. The webinars are shortly summarized in the following.

Webinar on **Status of District Heating Reactor Design in Finland** was organized on 15.6.2021. Professor Juhani Hyvärinen and Research Professor Jaakko Leppänen presented the district heating reactor concepts LUTHER and LDR-50 under development at LUT University and VTT in Finland. Both concepts include passive safety features. LUTHER is designed to be a 24 MWth modular unit and LDR 50 MWth unit. LDR is a conventional pool type reactor, where as in the LUTHER reactor fuel assemblies are placed inside pressure tubes.

Webinar on **Investment Modelling of District Heating in Finland** was organized on 24.11.2021. Tomi J. Lindroos from VTT presented an overview of European district heating markets and investment analysis in Finland. SMRs of < 100 MWth and annual operation time between 4000-6000 h were seen as the most promising concept. Konsta Värri from Fortum introduced Fortum's activities in co-operation with MIT in building an open source calculation tool for assessing the economic risks, costs and uncertainties in SMR projects.

Webinar on **Supply Chain for District Heating in Finland** was organized on 2.2.2022. Martti Kätkä from Technology industries stated that promotion of Finnish technology in the energy sector creates business opportunities in a wide scale from power to heat and fuel / hydrogen production. Karoliina Salminen from VTT explained how new supply chains for new concepts are built from existing competences. In the nuclear sector, this calls for collaboration and co-operation from all actors and re-evaluation of existing design and manufacturing processes.

Webinar on **Licensing Regulatory Policies Upgrade in Finland** was organized on 23.3.2022. Kirsi Hassinen from Platom presented the current state of legislation and development aspects. Juhani Hyvärinen from LUT explained how SMRs are already possible within the current Finnish nuclear regulations. However, the new legislation, currently under review, should consider the SMR specific features.

7.3 Nuclear Energy Ecosystems – Open Business Day 2022

EcoSMR project arranged a two-day seminar on 3.-4.5.2022 together with three other Business Finland funded nuclear related projects dECOmm, ECO-Fusion and FINUELS. The seminar was organized in Helsinki Congress Paasitorni. The programme was planned so that the first day comprised of general presentations covering the topics of all four projects and the second day comprised parallel sessions on the topics SMR, fusion and decommissioning followed by a joined final session. The detailed programme is presented in Table 7-2 and Table 7-3.

Table 7-2. Nuclear Energy Ecosystems - Open Business Day 2022 First day program.

Session	Speaker	Title
Welcome session **Chair: Erika Holt,** Customer Account Lead, VTT	Erika Holt, Customer Account Lead, VTT	Practicalities and opening
	Jussi Manninen, Executive Vice President, VTT	Welcome and introduction
	Petri Peltonen, Under-Secretary of State	Opening speach
	Tommi Nyman, Vice President, Nuclear Energy, VTT	Nuclear energy in Finland
	Anssi Paalanen, Business Finland	Nuclear innovation ecosystems and national funding

	Megumi Asano-Ulmonen, FinNuclear Association	Growth through partnership
	Netta Skön, Senior Environmental Lawyer, Ramboll	Green deal, EU taxonomy
Key speakers **Chair: Anssi Paalanen**, Business Finland	Professor Tony Donné, EUROfusion Programme Manager	Big picture in nuclear energy
	Sandro Baldi, Commercial Director, NUWARD™ - EDF	Roadmap to SMR development in Europe
	Petra Lundström, Vice Precident, Nuclear Engineering Services & Co-owned Assets, Fortum	Energy producer's perspective
Business opportunities **Chair: Matti Paljakka**, Solution Sales Lead, VTT	Ana Belen Del Cerro Gordo, Spanish Industrial Liaison Officer (ITER) CDTI	Big science in EU
	Tim Luce, Head of Science & Operation, ITER	ITER
	Sophie Macfarlane-Smith, Head of Customer Business, Rolls-Royce Plc	SMR business review, Rolls-Royce
	Hauke Grages, Key Account Manager, Framatome	Decommissioning business review
Poster session		
FinNuclear ry Spring Meeting		

Table 7-3. Nuclear Energy Ecosystems - Open Business Day 2022 Second day program on SMRs.

Speaker	Title
Chair: Heikki Suikkanen, LUT	
Fredrik Vitabäck, GE Hitachi Nuclear Energy	SMR case
Jaakko Leppänen, VTT	District Heating Reactor (LDR)
Chair: Jaakko Leppänen, VTT	
Juhani Hyvärinen, LUT	Known challenges in SMR deployment
Juha Poikola, TVO	Challenges in utility viewpoint

Debbie Francis, NUWARD™ - EDF	An International View on SMR Safety Approach and Licensing
Discussion and group work	
Chair: Ville Tulkki, VTT	
Sophie Macfarlene-Smith, Rolls Royce	Building Supply Chains
Aaron Held, U.S. Embassy in Finland	US public private partnership
Antti Rantakaulio, Fortum	Introduction to EU SMR Partnership
Discussion and group work	
Joint final session	

The seminar was 100 % face-to-face event without a possibility to participate remotely. The event gathered 170 participants from all over Finland and from abroad from Britain, Czech Republic, Denmark, France, Germany, Poland, Spain, Sweden, Switzerland and United States. More than half of the participants were from companies. Participant profile is presented in Figure 7-2.

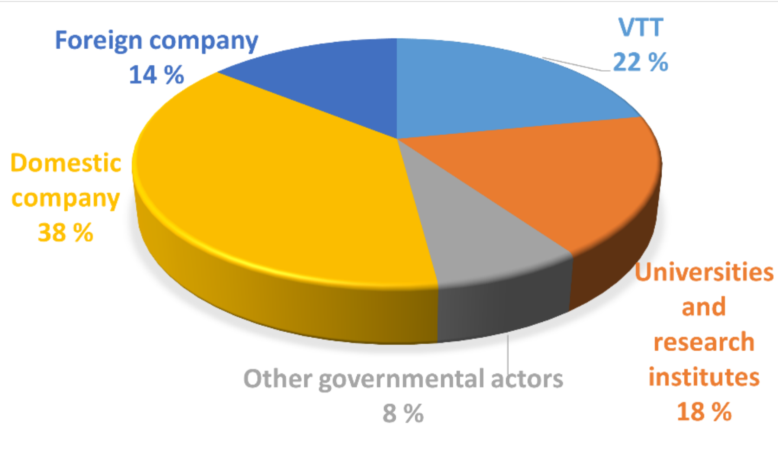

Figure 7-2. Participant profile in Nuclear Energy Ecosystems - Open Business Day 2022.

The first seminar day was organized in three speaker sessions and a poster session. In the first session, Tommi Nyman and Jussi Manninen presented VTT's nuclear energy related research in general. Under secretary of state Petri Peltonen had the opening speech and emphasized the importance of persevering and multidisciplinary energy and industrial politics. Anssi Paalanen from Business Finland presented the possibilities of public funding in the co-operation of research and industry and Megumi Asano-Ulmonen from FinNuclear introduced the activities of industrial liaison officer in Finland. Finally, Netta Skön from Ramboll explained the development of EU taxonomy and its effects on nuclear industry.

In the second session, EUROfusion programme manager Tony Donné presented the structures and capacity of European fusion research. Sandro Baldi from EDF talked about SMR development in Europe and introduced the French NUWARD™ reactor. There are lot of opportunities for SMRs in Europe including replacement of coal fired power plants, electrification of industry, mining, power to remote municipalities and cogeneration of heat and electricity. NUWARD™ has launched a European initiative for creating conditions for international SMR licensing together with French, Finnish and Tzech authorities. As the last speaker in the second session, Fortum's Petra Lundström presented Fortum's strategic decisions on nuclear. Fortum is committed to nuclear through decision to apply for lifetime extension of the Loviisa reactors until 2050. Fortum is currently in the process of defining its SMR strategy and Petra Lundström called for input from the audience. Fortum's view is that nuclear energy is needed also in the future.

The last session on the first day was dedicated to talks about business opportunities in the nuclear sector. Ana Belen Cerro Gordo from CDTI introduced the Big Science Business Forum 2022 and stated that it is important to involve companies already in the early stages of research programs. Tim Luce from ITER Head of Science & Operation described the progress of ITER construction and future phases of the project. Sophie Macfarlene-Smith from Rolls Royce and Fredrik Vitabäck from GE Hitachi introduced their SMR concepts Rolls-Royce SMR and BWRX-300 and energy market development in Europe. Sophie Macfarlene-Smith stated that the reason we are not using more nuclear power is behind economics and licensing issues. She explained that the reasoning behind Rolls-Royce SMR is to develop a concept that produces the maximum amount of electricity with minimum cost. GE Hitachi is active especially in Canada. Fredrik Vitabäck also stated that Sweden is no longer a decommissioning country, but public support for nuclear is growing. At the end of the last session, Hauke Grages from Framatome talked about decommissioning and how it is always part of every nuclear project.

FinNuclear ry had its spring meeting at the end of the first day. Conference dinner was also organized at the end of the first day.

The topic of the SMR session on the second day was "SMR deployment". Fredrik Vitabäck introduced BWRX-300 as an SMR case. One of the key messages was profitability. SMRs must be profitable without governmental subsidies. Profitability and staying on schedule was also the key message in Sophie Macfarlene-Smith's talk supply chain creation. Jaakko Leppänen introduced the LDR-50 district heating reactor under development at VTT. The idea behind LDR is that electricity is not the only need in the road to decarbonization. Particularly in Finland and in many central and eastern European countries district heating relies heavily on fossile fuels. LDR is a simple reactor designed to operate in low temperature and pressure to produce only heat.

One set of talks was dedicated to challenges in SMR deployment. Juhani Hyvärinen from LUT university introduced known challenges in SMR deployment. The key challenges and their status in SMR deployment are listed in Table 7-4.

Table 7-4. Challenges in SMR deployment and their status from the presentation of Juhani Hyvärinen.

Challenge	Status
Need	Exist e.g. in Finland
Societal acceptance	Exist e.g. in Finland
Readiness to license	Challenges related to acknowledging the special features of SMRs such as e.g. serial production.
Availability of technology	Several technologies under development, although no readily purchasable concept exists yet.

Competitiveness	More attention needs to be paid
Capability to deliver on time	More attention needs to be paid

TVO's Juha Poikola talked about challenges from a utility point of view. Main challenges are long and expensive licensing procedure, lack of harmonization and lack of SMRs in use. Poikolainen also stated that it is time to define TVO's SMR strategy. The need for clean heat exists now and must be answered within the next 10 years. With electricity there is more time. Debbie Francis from EDF – NUWARD expressed an international view on licensing. Her key message was to encourage regulators to communicate and collaborate with us.

In the afternoon, Sophie Macfarlene-Smith from Rolls Royce explained how some of these challenges are solved in the design of Rolls Royce SMR. Some key elements in cost reduction is the modularization of the whole plant and not just the nuclear part, standardization and increasing the use of commercial of-the-self products. These factors contribute also to keeping in schedule. At the end of the afternoon session Aaron Held from U.S. Embassy in Finland and Antti Rantakaulio from Fortum talked about US public private partnership and EU SMR partnership. Aaron Held emphasized the importance of building networks.

The SMR session included also group work whose aim was to discuss the strengths, weaknesses, opportunities and threats related to SMR delopyment. The conclusions of the particpants are shortly summarized in Table 7-5.

Table 7-5. Results of group work during the SMR session.

Strengths and opportunities	Threats and weaknesses
Decarbonization, efficient use of resources	Licensing and regulation
Cost efficiency	Too late, too expensive
Use of existing industrial sites	Waste management
Technical advancement	Manufacturing / supply chain immaturity

During the seminar some polls were conducted through a mobile application. The poll results are presented in Figure 7-3.

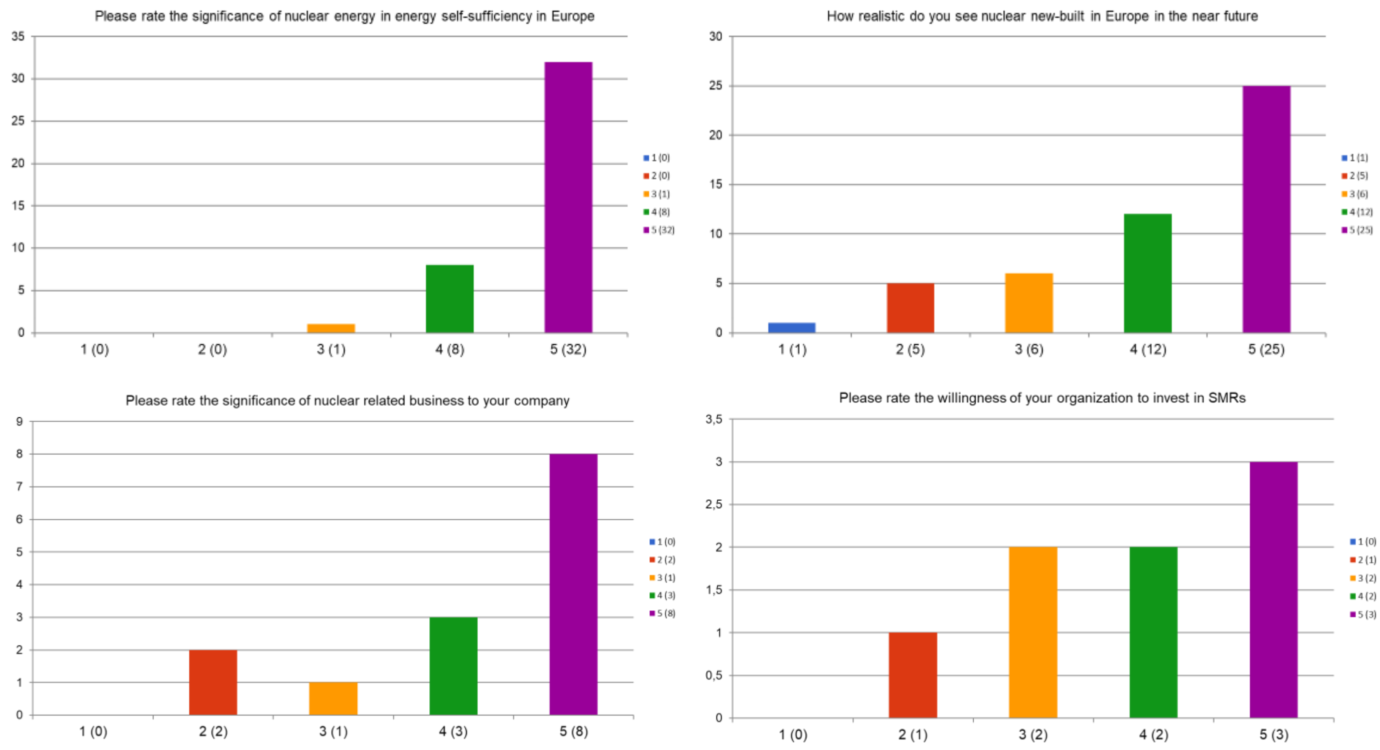

Figure 7-3. Poll questions during the Nuclear Energy Ecosystems - Open Business Day. Questions from left to right and top to bottom including number of answers in brackets:
i) Please rate the significance of nuclear energy in energy self-sufficiency in Europe (41).
ii) How realistic do you see nuclear new-built in Europe in the future (49).
iii) Please rate the significance of nuclear related business to your company (14).
iv) Please rate the willingness of your organization to invest in SMRs (8).

7.4 Final seminar

The Final Seminar of EcoSMR was joint-organized with dECOmm and SMRSiMa projects on Nov 23rd 2022 in Paasitorni. In total 68 domestic representatives of the nuclear energy industry had interactive multidisciplinary discussions during the seminar. The EcoSMR session presentations of the final seminar covered topics related to licensing, siting, environmental impact and economic analysis, social acceptability and spent fuel management of SMRs (see Table 7-6). The feedback from the seminar indicated participants' high appreciation for the free-form discussion between industry, research organizations and authorities. Methods for international harmonization of quality systems, passive cooling system verification, emergency planning zone approval and remote management were at the center of the discussions. Focus was also to find applicable best practices from around the world for the comprehensive reform of the Nuclear Energy Act currently underway in Finland. The feedback from the international participants highlights appreciation for the active cross-border dialogue in the Finnish nuclear energy industry. Broad collaboration between Finnish nuclear energy operators, mutual trust and appreciation were also pointed out as strengths in the Finnish nuclear industry during the seminar. Many participants were interested in attending more seminars around the themes of SMR development.

Figure 7-4. Participants in EcoSMR final seminar.

Table 7-6. Final seminar programme.

	ECOSMR (JUHO RISSANEN – 1,5. KERROS)		**DECOMM (TARMO – 0. KERROS)**
08.30 – 09.00	Morning coffee		
9.00	Introduction and welcome		
	Licensing and siting of SMRs (Ville Tulkki)		
09.10 – 09.25	Juhani Hyvärinen, LUT (remote participation): Streamlined licensing process		
09.25 – 09.40	Paula Keto, VTT (SMRSiMa): GTK study - SMR plant and repository siting		
09.40 – 09.55	Mikko Ilvonen, VTT: Review of SMR siting and emergency preparedness		
09.55 – 10.10	Jaakko Leppänen, VTT: Economical risks in licensing and available tools for safety analysis		
10.10- 10.20	Questions to speakers		
10.20- 10.50	Coffee break		
	Heating reactor prospects (Chair: Jaakko Leppänen)		Optional participation to EcoSMR programme
10.50 – 11.05	Heikki Suikkanen, LUT: Design requirements for a Finnish district heating reactor considering domestic deployment and export potential		
11.05 – 11.20	AEP group, Aalto University: Carbon footprint of district heating reactors		
11.20 – 11.40	Tomi J. Lindroos, VTT: Investment analysis in Finnish capital region and in the Baltic region (20 min)		
11.40- 11.55	Questions to speakers		
11.55- 13.00	**Lunch**		
13.00- 14.45	Company projects (Chair: Ville Tulkki)	13.00- 14.45	dECOmm project results (Chair: Nina Wessberg)
13.00 – 13.15	Jaakko Ylätalo, Fortum: Nuclear Heat as a Service - Analysis of business models	**13.00 – 13.30**	Markus Airila, VTT: Learnings from FiR1 decommissioning
13.15 – 13.30	Riku Turkia, Refinec Improving manufacturing capabilities and welding quality in favor of SMRs and related equipment		
13.30 – 13.45	Juha Poikola, TVO: EcoSMR project implications on TVO's scope of work	**13.30 – 13.45**	Tatu Harviainen, VTT: Robot demos in dECOmm project

13.45 – 14.00	Questions to speakers & Company Introductions	**13.45 – 14.00**	Daniel Kaartinen, VTT: Future decommissioning market in Europe
14.00 – 14.15	Olli Soppela: Round Table and Interview Key Takeaways	**14.00 – 14.15**	Ilkka Karanta, VTT: Risk ontology methods in decommissioning
14.15 – 14.30	Rebekka Komu, VTT: Load following and transient analysis LDR-50	**14.15 – 14.30**	Jyrki Jauhiainen, Sweco: Sweco company project results
14.30 – 14.45	Merja Airola & Matti Kojo (SMRSiMa): Societal acceptability of SMR plants	**14.30 – 14.45**	Otso Manninen & Ville Oinonen, Fortum: Fortum company project results
14.45-15.00	Questions to speakers	**14.45-15.00**	Questions to speakers
15.00-15.30	Coffee break		
15.30-16.30	JOINT FINAL SESSION (Chair: Jaakko Leppänen)		
15.30 – 15.45	Paula Keto, VTT (SMRSiMa): SMR spent fuel characteristics and waste management		
15.45 – 16.00	Olli Soppela, VTT: dECOmm main take aways and way forward		
16.00 – 16.15	Ville Tulkki, VTT: EcoSMR main take aways and way forward		
16.15 – 16.30	Closing Discussion		

7.5 Workshops

Two internal workshops were arranged during the project. These workshops were directed to the project partners in order to disseminate project results and have general discussions on the project direction. The first workshop was organized in April 2021 and concentrated on reporting the results achieved at the research institutes LUT and VTT. The topics of the talks are covered in other chapters of this report. The second workshop was arranged in October 2021 and its contents were generally similar to the first workshop. In addition, future plans and views of the partners were discussed regarding SMRs.

7.6 Travel

Most of the travel conducted within the project was realized in autumn 2022 because of the COVID pandemic which restricted travelling before that. Some remote participation to conferences was conducted before that.

7.7 Other dissemination

Some other dissemination was conducted through publication of articles in magazines and news papers. Four articles were published in the Finnish member magazine “ATS Ydintekniikka” published by Finnish Nuclear Society (Suomen Atomiteknillinen Seura, ATS). The first article presented VTT’s three Business Finland funded nuclear energy related ecosystem projects and was written together with the project managers of the two other projects dECOmm and ECO-FUSION. The topic of the second article was Finnish district heating reactor and it was written about the first short webinar organized by the EcoSMR project. The topic of the third article was Nuclear Energy Ecosystems – Open Business Day organized in May 2022 and was written together with the same projects as the first article. The fourth article discussed the final seminar of EcoSMR and dECOmm projects.

One “vieraskynä” article was written to Helsingin Sanomat, the largest national newspaper in Finland. The article was published on 2.12.2022 and it was about SMRs as energy sources in cities, Finnish title: “Pienydinvoimalat sopisivat kaupunkien energiaratkaisuksi”.

Press releases were given in the beginning of the project and at its end.

8. Company projects

8.1 Summary

This chapter shortly introduces the company projects within the EcoSMR co-innovation project.

8.2 Fortum

Fortum is a Nordic energy company. Fortum’s purpose is to power a world where people, businesses and nature thrive together. Fortum is one of the cleanest energy producers in Europe and their actions are guided by their ambitious environmental targets. Fortum generates and delivers clean energy reliably and helps industries to decarbonise their processes and grow. Fortum’s core operations in the Nordics comprise of efficient, CO2-free power generation as well as reliable supply of electricity and district heat to private and business customers. Fortum has ~5 000 employees, it commits to be a safe, and inspiring workplace. Fortum's share is listed on Nasdaq Helsinki. fortum.com

In Fortum’s company project they studied potential nuclear district heating business models. They had three main research areas: business models, licensing and supporting topics. During the project, more understanding of the business models and licensing were gained. It was found out that nuclear district heating business model has potential. However, due to uncertainties related to business environment and immaturity of the technologies more research is needed in the future.

8.3 Refinec

Refinec is an engineering workshop specialized in designing and manufacturing of heat-exchangers and pressure vessels. Core competences of Refinec lie in the in-house thermodynamical and structural designing as well as the ability to produce top quality products from a wide selection of materials for demanding applications. Refinec is also known for excelling in quality control and documentation. Having project management, designing, and manufacturing all under one roof ensures a smooth co-operation throughout the projects.

Refinec offers research institutes and companies services by developing and manufacturing prototype reactors for their SMR studies and by researching manufacturability and manufacturing technologies such as weldability of different reactor materials and structure types.

In Refinec’s EcoSMR company project they focused on the development of production methods for the manufacturing of SMRs. Production methods were made more efficient and quality was improved by utilizing the latest welding automation technologies available.

8.4 TVO

TVO has been researching the possibilities of SMR already since March 2020. The project name, SMR2029, refers to the ban of coal use starting in Finland in 2029, which will make it necessary to find new solutions for energy production. Also, SMR technology is expected to be already commercially available by 2029, with legislation in place to enable the construction of SMR.

The recruiting for the project inside the company generated a lot of interest and 13 professionals were appointed to take part in it. The final report for the project is ready. The continuation of SMR activities is now under planning at TVO.

During the project, public support for nuclear has increased to a historically high level and both decision-makers and the public are asking for more investments in nuclear power. It is also hoped that SMR technology will provide a solution for the production of district heat in urban areas. However, there are still several open questions regarding the realization of investments in SMR in Finland.

Conclusions from the project:

- SMR plant suppliers – No fully ready and proven technologies available in the market yet.
- SMR site – The need of energy-heat alone is not a sufficient basis for site selection, but other things must also be considered.
- Hydrogen – Producing of low-carbon hydrogen with electricity is in the early phase of scale up and economical support play important role when making investment decisions.
- District heating SMR – Single unit is highly expensive to construct and operate taking into account requirements and costs for full lifecycle.

The main conclusions can also be seen from a different perspective:

- SMR plant suppliers – Suppliers are active and have a lot of resources appointed on SMR work. Things are progressing and new developments may happen under rather fast schedule. Pilot projects ongoing and starting soon are very important for the deployment of SMRs.
- SMR site – Related key topics are acceptability, local competences, supply chains, actor and need. The current nuclear power plant sites have high acceptability, skillful workforce available and existing local supply chains. What is needed is an actor who is able to handle the project. After these comes the need.
- Hydrogen – Hydrogen is becoming as a new element in the low-carbon energy system to balance high variations of renewable electricity production.
- District heating SMR – A project aiming for realizing district heating SMR should consider possibility of a fleet of SMRs right from the beginning.

9. Other activities

9.1 Summary

Activities not covered under the work packages include SMR supplier meetings. These meetings were organized as a request from the steering group. Eight different reactor vendors were met during the project comprising discussions on nine different reactor designs in development in Europe, North America and Japan. The designs consist of five light water reactors relying on conventional proven technologies and four advanced designs relying on other than light water reactor technology in various states of development.

9.2 SMR supplier meetings

This chapter gives a short overview on the reactor designs discussed in EcoSMR project, their readiness level and basic technical details. Data in this chapter is mainly based on the discussions with the vendors and the IAEA “SMR book 2022” [IAEA, 2022]. Other sources are referenced in the text when applicable.

Only reactors discussed in the SMR vendor meetings are presented. Many other rather advanced designs also exist. For example, the marine based light water reactor KLT-40S has been in operation in Russia since 2020. The Chinese high temperature gas cooled demonstration reactor HTR-PM reached full power in December 2022. Other advanced designs include e.g. CAREM (Argentina), ACP100 (China), DHR400 (China), OPEN20 (USA) and STAR (Switzerland) which are all based on light water technology.

Table 9-1 presents a general overview and some characteristics of the reactor designs discussed with the SMR vendors. The following sub-chapters shortly present each design. Some technical details are further summarized in tables at the end of the chapter.

*Table 9-1. SMR vendors and their technologies discussed in meetings with EcoSMR partners. *Discussions with Rosatom were conducted in 2021 before the war in Ukraine.*

Reactor	Supplier	Type	Power [MWe]	Site	FOAK year
BWRX-300	GE-Hitachi	BWR	270 - 290	Darlington, Canada	2028
Rolls-Royce SMR	Rolls Royce	PWR	470	UK	2030
VOYGR™	NuScale Power	Integral PWR	4/6/12 x 77	Idaho Falls, Idaho, USA	2029
NUWARD™	EDF	Integral PWR	2 x 170	France	2030s
RITM-200N	Rosatom*	Integral PWR	55	Ust-Yansky, Sakha	2028

				Republic, Russia	
IMSR®	Terrestrial Energy	MSR	2 x 195	(Canada)	2031
MMR™	USNC	HTGR	5	Chalk River, Canada	2026
Natrium™	Terrapower	SFR	345	Wyoming, USA	late 2020s
MCFR	Terrapower	MSFR	180		2035

9.2.1 BWRX-300

BWRX-300 is developed by GE-Hitachi Nuclear Energy and Hitachi-GE Nuclear Energy in USA and Japan. It is a BWR reactor with electric output between 270 - 290 MWe. Target applications include electricity production, district heating, process heat, hydrogen and synthetic fuel production. The reactor operates with natural circulation in all operational states and all postulated off normal conditions. Reactivity control is provided with burnable absorbers and control rods. The reactor is capable of load following within the range of 50-100 % of full power. The fuel design is GNF2 which is used in majority of BWR fleets today. The BWRX-300 core comprises of 240 GNF2 10x10 square assemblies with 79 full-length rods, 14 part-length rods and two large central water rods. The fuel is UO_2 with maximum enrichment 4.95 %. The fuel cycle is either 12 or 24 months. Depending on the cycle length either 32 or 72 assemblies are replaced during the outage. BWRX-300 is undergoing different licensing reviews in UK, USA and Canada. The licensing process is furthest in Canada where the BWRX-300 is undergoing a combined Phase 1 and 2 Vendor Design Review process that is expected to be completed in the Fall of 2022. Construction license application is expected to be submitted by Ontario Power Generation for a FOAK reactor in Darlington, Canada in late 2022. Commercial operation is targeted to begin in 2028.

9.2.2 Rolls-Royce SMR

The Rolls-Royce SMR is developed by Rolls-Royce in UK. It is a 3-loop PWR reactor with electric output of 470 MWe. The design philosophy is based on maximizing power output while keeping the plant size such that modularization and standardization is enabled throughout the whole plant. The plant is 90 % factory fabricated with road transportable modules. Rolls-Royce aims to deliver the whole power station as a turn key product within 4 year construction time. The cost estimate of one plant is under £2 billion. The main application of the Rolls-Royce SMR is electricity production. However, various other applications have also been reviewed including e.g. heat production, desalination, hydrogen production and synthetic fuel production. The reactor is capable of load following at the minimum between 50-100 % of full power. The reactor core consists of 121 standard 17x17 square assemblies. The fuel is UO_2 with less than 4.95 % enrichment. In every 18 month cycle one third of the core is replaced with fresh fuel. Spent fuel is stored on site for about 10 years. Reactivity control is handled with burnable absorbers (gadolinium) and control rods. In normal operation boron is not applied in the coolant, although emergency boron injection is possible. The site for the FOAK reactor has not been confirmed yet, but possible sites are under investigation. According to recent news [WNN, 2022a], Four sites owned by the Nuclear Decommissioning Authority (NDA) are prioritized. These include land parcel in Trawsfynydd, land neighbouring the Sellafield site, Wylfa and Oldbury. Other possible sites for Rolls-Royce SMR have also been identified, but may require further investigation. Construction of the FOAK is supposed to start in 2026 and commercial operation in 2030.

9.2.3 VOYGR™

VOYGR™ is an integral PWR reactor developed by NuScale Power Corporation in USA. VOYGR™ comprises of 4, 6 or 12 independently operated reactor modules with 77 MWe power each. Load following is possible with the design. The six-module plant is the reference plant and will be the FOAK nuclear plant. The target application of VOYGR™ is electricity, but the reactor can also be used for process heat applications. All reactor modules are immersed in a combined pool of water. Coolant flow is based on natural circulation. All design basis accidents can also be handled without operator action. The 12 unit plant requires approximately 270 employees during normal operation. Reactivity control is handled with soluble boron and control rods. Gadolinium is also used as a burnable absorber in the fuel. Reactor core consists of 37 fuel assemblies of standard 17x17 PWR design. The length of the assemblies is approximately half of standard large reactor fuel and is supported by five spacer grids. VOYGR™ fuel is UO_2 with maximum 4.95 % enrichment. Spent fuel can be stored for up to 10 years along with fresh fuel assemblies. The VOYGR™ reference plant received standard design approval from NRC in September 2020 [WNN, 2020]. Component manufacturing has begun in 2022. NuScale received approval for its method of determining the emergency planning zone (EPZ) from NRC in October 2022 [NRC, 2022]. Combined license application is to be submitted to NRC in 2023. Construction of the six-unit reference plant is scheduled to begin in 2025 in Idaho Falls, Idaho, USA and commercial operation in 2029.

9.2.4 NUWARD™

NUWARD™ is an integral PWR developed by EDF in France with significant contributions from CEA, Naval Group, Framatome, TechnicAtome, and Tractebel-Engineering. NUWARD™ has secured funding also from the French government [WNN, 2022b]. The plant comprises of two reactors of 170 MWe each. Both reactors are immersed in a common pool of water which acts as an ultimate heat sink. The reactors and pool are located below ground level. The target application of NUWARD™ is to replace fossil-fuelled plants of the size 300 - 400 MWe. It is designed for multipurpose applications such as electricity production, heat, hydrogen production and water desalination. NUWARD™ is also capable for load following. The reactor core comprises of 76 standard shortened height 17x17 PWR assemblies. Fuel is UO_2 with less than 5 % enrichment. Reactivity is handled by control rods and burnable absorbers in the fuel. No boron is utilized in the coolant. Refuelling cycle is 2 years during which half of the core is replaced with fresh fuel. Spent fuel can be stored on site for 10 years. EDF has launched an initiative to make NUWARD™ as a case study for a European early joint regulatory review led by ASN (French nuclear safety regulator) with the participation of STUK and SUJB, the Finnish and Czech nuclear regulators [WNN, 2022c]. First concrete for the FOAK reactor is targeted for 2030 in France. Potential sites are being investigated.

9.2.5 RITM-200N

RITM-200N is an integral PWR reactor based on long experience in icebreaker technology. RITM-200N is developed by Rosatom in Russia. The reactor takes advantage in modular design both for construction and transportation. The target applications include electricity production, cogeneration of electricity and heat and desalination. The primary coolant system operates with forced circulation, but natural circulation is exploited in accident conditions. Reactivity control is handled with control rods. The reactor core comprises of 199 hexagonal fuel assemblies with UO2 fuel enriched under 20 %. Refuelling cycle of the reactor is 5-6 years. The FOAK reactor will be built near a town called Ust-Kuiga in the Ust-Yansky district in the Republic of Sakha in Russia. Site license is expected in March 2023 and construction license in 2024. Commercial operation is targeted to begin in 2028.

9.2.6 IMSR®

The IMSR® is a molten salt reactor developed by Terrestrial Energy Inc. in Canada. The plant consists of a nuclear facility and a thermal and electric facility. The nuclear facility contains two molten salt reactors of 195 MWe each. Target applications include electricity and process heat for several uses such as hydrogen production and synthetic fuels. The fuel is uranium tetrafluoride UF_4 infused in primary coolant that comprises of other fluoride salts. The primary circulation is achieved through pumping the fuel-coolant-mix through the core and the solid graphite moderator. Secondary coolant loop also comprises of fluoride salts, but without the fuel. The third coolant loop is also salt and is pumped to the thermal and electricity facility. There it is used to generate superheated steam for electricity production and/or directly connected to a process heat application. Reactivity control is achieved through strong negative temperature feedback. Operational control is provided by control rods which can be used also for reactor shutdown. Cooling is guaranteed in all circumstances, because of the molten nature of the fuel. The whole core unit is manufactured in a factory and placed in a below ground level silo in the plant site. The whole unit is replaced with a new one every 7 years. The used fuel from the old unit is recycled and used in the next unit. Phase 1 of the Canadian Nuclear Safety Commission's (CNSC) Vendor Design Review has been completed for IMSR®. Phase 2 submissions have been completed in early 2022. Necessary licenses are expected to be secured in Canada in 2026 and construction of the FOAK unit is supposed to start in 2027. The FOAK is targeted to be operational in 2031.

9.2.7 MMR™

The MMR™ is a high temperature gas cooled reactor (HTGR), a micro modular reactor, developed by Ultra Safe Nuclear Corporation in USA. The plant comprises of two parts: i) the nuclear plant and ii) an adjacent plant. The nuclear plant houses a HTGR reactor that provides heat for the adjacent plant. The adjacent plant acts as a molten salt heat storage system where the heat is transferred to process heat applications and/or steam generation for an electric turbine. The MMR™ is specifically designed as a stand-alone micro grid or as "nuclear battery" in remote locations providing electricity and process heat. The reactor is helium cooled and graphite moderated. The core consists of hexagonal graphite blocks containing the fuel pellets. The fuel is fully ceramic micro encapsulated fuel manufactured with Triple Coated Isotropic (TRISO) particles. Reactivity control is handled with control rods. The reactor is designed to operate for 20 years with one fuel loading. After that, the fuel can be replaced once and after 40 years of operation, the reactor will be decommissioned. A license to prepare site initial application has been submitted to the Canadian Nuclear Safety Commission (CNSC). Licensing in USA has also been initiated. Site preparation and FOAK construction is supposed to take place during 2021-2027. The first demo plant is planned to start operation in 2026 in Chalk River, Canada.

9.2.8 Natrium™

The Natrium™ is a 345 MWe sodium cooled fast reactor developed by Terrapower and GE Hitachi. The plant comprises of a nuclear part and a non-nuclear molten salt storage system. Heat is transferred from the reactor by nitride molten salt into a hot salt tank. From the hot tank the molten salt is directed through steam generators for generating steam to the turbine building. After the steam generator, the molten salt travels to a cold tank from where it is pumped back to the reactor site. Electricity can be generated directly or it can be stored in the tanks for later use. The storage system allows a boost in power production of 500 MWe for 5.5 hours. This allows the design to follow daily electric load changes. The separate electricity system allows that part to be constructed as a fully commercial non-nuclear project which reduces costs. The reactor uses high-assay low-enriched uranium (HALEU) metallic fuel with enrichment between 5-20 %. It applies once-through cycle and operates at near atmospheric pressure. A demonstration plant is planned to be built in a retiring coal plant in Kemmerer, Wyoming, USA by 2028.

9.2.9 MCFR

MCFR is a Molten Chloride Fast Reactor developed by Terrapower, USA. The target applications of the design include electricity production and process heat for industry. The fuel is incorporated in molten chloride salt. The design includes multiple products including e.g. HALEU fuelled reactor and a waste burning reactor for transmutation of transuranics. Much of the current development is happening under two DOE funded projects: i) Advanced Reactor Concepts (ARC15) and ii) Advanced Reactor Demonstration Program (ARDP). ARC15 is meant for separate and integrated effect tests whereas the goal in ARDP is to built an experimental reactor, Molten Chloride Reactor Experiment (MCRE). MCRE will be built at Idaho National Laboratory (INL). First criticality is planned for 2025. The first demo MCFR reactor is expected to be built by 2035 with 180 MWe power capacity [WNN, 2022d].

9.2.10 Summary on SMR designs in the SMR supplier meetings

Time scale of FOAK reactors and power output of the SMR designs discussed in the EcoSMR project are summarised in Figure 9-1.

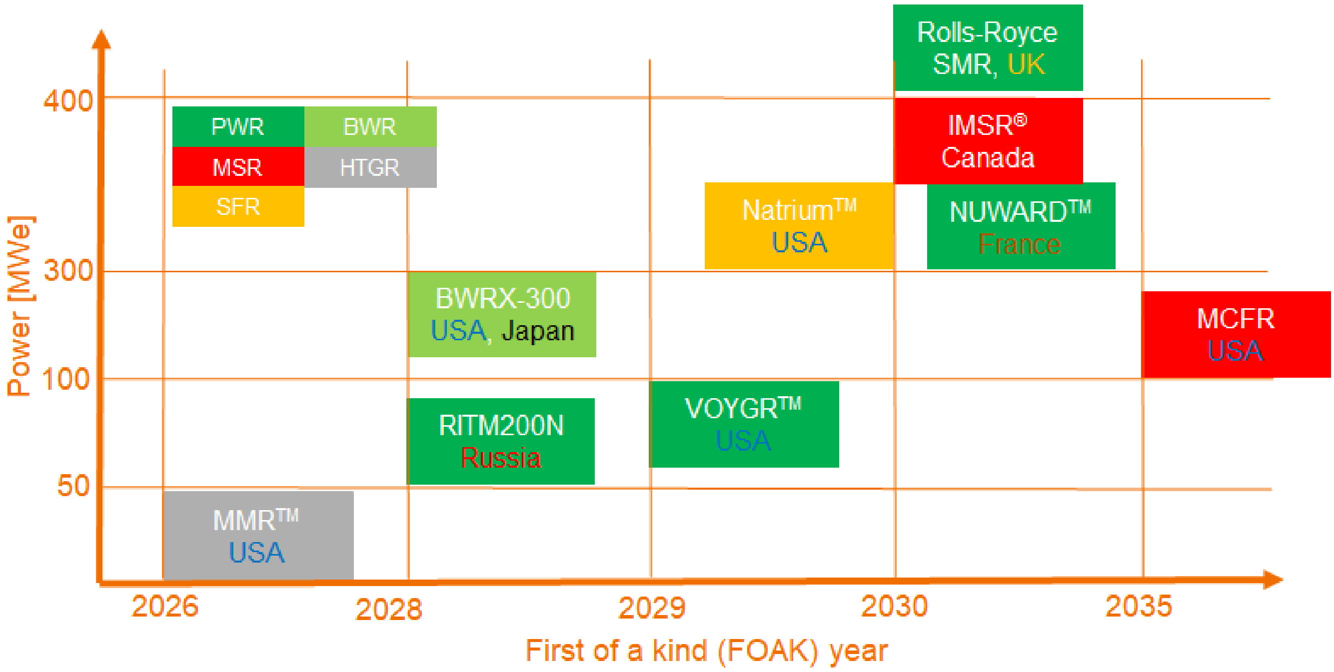

Figure 9-1. Timescale of the SMR designs discussed in EcoSMR project. Time of the FOAK reactor is given in the horizontal axis and power output in MWe in the vertical axis. Reactor types are indicated in colours.

Target applications of the SMR designs discussed in the EcoSMR project are outlined in Table 9-2.

Table 9-2. Target applications of the SMR designs discussed in EcoSMR project.

Design	Electricity	District Heating	Process Heat	Hydrogen Production	Desalination	Synthetic Fuel Production
BWRX-300	X	X	X	X		X
Rolls-Royce SMR	X		X			X
VOYGR™	X		X			
NUWARD™	X	X	X	X	X	
RITM-200N	X	X			X	
IMSR®	X	X	X	X		X
MMR™	X		X	X		
Natrium™	X					
MCFR	X		X			

Some technical details of the SMR designs discussed in the EcoSMR project are listed in Table 9-3.

Table 9-3. Technical parameters of the SMR designs discussed in the EcoSMR project.

Design	Primary circulation	Pressure [Bar]	Inlet / Outlet [°C]	Fuel	Max enrichment [%]	Number of assemblies in the core	Refuelling cycle [m]
BWRX-300	Natural	72	270 / 288	UO_2	4.95	240	12-24
Rolls-Royce SMR	Forced	155	195 / 325	UO_2	< 4.95	121	18
VOYGR™	Natural	138	249 / 316	UO_2	≤ 4.95	37	18
NUWARD™	Forced	150	280 / 307	UO_2	< 5	76	24

RITM-200	Forced	157	283 / 321	UO_2	< 20	199	60-72
IMSR	Forced	< 4 bar	620 / 700	UF_4	< 5	-	84
MMR™	Forced	30	300 / 630	Triso	19.75	-	240
Natrium™	Natural	~atm	No info	HALEU	< 20	No info	No info
MCFR	Forced	Low	No info	NaCl-UCl_3	12 (start-up)	-	Continuous

[IAEA, 2022] IAEA (2022), "Advances in Small Modular Reactor Technology Developments", A Supplement to: IAEA Advanced Reactors Information System (ARIS), 2022 Edition.

[WNN, 2022a] WNN (9.11.2022), World Nuclear News, url: https://www.world-nuclear-news.org/Articles/Study-identifies-potential-Rolls-Royce-SMR-sites, accessed 21.11.2022.

[WNN, 2020] WNN (1.9.2020), World Nuclear News, url: https://world-nuclear-news.org/Articles/NuScale-SMR-receives-US-design-certification-appro, accessed 22.11.2022.

[NRC, 2022] U. S. Nuclear Regulatory Commission, "Safety Evaluation for NuScale Topical Report, TR-0915-17772, "Methodology for Establishing the Technical Basis for Plume Exposure Emergency Planning Zones at NuScale Small Modular Reactor Plant Sites", Revision 3", October 19, 2022 (ML22287A155), url: https://www.nrc.gov/docs/ML2228/ML22287A155.pdf.

[WNN, 2022b] WNN (11.2.2022), World Nuclear News, url: https://www.world-nuclear-news.org/Articles/Macron-announces-French-nuclear-renaissance, accessed 22.11.2022.

[WNN 2022c] WNN (6.6.2022), World Nuclear News, url: https://www.world-nuclear-news.org/Articles/European-regulators-to-cooperate-on-Nuward-licensi, accessed 22.11.2022.

[WNN, 2022d] WNN (19.10.2022), World Nuclear News, url: https://www.world-nuclear-news.org/Articles/World-s-largest-chloride-salt-system-in-place, accessed 24.11.2022.

10. Summary, conclusions and way forward

EcoSMR was a 2.5 year co-innovation project funded by Business Finland. The main goal was to enable Finnish companies to participate in emerging international SMR markets. This was aspired by creating an ecosystem of SMR actors in Finland and linking the Finnish ecosystem to international actors through networking and dissemination activities and by developing Finnish know-how on selected topics. These topics included licensing issues, heating reactor prospects, scenario analysis, business model examination and ecosystem creation. The main conclusions and future work are outlined in the following.

10.1 Licensing issues

While current nuclear regulations enable SMR construction and operation, they do not account for SMR specific characteristics like for example serial production and wide geographical deployment of SMRs. Regulation renewal is needed to take these factors into account. Otherwise SMR projects will simply not be economically feasible. One solution would be to change the regulations so that site and technology could be licensed separately, the same applicant would not have to hold both licenses and other actors could benefit from previously licensed technology and sites.

Prediction of licensing costs is important in order to guarantee economic feasibility of SMR projects. Licensing costs may be difficult to separate from other overall costs. On the other hand, estimation of costs by component or structure is highly dependant on the plant design. More comprehensive studies for predicting licensing costs are required.

Emergency planning zone (EPZ) size is important when SMRs are sited close to population. This is important especially with heating reactors whose costs depend heavily on distance from end users. Different procedures have been suggested for EPZ determination. A definitive, but laborious method is a full-scale PSA. It is suggested that some long advanced projects in UK, USA and Canada are followed to understand the procedures that will be applied in other countries. E.g. US regulator has approved a method for determining the EPZ for NuScale.

Currently developed safety analysis tools are mostly applicable especially for the analysis of SMRs based on light water technology. Sufficient effort must be paid on education of new experts in order to maintain the expertise.

10.2 Heating reactor prospects

The market potential for district heating reactors was found to be significant in Finland. Depending on the reactor size (50 MWth or 24 MWth) altogether around 50 or close to 100 reactors could be fitted in 12-19 district heating networks in Finland. Investment analysis in the capital region also showed this to be an economic option. When studying replacement of fossil fuels in district heating by SMRs or heat pumps in the capital region of Finland, SMRs were cheaper than heat pumps based on ambient sources. Since information on capital costs was not well available at the time of study, these costs were varied. In the future, the calculations should be updated, because more information on the capital costs has become available.

Similar studies in the Baltic regions indicated that SMRs would be profitable in Tallin and Riga regions, but not in Vilnus. The different results in Vilnus were caused by recent investments in waste incineration and biomass. On the other hand, the market potential in the Baltic region is significantly smaller than in Finland due to smaller grids and warmer climate. A few units could be exported to the capital regions of the Baltic countries. Market potential in Poland would, however, be significant due to larger grids and high dependability on coal in district heating.

District heating demand depends strongly on outdoor temperatures which may vary rather rapidly. This places a requirement of load following capability for a potential district heating reactor. Load following capabilities were analysed in three difficult load following cases for the LDR-50 reactor design. It was found that the thermal hydraulic design poses no limitations to reactor operation and the reactor survived these cases without difficulty. The next step would be to examine possible limitations due to neutronics design.

Carbon footprint of district heating reactors was estimated by varying the number of LDR-50 reactors in the capital region. Reduction in carbon emissions was found to be 30 %. The reduction was limited by the fact that in the calculated scenarios district heating reactors acted only as base load and peak demand was always handled by fossil fuels. The study pointed out the complexity of a district heating system involving multiple heating sources and variation in demand.

Preliminary design of the primary heat exchanger of a 50 MWth district heating reactor has been completed and is described in more detail in chapter 4.6.

10.3 Business models and ecosystems

EcoSMR project researched the key boundaries to financing the life-cycle of an SMR. The right division of responsibilities and rights enables unlocking finances, financial risk management and distribution of profits along the lifetime of the planned facility. Key financial decision topics relate to the ownership structure of the related plants and licensees, financing terms of each project stage, sales contracts of production, distribution of the revenue, insurance of SMR fleets, waste management & decommissioning funds. The significantly higher share of OPEX in the total SMR lifetime budget compared to traditional nuclear energy projects requires new types of financial risk management methods.

The ecosystem work enables parties to co-innovate and negotiate complex contract terms, find alternative partners for each project stage and ensure the availability and viability of business partners for the long-term commitments in the SMR projects.

10.4 EcoSMR Hub

EcoSMR project created an ecosystem of SMR actors in Finland and acted as a facilitator for discussions related to all things SMR. This work will be continued in EcoSMR Hub. The Hub will facilitate discussion and small preliminary studies on selected topics for the basis of decisions on future projects and actions. The Hub will be funded by fees collected from the participants. All Finnish actors are in principle welcome to join. At least in the beginning of the Hub, it will be coordinated and managed by VTT.

Appendix A Reports and publications

Table A-1 includes research reports, conference articles and journal papers published in the EcoSMR project.

Table A-1. Research reports, conference papers and journal articles published in the EcoSMR project.

Journal articles
Pursiheimo, E., Lindroos, T.J., Sundell, D., Rämä, M., Tulkki, V., (2022), ”Optimal investment analysis for heat pumps and nuclear heat in decarbonised Helsinki metropolitan district heating system”, Energy Storage and Saving, 1, 80-92, https://doi.org/10.1016/j.enss.2022.03.001.
Saari, J., Suikkanen, H., Mendoza-Martinez, C., Hyvärinen, J., (2023), “Optimization of natural circulation district heating reactor primary heat exchangers”, Energies, 16, 2739, https://doi.org/10.3390/en16062739.
Conference papers
Komu, R., Lindroos, T.J., Hillberg, S., Leppänen, J., (2022), ”District Heating Reactor LDR-50: Thermal-Hydraulic Analysis of Difficult Load Following Cases”, The 13th International Topical Meeting on Nuclear Reactor Thermal-Hydraulics, Operation and Safety (NUTHOS 13) Hsinchu, Taiwan, September 5-10, 2022.
Häkkinen, S., Lindroos, T.J., Soppela, O., Leppänen, J., Tulkki, V., Suikkanen, H., (2022), ”EcoSMR - Ecosystem for Small Modular Reactors”, Nuclear Science and Technology Symposium - SYP2022 Helsinki, Finland, 1-2 November 2022.
Lindroos, T.J., Putkonen, N, Niemi, A., Alblouwy, F., Suikkanen, H., (2022), ”Prospects of electricity and heat-only SMRs in the Baltic Region”, Nuclear Science and Technology Symposium - SYP2022 Helsinki, Finland, 1-2 November 2022
Pursiheimo, E., Lindroos, T.J., Tulkki, V., (2022), “Investments in Nuclear Heating in Helsinki Metropolitan Area During Volatile Energy Markets”, Nuclear Science and Technology Symposium - SYP2022 Helsinki, Finland, 1-2 November 2022
Research reports
Häkkinen, S., Lindroos, T.J., Leppänen, J., Ryynänen, T., Soppela, O., Komu, R., Ilvonen, M., Helminen, A., Suikkanen, H., Hyvärinen, J., Saari, J., Rantakaulio, A., Perälä, H., Turkia, R., Heinonen, S., “EcoSMR, Finnish Ecosystem for Small Modular Reactors – Final Report”, VTT-R-00270-23.
Ilvonen, M., ”Review of SMR siting and emergency preparedness”, VTT-R-01612-20.
Leppänen, J., ”Overview of calculation tools used for SMR safety analysis”, VTT-R-01008-22.
Helminen, A., Tulkki, V., ”Licensing costs of SMR and challenges in their estimation”, VTT-R-00221-23.
Vankeirsbilck, A., Shrestha, B., Muralidharan, A., Khalid, F., Tanny, N.I., ”Carbon Footprint of District Heating SMR”, Advanced Energy Project Report, 2022.