RESEARCH REPORT VTT-R-00084-24

SMRSiMa:

SMR Waste Management and Siting

Waste Management and Societal Engagement

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Confidentiality: VTT Public

Version: 23.1.2024

VTT

beyond the obvious

Report's title	
SMRSiMa: SMR Waste Management and Siting, Loading Curves, Waste Management and Societal Engagement	
Customer, contact person, address SAFER2028 Research Programme	**Order reference** SAFER 23/2023
Project name SMRSiMa SMR Waste Management and Siting	**Project number/Short name** 136018 SMRSiMa
Author(s) Sami Naumer, Paula Keto, Nadezhda Gotcheva, Matti Kojo, Pauli Juutilainen, Niina Kiviluoma, Ville Rinta-Hiiro, Sarah Tornberg, Timothy Schatz, Anni Vainio, Merja Airola, Markku Lehtonen, Tapio Litmanen, Mika Kari	**Pages** 41 + 4
Keywords SMR, Spent Fuel, Waste Management, Loading Curve, Societal Engagement, Siting	**Report identification code** VTT-R-00084-24

Summary

Meeting European Unions ambitious carbon neutrality targets requires low carbon intensity electricicity and other energy production. Finland's target is to reach carbon neutrality by 2035 and Small Modular Reactors (SMR) are envisioned to help reaching the target, especially in heat production. Nuclear Energy is a low carbon intensity power source and modularity and serial production is estimated to bring the price of SMRs down when compared to conventional Nuclear Power Plants (NPP)s. While need for nuclear power and SMR siting topics have been discussed by the stakeholders in media during the past years, waste management issues have not been as common topics.

This report summarises work conducted in the SMRSiMa project during 2023 on both SMR waste management and societal engagement topics. The project is funded by SAFER2028 and is a continuation of KYT funded SMRWaMa and SMRSiMa-projects. The project is coordinated between VTT, GTK and LUT and divided into four work packages, out of which WP1, WP2 and WP4 results are reported here. GTK also prepared a research report on WP3 considering geological siting topics for the project.

In the first WP, preliminary studies were performed on criticality safety related to the final disposal of the spent fuel. These calculations were based on the fuel assembly models available in public NuScale and LDR-50 documentation and supposed to provide applicable results to any similar LWR concepts with UOX fuel in 17 x 17 asseblies. The results suggest that when e.g. 2.4 % U-235 enriched fuel is considered for LDR, the fresh fuel assumption may be acceptable for final disposal criticality safety studies. This would probably not be the case for the studied higher enrichment, i.e. 3.0 % or more, fuel. For these and the more than 4 % enriched NuScale assmeblies burnup credit will thus be needed. The WP1 chapter provides results based on several simplifications and are therefore to be understood as indicative only, with large uncertainties.

In the second work package the focus was on SMR waste management topics. The objective was to find out Finnish stakeholders research and development needs regarding SMR's. It also investigated disposability of both SMR Spent Nuclear Fuel (SNF) and Accident Tolerant Fuels (STF) into a KBS-3 type repository and assessed SNF storage concerns for SMRs. Fortum and TVO, both power companies operating NPPs in Finland, have preliminary considered deployment of Light-Water Reactor (LWR), while the Technical University of Lappeenranta is considering a Hight Temperature Gas-cooled Reactor (HTGR) for research purposes. The stakeholders considered both disposability of SMR fuel in KBS-3 repositories and business and modularity related concerns as important topics to be researched. Investigating disposability of both SMR SNF and ATF, it was found out that both fuel disposability, source-term information and gas generation potential of the fuels should be further investigated. Finally, dry storage in Finland is supported by the regulation, but not carried out historically in the Nordic region. Thus, best practices from Canada should be looked into to ensure long-term durability of canisters in long-term storage.

In the fourth work package the focus was on stakeholder engagement regarding SMR siting. LUT analysed results of a 2022 resident survey to Helsinki Metropolitan area. The survey investigated how opinions of residents for and against SMRs differ on SMR-related topics. The survey showed that more than half of the residents are supportive for deployment of SMRs in their municipalities, while only a third would accept disposal of spent fuel there. Trust into key actors differed between the opponents and supporters, where opponents were more likely to trust environmental organisations, while supporters trusted the Radiation and Nuclear Safety Authority, VTT and universities. In the work package, a preliminary roadmap for stakeholder engagement during SMR deployment was developed and presented in a workshop. The roadmap is a step towards building a common understanding among stakeholders in Finland.

Confidentiality	VTT Public

Espoo 27.2.2024

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Distribution (customer and VTT)

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Preface

This report has been compiled on behalf of VTT between August 2023 and January 2024. It presents work conducted in work packages 1, 2 and 4 in the SAFER2028 funded SMRSiMa project. It is a continuation of KYT2022 funded SMRWaMa and SMRSiMa projects with the objective to study Small Modular Reactor (SMR) related waste management, siting and societal engagement aspects. The project belongs to the Technical Advisory Group (TAG) 3.3 Rock, Site and Biosphere where project progress and schedule have been followed and advice on future efforts given in two TAG meetings during 2023 and one in early 2024.

Results of the two KYT-funded projects, and preliminary results of this project were presented in the SMR Business Day (3.10.2023, Espoo) as two posters. The first poster *"Societal engagement on SMRs and SMR waste management"* was presented by Matti Kojo (LUT) and Nadezhda Gotcheva (VTT). The second poster *"Continuation of the SAFER2028 project SMR Siting and Waste Management"* was presented by Paula Keto and Pauli Juutilainen (VTT).

Results of this project have been shared in ATS Ydintekniikka, 52(4), 30-34 with an article called "*Mitkä periaatteet ohjaavat mahdollisten pienydinvoimaloiden ydinjätehuoltoa? Suurten kaupunkien asukkaat kannattavat keskittämistä"* by Matti Kojo, Tapio Litmanen, Niina Kiviluoma and Mika Kari. GTK has also shared their results as a research report on *"Deep borehole program planning and spent nuclear fuel facility siting in the SMR framework in Finland. Geological Survey of Finland"* by Jaakko Hietava and Ismo Aaltonen. Finally, two conference papers on the project results have been submitted to the The International Conference on Management of Spent Fuel from Nuclear Power Reactors: Meeting the Moment, 10–14 June, 2024, Vienna, Austria. We would like to thank everyone who have been contributing to these papers.

Stakeholder interviews on SMR related plans and research needs were held together with representatives of TVO, Fortum and an expert from LUT. We thank all of you for the valuable discussion and contribution to the results presented in this report. We also thank Ville Tulkki (VTT) for reviewing this report.

Finally, we would like to thank the members of the TAG 3.3, especially the SAFER2028 Director Suvi Karvonen and the TAG3.3 chair Antti Poteri for the advice and interest in our projects progress.

Espoo 27.2.2024

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Contents

1. Introduction

1.1 Background

Small Modular Reactors (SMR) are nuclear reactors that are smaller in size and provide typically lower output power than conventional nuclear reactors. SMRs also aim to achieve serial production through modularity. Their designs target inherent safety through inherent and passive features (IAEA, 2022). SMR technologies can be based on conventional Light Water Reactor (LWR) technology or on less prevalent technologies such as high-temperature gas cooled or liquid metal cooled technologies.

As a member of the European Union, Finland is obliged to do its part in meeting the EU's targets on reaching carbon neutrality by 2050. In the National Climate and Energy Strategy the target for Finland to meet its carbon neutrality goal is 2035 (MEAE, 2022a). Due to the low carbon intensity of nuclear power, it has been included in the strategy to meet the targets, especially in heat production, where the share of fossil fuels is still quite large in Finland (Keto, et al., 2024). SMR's are proposed for meeting heat production needs as they can potentially be situated closer to heat distribution systems than large NPPs.

To enable safe deployment of SMR's in Finland, the current National Nuclear Safety and Waste Management Programme (MEAE, 2022b), in addition to previous programmes (MEAE 2018a & MEAE 2018b), includes various research topics on SMR's. This project is a continuation of two projects funded by the previous program. In the first project, SMR Waste Management in Finland (Keto, et al., 2022), SMR waste characteristics and waste management strategies were studied. The 2D reactor physics calculations with Serpent showed that spent nuclear fuel (SNF) from LWRs with different burnups and enrichments caused main differences in its characteristics. Lower burnups lead to lower radioactivity and decay heat of the spent fuel, but it also meant that more fissile material was leftover in the fuel, possibly leading to criticality concerns. Research on the waste management strategies proposed three different strategies; a centralised, decentralised and a hybrid waste management strategy. The study also implied that waste management of non-LWR SNF or alternative disposal methods, such as borehole disposal, would require significant additional research and development effort.

In the second project (Keto, et al., 2023), a preliminary comparison with 2D and 3D reactor physics calculations was conducted. It indicated some differences between the two cases, and thus more detailed calculations were suggested. Such work can be performed with the Serpent – Ants computing sequence, for which the verification work on the Ants micro-depletion mode is underway and supposed to proceed to full-core 3D demonstrations in later 2024. The study also summarized the nuclear energy regulatory framework update ongoing in Finland regarding issues affecting SMR's. It was noted that a separate government Decision in Principle would be needed for SMR SNF storage and disposal facilities, if they would be situated apart from a power plant area. It was also considered that under current legislation it should be possible to transfer a waste management obligation, for example from a power plant operator to a separate waste management organisation, but it has not been carried out in practice yet. Finally, the study also investigated SMR societal engagement issues. It was emphasised that local acceptance of municipalities is vital for storage or disposal site siting. The study also highlighted the need for regional collaboration between cities and other stakeholders early in the SMR plant siting process.

1.2 Recent SMR updates

There has been significant discussion on SMRs in Finland during 2023, and public willingness for increasing nuclear power supply is seemingly at a high level (Energiateollisuus, 2023; Kojo, et al., 2023 a). During the year multiple letters of intent on potential SMR deployment have been signed. Finland's largest electricity producer, Fortum, signed a letter of intent with Rolls-Royce SMR to cooperate on SMR topics (Fortum, 2023), as a part of Fortums two-year investigation on Nuclear Powers future perquisites (Fortum, 2022). Recently, Fortum announced that they would decide by the end of 2024 whether they would be investing in new nuclear power. They stated that as a prerequisite for new investments, governmental subsidies or other arrangements to profit from stable electricity production, are needed to make additional nuclear power capacity economically viable (Lassila, 2024).

The Helsinki-based power company HELEN has also signed a letter of intent with the VTT spin-off Steady Energy to plan a pre-investment agreement on nuclear heat production using the LDR-50 concept (HELEN, 2023). This was followed with another letter of intent between Steady Energy and Kuopion Energia -power company on an option to deploy five of the reactors from the year 2030 onwards (Niemi, 2023). Steady Energy plans to build an operational heating power plant by 2030, and they recently raised 2 M€ in funding for the its development (Manninen, 2023).

Lappeenranta-Lahti University of Technology also signed a letter of intent with Ultra Safe Nuclear Corporation for investigating SMR deployment for research purposes (Manifesto, 2022) already in 2022. While the plans of the power companies are focused on Light-Water Reactors (LWR) for power and electricity production, the Ultra Safe Nuclear Corporation reactor is a High-temperature gas cooled design. The plan is to procure and construct the reactor before 2030 (Schönberg, 2023). While returning spent fuel from a research reactor to its country of origin is possible under current Finnish legislation (Valtioneuvosto, 1987), investigating possible waste management related research needs of non LWR-SMRs is important for the possible deployment of such reactors on a larger scale for commercial purposes.

Siting discussions of SMR power plants have also been started. In addition to the letter of intent with Steady Energy, Kuopion Energia has started the process of identifying possible sites for the reactors. Eleven other Finnish cities, including Lahti, Tampere and Oulu were also involved in a VTT and LUT study on deployment of SMR’s for heat production, out of which seven showed interest in the possibility of siting a pilot plant (Tulkki, et al., 2022). The distance to the nearest SMR plant was however been considered as an issue regarding plant siting. 36% of residents of Helsinki, Vantaa and Espoo would accept a SMR to be sited 10 km away from their residencies, while 20% if the distance is decreased to 2 – 5 km (Kojo, et al., 2023 a). An ongoing regulatory update is aiming to better account for SMR locations closer to urban areas (Tulkki, et al., 2022; STUK, 2023), possibly changing the current Emergency Planning Zone (EPZ) of 5 km to a case-by-case investigation. This became valuid recently, as as a part of the renewal of the Nuclear Energy Act (990/1987), STUK published a new regulation (Radiation and Nuclear Safety Authority Regulation on the Emergency Arrangements of a Nuclear Power Plant, STUK Y/2/2024, valid from 1st of February 2024 onwards) applicable for siting of an SMR in urban environments (STUK, 2024). This regulation includes new definitions for the precautionary action zone and the emergency planning zone for a NPP. Based on this new regulation, the party applying for the licenses to construct and operate a plant shall define for the specific case at hand what kind of protection zones are sufficient for ensuring safety.

2024 has also started with yet another SMR-related letter of intent being signed. This time between Tornio municipality and the steel manufacturer, Outokumpu Europe Oy (Nuutinen-Kallio, 2024). The letter states that if the company obtains a license for an SMR, the city preliminary agrees to zone a plot accordingly.

Interesting developments abroad regarding SMR’s have also been observed throughout 2023. NuScale , which has a design license for their SMR in the U.S., terminated a project to build the first SMR plant in the US. The project was cancelled due to concerns about low subscription rates for the plant's power. (Gardener and Mishra, 2023). Despite the setback, the company is still striving for SMR deployment in the near future and has launched studies to assess possibilities to provide, e.g., process heat for industrial plants. NuScale is also investigating methodology to define an EPZ for SMRs (World Nuclear News, 2022).

The European Commission has committed to continue training, research, innovation and education on safety of SMR’s through a Declaration on “EU Small Modular Reactors 2023”. The European Parliament also expressed its position on SMRs, through adopting a report on them (European Parliament, 2023). The report takes the position that SMRs have the potential to help meet EU greenhouse gas emission reduction targets and to increase energy security in the region. Europe was recognized as a potential market area for the deployment of SMRs. The European Parliament also acknowledges that deep geological repositories are currently the most effective and safest option for spent fuel management from SMR’s.

Furthermore, at COP28, a Declaration to Triple Nuclear Energy output was endorsed by 22 national governments (United Nations, 2023). The need to include nuclear power in achieving carbon neutrality was recognized and thus a committment to triple global nuclear capacity by 2050 was made. Managing spent fuel in a responsible manner, despite not giving more specific issues on the topic.

Despite the high interest for deploying SMR’s in the near future, discussion related to waste management has been less pronounced in news and media. A recent article (Ojalainen, 2024) briefly discussed how SMR waste management could be carried out. Both centralised and decentralised options were mentioned. Interestingly, Fermi Energia, planning to deploy SMR nuclear power in Estonia, announced that they will continue cooperation on Deep Borehole Disposal with the US-based Deep Isolation (Fermi Energia, 2024). As discussed in the previous SMRSiMa and SMRWaMa projects, borehole disposal requires significant R&D efforts. Thus Fermi Energias interest in the methodology might bring the technology closer to reality.

Some interesting articles that have been published recently on SMR waste management. Krall, et al. (2022) studied waste produced in SMR’s. They stated that they would produce more LILW per unit of energy produced, in comparison to conventional NPP’s through i.a. usage of neutron reflectors. They also stated that SNF from SMR’s would not provide additional benefits again in comparison to conventional NPP’s, as the decay heat would be on a comparable level, and in the case of more low-burnup SMR’s have higher concentrations of ^{239}Pu and ^{235}U, leading to criticality issues.

Keto, et al. (2023) indicated that the SF characteristics for LWR SMRs with comparable enrichment and burnups would not have major effects on disposability. It is evident that more research into the disposability of SMR waste must be conducted.

A study by Zohuri, et al. (2023) investigated the strength and weaknesses of more advanced Gen IV reactors and SMRs in relation to closed fuel cycles, where some of the SNF is reprocessed. They stated that feeder-type reactors utilizing spent fuel could increase the sustainability of the nuclear fuel cycle. However, even using such advanced designs some HLW is generated and, therefore, a deep geological repository, or other disposal route, is still required in the end.

Finally, in Finland, as a part of this project, a resident survey regarding SMR waste management has been published by Kojo, et al. (2023 b). Some of it’s implications regarding waste management strategies are discussed in Keto, et al. (2024).

Objectives and methods

The purpose of this report is to continue the research on SMR siting and waste management that has been carried out in the previous SMRWaMa (Keto, et al., 2022) and SMRSiMa (Keto, et al., 2023) projects. The project is split into four work packages, out of which WP1 and WP2 are entirely presented in this report. WP3 is reported in a separate, upcoming report by GTK, and WP4 is partially reported here.

In WP1, Spent fuel characteristics the objective is to coarsely evaluate the impact of the smaller fuel assembly size on the criticality safety requirements in the final repository, discussed in Section 2. Several SMR designs use the same 17 x 17 fuel assembly type as the EPR, but with different axial lengths. Therefore, we assume that the KBS-3 canister designed for EPR spent fuel assemblies - as well as those used in Swedish PWRs – would be a suitable design for the SMR fuel assemblies with adjusted canister length. It has been previously shown that for these large reactor fuel the criticality safety analyses for such a 17 x 17 assembly canister requires the use of burnup credit, i.e. the sufficient subcriticality of the spent fuel can be shown only if the reduced reactivity during the irradiation is taken into account, or credited (Anttila, 2005; Agrenius, 2002; Agrenius, 2010). In this work, we check whether the same requirement applies for smaller assemblies and if so, how much the loading curves (the required minimum discharge burnup as a function of fresh fuel U-235 enrichment) differ from those of the large reactors.

In WP2, Waste Management Strategies and Adaptation of Current Disposal Methods, the objective is to study how LWR SNF compositions affect engineered barriers and other components of a KBS-3 repository design. The impact of accident tolerant fuels is also assessed. WP2 also continues the studies on waste management, especially to understand what the R&D needs and plans of some Finnish stakeholders regarding SMR deployment are. Furthermore, storage considerations are examined and an update on the regulatory changes presented. The WP is carried out as a literature review.

In WP4, Societal Engagement on SMRs and SMR waste management, the aim is to advance our understanding on the societal engagement related to deployment of SMRs for district heating in Finland. LUT focused on studying the public opinion on SMR siting and Nuclear Waste Management Strategies, as well as bringing up insights on stakeholder engagement experiences in Canada, while VTT focused on resident engagement in pre-zoning phase. Based on scoping review of public documents, interviews (3) with representatives of different stakeholders and survey results, VTT and LUT have developed a preliminary roadmap (a living document) for addressing societal engagement issues related to SMRs in district heating. On 12.1.2024 VTT and LUT organized a public webinar entitled “Empowering communities: How to ensure resident engagement when planning SMRs for district heating”.

The results of this report can be used in planning for deployment of SMRs in Finland and in understanding issues related to social engagement on SMR deployment. The waste management aspects of the work can be used to further assess research and development needs as well as informing Finnish decision makers about legislative and regulatory concerns specific to SMR deployment and waste management in.

2. Work Package 1 (WP1) SMR-specific criticality safety considerations

Pauli Juutilainen, Silja Häkkinen, Ville Tulkki (VTT)

2.1 Computational model

Criticality calculations in a final disposal canister configuration were calculated for assemblies representing EPR, a NuScale-like design and LDR-50. The fuel data and irradiation conditions for the first two of them were the same as in an earlier SMRWaMa study (Keto, et al., 2022), whilst the LDR-50 material compositions were based on the LDR Lite benchmark. All calculations were performed with the Serpent Monce Carlo code (Leppänen, et al., 2015) . More accurately, the various EPR assembly models have originally been presented in journal and conference articles, but may not necessarily ever been used as such in the power plants. NuScale assemblies are originally based on the public FSAR data of its old, 160-MW_{th} design, but somewhat modified and complemented within the EU-McSAFER project (NuScale 2020, Valtavirta, et al., 2020). The main specifications for the two NuScale types of assemblies used in the study were

- 4.05 wt-% enriched UO_2 fuel, no Gd rods
- 4.55 wt-% UO_2 fuel with 8 % Gd in 16 rods; the same U-235 enrichment was used in Gd rods too

Additionally, a calculation with 2.6 % enriched NuScale assembly was performed with fresh fuel in the canister configuration. However, only one out of 37 assemblies in the applied NuScale design was planned to utilize this enrichment, the burnup calculations and subsequent calculations over final disposal were performed only with the two above-listed fuel types.

Considering the LDR models, the 2.4 % enriched UO2 fuel is based on the specifications of the LDR Lite benchmark, but also assemblies of 3.0 % and 3.5 % enriched fuel were studied. The latter ones are not based on any official documentation, though fuel with these enrichments were studied earlier containing erbium as burnalble absorber. In all of these, 8 Gd rods with 9 % Gd contents were included in the assemblies.

The reader should note that despite using the names of NuScale and LDR throughout the chapter, the referred fuel and assemly types are not to be understood literally representing these specific designs. They are used to represent models that have been in serious considerations and should provide applicable results for any reactor type with similar features, such as assembly type, core dimension and operating parameters. As mentioned above with EPR, it is possible that none of the studied assemblies will be used as such in these or any other reactor types.

All assemblies were modelled with uniform axial fresh fuel compositions, thus ignoring any lower-enriched end segments that might be part of the designs. All structural elements, such as assembly grids and axial end structures were also ignored. The canister material compositions and dimensions are based on the information provided in the earlier reports (Anttila, 2005; Agrenius, 2010). They have minor differences between each other, but they are assumed to have negligible impact on calculations. Axially, the iron insert length was set to presicely accommodate the active fuel length, which made the canisters somewhat shorter than they would actually be. The canister is fully filled and surrounded by water, representing the limiting case as far as the breached water does not cause changes to the geometry and material compositions. The dimensions of the canister as used in the calculations are presented in Figure 2-1.

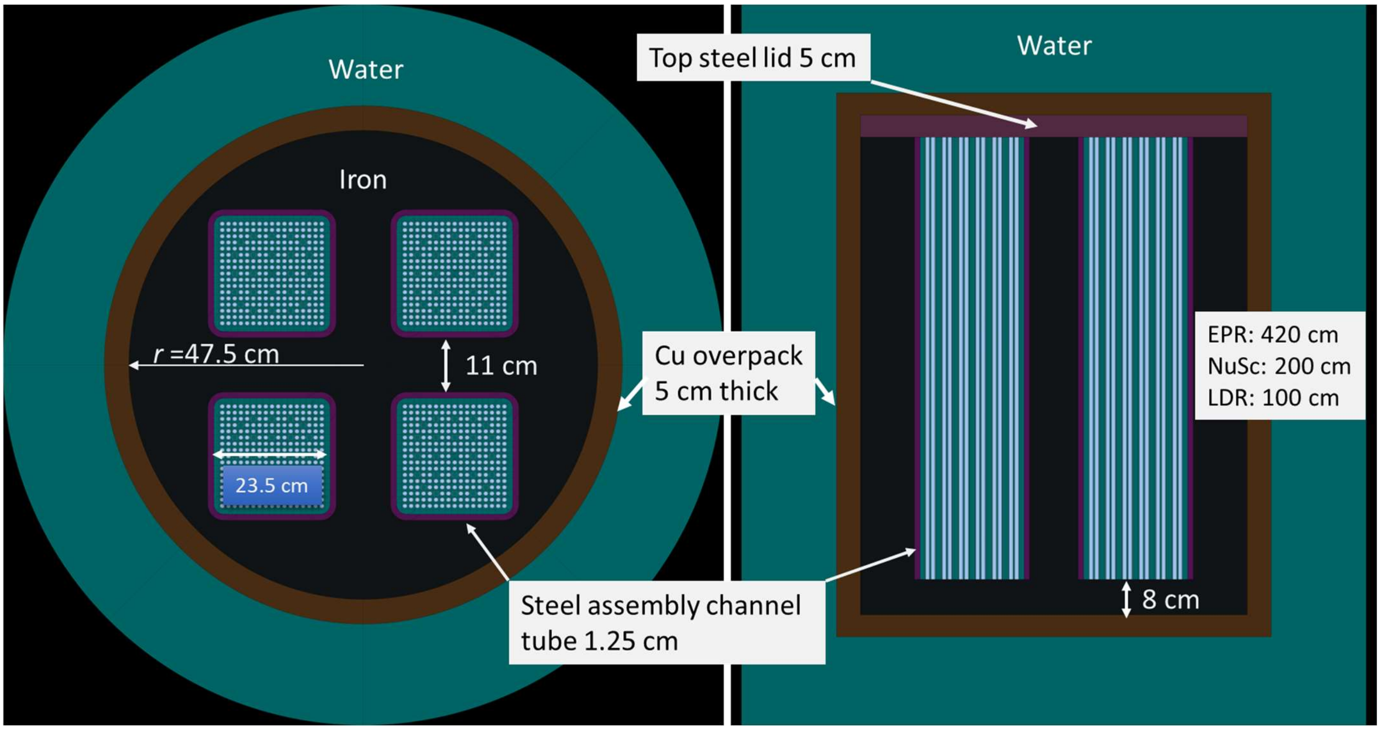

Figure 2-1 The canister geometry as used in the calculations, including the assumed assembly length of various reactor types.

The impact of neutron leakage related to various assembly lengths in the canister was illustrated with comparison calculations between 2D and 3D models, out of which the 2D model is fully presented by the left subfigure in Figure 2-1. All fresh fuel calculations were performed for fuels without gadolinium or any other burnable absorbers, even if Gd was involved in the original design of the assembly.

For burnup calculations, a 3D assembly model was used with reflective radial and black axial boundary conditions, i.e. the assemblies formed infinite lattice radially and any neutrons escaping from the ends leaked for good instantly. Gd rods were present in these calculations according to the original specifications. No control rod usage was involved, which may be a significant element of non-conservatism particularly for LDR. Its applied design does not contain soluble absorber, but active use of control rods is planned, resulting in higher residual fissile contents in nearby fuel rods.

For NuScale assemblies, constant boron concentration of 600 ppm was used throughout the irradiation. Coolant temperature was assumed to be 284°C for NuScale and 105°C for LDR. These are close to the core average temperatures, which adds another non-conservative element. The harder neutron spectrum, encountered in lower water density, adds fissile contents in the spent fuel.

The follow-up calculations over several thousands of years utilized the spent fuel compositions as such, making a slight error with respect to the general requirement in criticality calculations with burnup credit that only a certain set of nuclides can be included in the spent fuel compositions. Fuel in Gd rods, though, was replaced with fresh fuel for the post-irradiation calculations.

With Serpent, the calculations with spent fuel can be performed starting from any and only of the burnup steps. In this study, the burnup steps over the irradiation were (in MWd/kgU or GWd/tU):

NuScale	0.1, 0.2, 0.4, 0.7, 1.5, 3, 5, 7.5, 10, 12.5, 15, 15.5, 17.5, 20, 25, 30, 35, 40, 45, 50
LDR	0.1, 0.2, 0.4, 0.7, 1.0, 1.5, 2.25, 3, 4, 5, 6, 7/7.5, 8.5, 10, 12.5, 15, 15.5, 17.5, 20, 22.5, 25, 27.5 30

The administrative requirement in criticality safety analyses is that

$$k_{calc} + \Delta k_{calc} < 0.95$$

where Δk_{calc} represents all uncertainties related to the calculations. These are mainly outside the scope of the study, but some magnitude for the term can be obtained from (Agrenius, 2010), where the sum of uncertainties for PWRs was evaluated to roughly 0.05 in k_{eff}. The present study contains additional uncertainties due to reasons mentionded above, so we may relatively safely assume that the absolutely highest allowed limit for calculated k_{eff} is 0.90, but it would likely be even lower than that.

2.2 Results

2.2.1 Fresh fuel in canister

First, the canister k_{eff} was calculated for various assembly types in both 2D and 3D models. The results are presented in Table 1. Considering that the sum of the calculated k_{eff} and the evaluated computational margin must not exceed 0.95, it is obvious that for all studied EPR assemblies the fresh fuel assumption is not acceptable, as it is not for NuScale assemblies with enrichment 4.05 % or 4.55 %. Depending on the associated margin, the 2.6 % enriched NuScale assembly, however, might qualify as such. The 2.4 % enriched LDR is also likely to be sufficiently subcritical, but for e.g. the 3.0 % enriched version some burnup credit may be needed. The results also show the significance of 3D modelling for SMR assemblies, assuming no axial stacking: whilst the modelling impact on EPR assemblies is modest ~300 pcm, for NuScale assemblies it is around 1000 pcm and LDR assemblies more than 3000 pcm.

Table 1 Final disposal canister multiplication factors (k_{eff}) for a few fuel assembly types with fresh fuel and no burnable absorbers, calculated with 2D and 3D canister models.

Reactor	U-235 enrichment	Canister k_{eff} 2D	Canister k_{eff} 3D	2D – 3D difference (pcm)
EPR	4.5	1.05975	1.05623	352

EPR	4.0	1.03643	1.03367	276
EPR	3.6	1.01442	1.01172	270
NuScale	4.55	1.06854	1.05808	1046
NuScale	4.05	1.04609	1.03614	995
NuScale	2.6	0.94938	0.92764	942
LDR	2.4	0.91847	0.88782	3065
LDR	3.0	0.97209	0.93979	3231
LDR	3.5	1.00680	0.97355	3325

2.2.2 Burnup profiles

The axial burnup profiles were defined with the help of the released fission energy detector functionality of Serpent, using 5 cm high segments. Examples of the axial burnup profiles defined with such an approach are presented in Figure 2-2 for 3.5 % U-235 enriched LDR fuel at 20 MWd/kgU and 4.05 % enriched NuScale fuel at 25 MWd/kgU. These calculations were run to somewhat lower burnup levels than the assumed corresponding discharge burnups, which may cause higher peaking factors than what would be obtained with higher burnup.

With the 17.5 to 20 MWd/kgU burnup for LDR assemblies, the highest peaking factors were 1.32 … 1.34 and the lowest 0.26 to 0.27. For NuScale fuels at 20 MWd/kgU, the extreme factors were 1.25 and 0.19 for the 4.05 % U-235 enriched fuel and 1.31 and 0.16 for the 4.55 % enriched fuel. The use of completely black axial boundary conditions distorts the profiles as there would, of course, be some neutrons in the axial ends too, increasing the specific power and thus the burnup in the end segments. For comparison, the existing statistics on burnup profiles observed with e.g. Swedish (Agrenius, 2010) and French (IRSN, 2017) commercial PWR spent fuel assemblies show indeed somewhat more flattened behaviour, with the mean of the lowest factors around 0.5 and that of the highest less than 1.1.

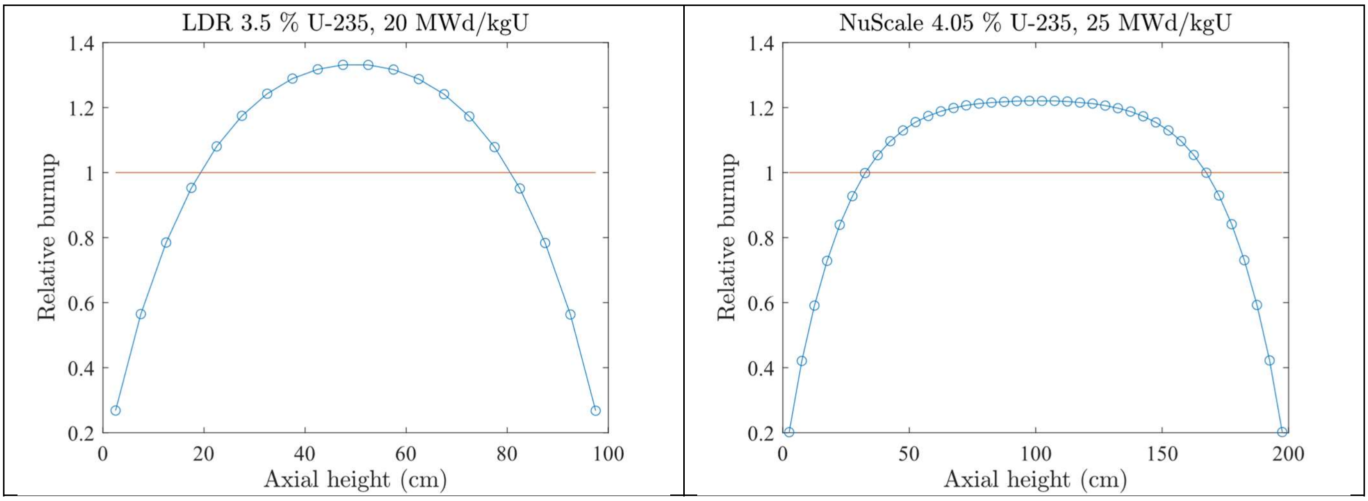

Figure 2-2 Normalized axial burnup profiles of an LDR assembly with 3.5 % enriched fuel at 20 MWd/kgU (left) and NuScale assembly of 4.05 % fuel at 25 MWd/kgU burnup (right).

2.2.3 Post-irradiation criticality calculations

The calculated k_{eff} with spent fuel of NuScale assemblies at various discharge burnups is shown in Figure 2-3. Bearing in mind the computational safety margin, the k_{eff} should stay below 0.90 the whole calculated period. For 4.05 % enriched fuel, the requirement seems to be fulfilled with somewhat high likelihood, if the discharge burnup is at least 20 MWd/kgU. The same discharge burnup is probably too low for 4.55 % enriched fuel, but 25 MWd/kgU could be enough.

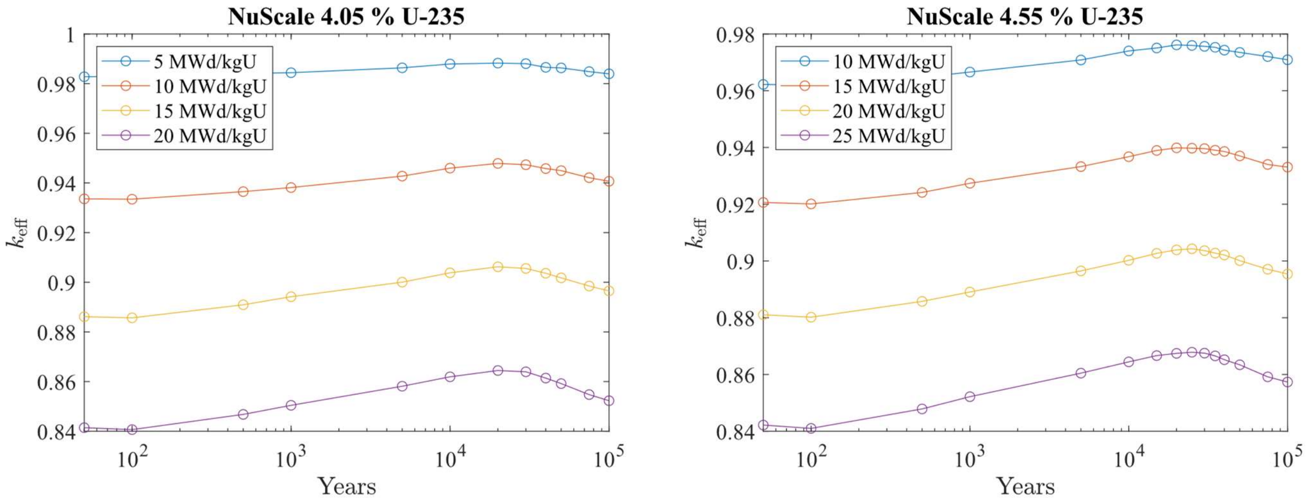

Figure 2-3 Calculated keff for canister with spent NuScale fuel, originally 4.05 % enriched (left) and 4.55 % enriched (right).

For 4.05 % enriched fuel with burnup 15 MWd/kgU, the highest calculated k_{eff} was 0.9062 observed 20,000 years after the discharge. For the 20 MWd/kgU fuel, the maximum k_{eff} = 0.8645 was also found at 20,000 years.

With 4.55 % enriched fuel, the peak k_{eff} was observed at 25,000 years after discharge for both 20 and 25 MWd/kgU discharge burnup, being 0.9043 and 0.8678, respectively

Considering the LDR fuel types, the one with 2.4 % was seen to comply with the criticality safety requirements with fresh fuel assumption, so we concentrate on the calculated assemblies higher enrichment. For the spent 3.0 % and 3.5 % enriched LDR fuel assemblies, the associated k_{eff} curves with various discharge burnup values are presented in Figure 2-4.

For 3.0 % enriched fuel, the highest calculated k_{eff} for 5 MWd/kgU discharge burnup was observed to be 0.8863 at 10,000 years and 0.8601 at the same time for the 7.5 MWd/kgU fuel. Thus, it strongly depends on the combined uncertainty term, whether either of these is sufficient to meet the criteria. For the 10 MWd/kgU fuel, the highest k_{eff} was 0.8328, so it should be enough with rather high confidence.

When the 3.5 % enriched fuel is considered, the 7 MWd/kgU discharge burnup very likely is not sufficient, causing the max. k_{eff} = 0.9045 at 15,000 years after discharge. Irradiation to 10 MWd/kgU might be enough, yielding the highest k_{eff} to be 0.8756. Increasing the discharge burnup to 12.5. MWd/kgU would decrease the highest keff to 0.8500.

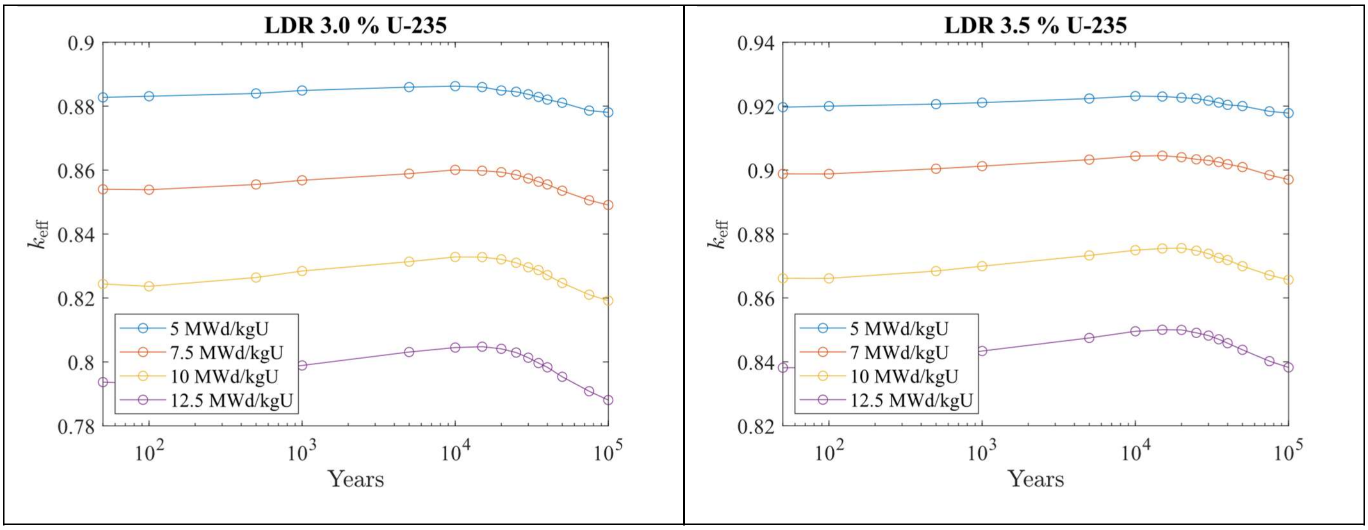

Figure 2-4 The calculated k_{eff} in the assumed final repository conditions for 3.0 % (left) and 3.5 % (right) enriched LDR fuel following various discharge burnup values

2.3 Notes

In summary, the analyses above suggest that the planned 2.4 % U-235 fuel for LDR-50 would not necessarily require burnup credit for its final disposal criticality safety studies, assuming a KBS-3 type disposal canister and provided that the modelling simplifications do not make the analysis significantly non-conservative. For all other studied assembly designs burnup credit seems to be needed. Coarse minimum burnup requirements were forked, but it will require much more detailed computational models and uncertainty analyses to confirm or reject them. These include, but are not limited to, more realistic axial boundary conditions, evaluations concerning the impact of control rod usage, axial coolant density variations, removal/substitution of the non-credited nuclides of the spent fuel for actinides only or actinides and fission products credit, etc.

In addition to methods improving accuracy of the fuel depletion calculation over the irradiation and crediting only the accepted group of nuclides, a major modelling issue is related to the corrosion effects. In this study, the geometry and material compositions were assumed stable, but if water manages to breach into the canister, it will cause notable impact on them in the long term. It naturally affects the neutronics properties of the canister, or its residuals, and in certain sequences of events, may increase the risk of criticality (e.g. Agrenius & Spahiu, 2016).

3. Work package 2 (WP2) Waste Management Strategies and Adaptation of Current Disposal Methods

Sami Naumer, Paula Keto, Timothy Schatz (VTT)

This work package builds upon the research on waste management strategies carried out in Keto, et al. (2022) and Keto, et al. (2023). In the latter, multiple different LWR-designs were compared from a technical perspective. In this report one aim is to discuss with some Finnish stakeholders to learn more details on their future SMR plans as a way to direct further studies, such as neutronics calculations, to relevant SMR designs. Results of the discussions with the stakeholders are presented in the next subsection.

This section also indicates that numerous possible options exist with respect to SMR SF management from reactor discharge to disposal (Section 3.2) and investigates how different spent characteristics could affect disposability (Section 3.3). The latter includes a summary on accident tolerant fuels and a discussion on how different fuel properties need to be accounted for in the KBS-3 disposal system.

In Keto, et al. (2020), it was recommended that SMR intermediate storage aspects would be studied further at a later stage. These issues were discussed in Keto, et al. (2024), but some further details on the topic are presented here in Section 3.4, including storage related regulations and how they could affect SMRs.

3.1 Finnish stakeholder’s SMR plans

In Keto, et al. (2023), technical designs of six LWR-SMR designs were compared. They were partially selected based on their inclusion in a previous SMR-related project in Finland (Häkkinen,et al., 2023), but also an advanced design (NuScale) and a design by KAERI were included. The reactor designs had differences such as different reactor sizes and output powers, burnups and fuel cycle lengths. These differences could lead to some differences in nuclear management practices. These differences stem for example from lower decay heats allowing closer disposal of spent fuel canisters in a KBS-3-type repository and shorter assemblies causing differences in canister dimensions. Different vendors also have different plans on how waste from their power plants will be managed. For example, some vendors opt in for wet storage of spent fuel, while others for dry storage (IAEA, 2022).

As was discussed in Section 1, there have been multiple press releases on ongoing SMR-plans ongoing in Finland. In most of them, the information available on SMR designs is on a general level, and plans regarding Radioactive Waste Management (RWM) practically omitted. As different SMR designs, especially if non-LWR SMRs would be selected, can have an effect on RWM practices, possible R&D needs will be affected by eventual vendor selection by operators. Furthermore, some RWM-related questions, such as siting considerations need to be investigated before SMR’s can be deployed, no matter which vendor is selected.

In this section the aim is to discuss SMR-related plans with selected Finnish stakeholders, especially on SMR vendor selection and waste management plans. For the stakeholders, both current operators of NPP’s, Fortum and TVO were selected. In addition, University of Lappeenranta was included, due to their plans on deploying a non-LWR SMR as a research reactor.

Questions for the three stakeholders were prepared. They were related to SMR needs and possible vendors, SMR locations, RWM strategies and identified R&D needs of the stakeholders. Questions to all three stakeholders were on the same topics, but tailored based on available information of their plans. The questions were also provided to them in different ways. A meeting with Fortum was held, during which the questions were presented and answered orally. A memo of the meeting was sent to them after the meeting to enable Fortum to comment whether the answers were documented in a correct way. For University of Lappeenranta, the questions were provided and answered through email. Finally, for TVO, a list of questions was sent and answered in prior to a meeting. During the meeting, the topics were further discussed. The list of the questions and the respective answers for Fortum is available in Appendix A, for

University of Lappeenranta in Appendix B, and for TVO in Appendix C. Next the responses are summarized and discussed.

Out of the three, only LUT has indicated a specific vendor for SMR deployment. A helium-cooled micro reactor, the MMR by UltraSafe Nuclear Corporation (IAEA, 2022) is being investigated at a pre-feasibility study phase for usage as a research reactor. The reactor is fuelled once per 20 years and has a thermal output power of 15 MW. Fortum did not specify a vendor but had limited their case-study to only LWR-SMRs. In a recent news article, Fortum had stated, that SMRs they consider would have an output power of 300–500 MW (Lassila, 2024). In TVO's crude plans, low-enrichment LWRs with a minimum output power of 50 MW have been considered. They also indicated that accident-tolerant TRISO fuel (ATF discussed in Section 3.3.1) could be used.

Fortum and LUT have stated possible SMR-sites on a municipal level. In-line Fortum's with press releases (Discussed in Section 1), Tornio and Loviisa were mentioned as sites. LUT stated that candidates for an SMR site have been identified, but as of now Lappeenranta city on a general level has been publicly stated (Hyvärinen, 2023). TVO did not specify any sites but have investigated siting requirements on a general level. They also discussed the emergency planning zones of SMRs and how the regulatory update could change them from a pre-defined radius to a case-by-case evaluation.

LUT did not specify any waste management plans or strategies but have identified options to do so. For Fortum, using the current LILW repository in Loviisa and the Eurajoki repository for SNF was one option, but they also are investigating other options. TVO did not have final disposal sites selected but emphasized that the current license holders cannot be forced into taking in new radioactive waste from outside the amounts agreed in the decision in principle. With this in mind, they however stated that technically extending TVO's current LILW cavern could be possible.

Both TVO and Fortum saw local-level societal acceptability as an important topic. Fortum was interested in what residents of potential SMR sites think about final disposal of radioactive waste within their municipality. Fortum was also interested in a resident survey for Tornio region, one of the possible sites for an SMR. TVO saw that transportation of nuclear fuel is not a large societal issue, and SNF transport might as well not be problematic, due to it being commonplace already elsewhere in Europe. This could allow also for a centralised radioactive waste management strategy.

TVO saw modularity and serial production related topics as the key research need for SMR's. In their opinion, concept reviews by the regulatory authority could make deployment of SMR's easier. This way a power plant design could be licensed, and amount of repeated analysis decreased. A specific SMR design could for example have all site-related requirements listed, making site-selection easier. LUT identified economic optimisation of product portfolio as their key research need but did not provide details. Fortum were interested if there would be differences in SNF originating from SMR's in comparison to currently operated NPPs in Finland. Currently, they have not found significant differences with comparable burnups and enrichments, but stated that if there would be differences, it would be important to understand how they affect disposability of the radioactive waste.

3.2 Backend Considerations for SF Management

Spent fuel management is an issue requiring attention regardless of which SMR technology may be chosen for energy production purposes. It is important to identify approaches available for SF management, their advantages and disadvantages, as well as which are best suited to meet national needs and context. Figure 3-1 below presents a preliminary flow diagram showing some of the possible options for the domestic handling and disposal of SMR SF from the reactor to disposal including related infrastructure and transport projections. Primary considerations are whether separate interim storage facilities (wet/dry, on-site/off-site) are to be used both before and after disposal packaging (encapsulation) of the SF and whether this packaging will take place at the disposal facility location or elsewhere. Figure 3-1 also makes clear that as the number of separate site locations increases, so to do the number of movements of SF from one place to another. It can also be assumed that as the number of fuel handling sites and journeys increase, the potential for public interaction may increase as well. In order to make the most informed choices when selecting a strategy for SMR SF management, it will be necessary to assess not only all the technical alternatives available and their economic costs, but also legislative aspects and social acceptability.

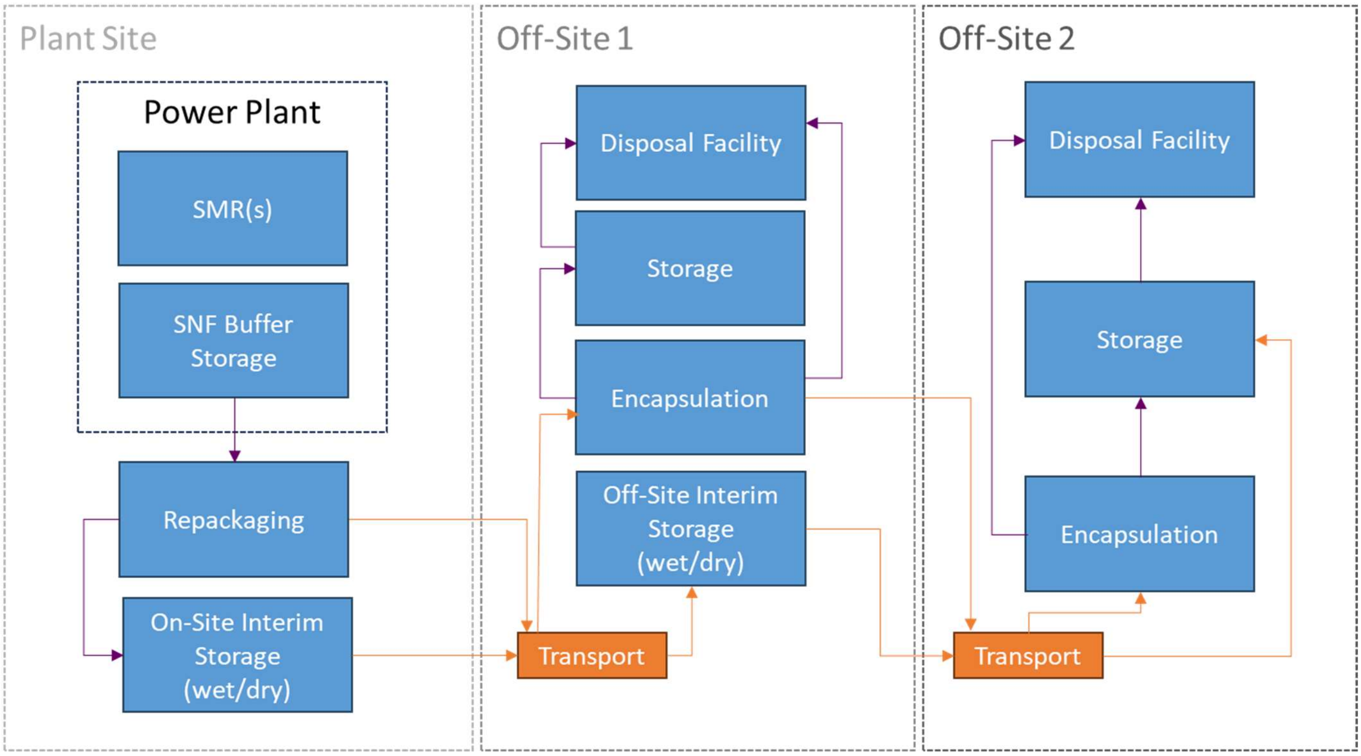

Figure 3-1. Flow diagram showing possible SMR SF management options from reactor discharge to disposal. This diagram is only indicative and is not meant to provide an exhaustive list of all possible options and permutations, only that numerous possible options exist.

3.3 Applicability of KBS-3 to spent SMR fuel and ATFs

As indicated by Fortum in Section 3.1, it is important to understand whether different Spent Nuclear Fuels (SNF) are disposable in the currently used KBS-3 disposal system without drastic design changes. In this study, the spent fuel originating from LWR-SMR's with comparable burnups and enrichment to conventional nuclear plants and spent Accident Tolerant Fuels (ATF) are discussed. The results were first discussed in Keto, et al. (2024), but some further discussion is provided here. While assessing the effect of the changes to KBS-3 is outside the study of this phase of SMRSiMa-project, the discussion is useful for determining key research needs for the future. These identified needs can for example be addressed in future phases of this project, or for example in the upcoming EURAD-2 -project.

3.3.1 Accident tolerant fuels in final disposal

Disposability of ATFs was discussed in Keto, et al. (2024). In here a summary and further discussion on the topic is provided. Traditionally, zirconium alloy cladding has been used in light-water reactors with UO_2 fuel. After the accident at the Japanese Fukushima Daiichii NPP, there has been a lot of discussion on its role in nuclear accidents and on how to improve the safety of the LWR-NPPs during severe accidents (OECD 2018, IAEA 2014). During an accident scenario, where the temperature of the reactor core increases significantly, the UO_2-Zr alloy fuel rod burst at ~800°C leading to release of volatile fission products (Zinkle et al. 2014). In addition, attempts to cool the core during the accident can lead to an oxidation reaction between steam and a large amount of Zr alloy resulting in production of heat and hydrogen gas (Zinkle et al. 2014). This can then lead to increase of pressure and/or explosions which have the ability to damage NPP containment structures (Zinkle et al. 2014).

In order to prevent this from happening, use of accident tolerant fuels ATFs has been discussed internationally (OECD 2018, IAEA 2014). In addition, new EU policies require use of ATFs in future NPP's so that: "*The project fully applies the best-available technology and from 2025 accident-tolerant fuel. The technology is certified and approved by the national safety regulator*" (Commission delegated regulation (EU) 2022/1214 of 9 March 2022 amending Delegated Regulation (EU) 2021/2139 as regards economic activities in certain energy sectors and Delegated Regulation (EU) 2021/2178 as regards specific public disclosures for those economic activities, 4.27 technical screening criteria 2). What this means on a practical level in a specific country is currently under discussion and it seems clear that national certifications will not be performed by 2025.

By definition accident tolerant fuels (ATFs) are not a single solution, but number of different technologies that are able to safety of nuclear power plants during normal operation and different accident scenarios (OECD 2019, Zinkle et al. 2014). These options can be classified intofollowing main categories (Zinkle et al. 2014, OECD 2019):

- Coated or improved of Zr alloy cladding.
- Replacement of the Zr alloy cladding with oxidant resistant cladding material, e.g. with advanced steels (FeCrAl), refractory metals (lined Mo-alloy cladding) or SiC/SiC composite cladding.
- Replacement of other materials in reactor core including control rods and channel boxes.
- Use of new fuel forms including improved UO_2, high-density fuels and microencapsulated fuels.
- Different combination of options stated above.

Due to different technical readiness levels of these alternatives, the first and most likely option for future Finnish SMRs can be assumed to be coated Zr alloys (Keto, et al., 2024). According OECD (2019), optimal cladding material should reduce corrosion and hydrogen production during normal operation, improve physical and mechanical properties (also at high temperature) and reduce oxidation and hydrogen production during accidents. Considering waste management, the new cladding materials should preferably be transportable, have good long-term storage behaviour, provide low tritium penetration and have very little effect on repository design or reprocessing (OECD 2019). However, it is likely that not all of these targeted properties can be achieved with a new cladding material.

The material alternatives for coating a Zr alloy cladding include:

- Metallic coatings with either single or multiple layers consisting e.g. of Cr, Cr-Al, FeCrAl and Cr/FeCrAl.
- Ceramic coatings consisting either of single or multi-layer nitrides (for example CrN, TiN, TiAlN) or MAX phases that are ternary cabides and nitrides with poperties typical both for metals and ceramics (Ghosh & Harmikar 2012) including for example Ti_2AlC, Cr_2AlC, Zr_2AlC, Zr_2SiC.

According to experimental data, it seems that corrosion in LWR conditions is reduced e.g. with majority of metallic Cr-coatings (Cr, Cr-Al, FeCrAl) and in some ceramic coatings (CrN, TiN) coating, while Al in some ceramic coating materials can dissolve in water (OECD 2019). Preliminary estimation is that this would be the case also in deep geological repository conditions, but this should be verified with further studies. If the dissolution rate of the disposed ATF differs from conventional UO_2 fuel, this would affect the release and transport of radionuclides (IAEA, 2003). The effect of this on the transport of radionuclides to the surface must be studied and the safety case must show that the dose on the surface is below regulatory limits. If the release of nuclides differs from conventional fuel, this can affect performance targets of the engineered barriers.

Furthermore, most of the coatings result in production of less hydrogen within the operation and storage, which is also useful from final disposal point of view. However, the role of N within the coatings requires further studies from long-term safety perspective, since irradiated N is known to be able to produce ^{14}C in LWR conditions (Yim & Caron 2006).

As a summary, the role of applying ATF technology for LWR-NPPs requires further studies considering their impact at final disposal. It should be noted that the KBS-3 system is designed for zirconium-alloy cladded fuels (Posiva-SKB, 2017) and to ensure disposability of ATF, at least following should be considered:

- Effect of dissolution in coating/cladding in water, also in groundwater with typically higher salinity levels.
- Effect on source terms used for the cladding in safety case calculations (Haavisto 2014).
- Risks linked to formation of hydrogen and mobile nuclides (such as 14-C) in repository conditions.
- Effect on effect on radionuclide releases and doses.

3.3.2 Compatibility of KBS-3 for the disposal of SMR fuel

In Keto et al. (2022), it was concluded that the main differences of SMR spent fuel compared to the traditional NPP spent fuel are linked to cases, where the burnup is lower, leading to lower radioactivity, and lower decay heat. However, SMR spent fuel can also be linked to more fissile material left in the fuel which could lead to criticality concerns. In the Swedish ANItA program, it was pointed out that the SMR fuel differs from the traditional NPP fuel by factors such as core sizes, fuel heights, core power and flow densities, operating pressure, fuel cycle lengths, and fuel burnups (Håkansson 2024).

As a summary, Keto et al. (2022) concluded that KBS-3 could be used as a basis for the disposal of SMR spent fuel from the LW-SMRs, taking account of the differences in the fuel properties, especially with new fuel types as ATFs. Factors to take account of when examining the suitability in more detail include fuel assembly dimensions, fuel configuration, fission product inventory, cooling times and decay heat generation, physical and chemical form and fissionable material content.

The KBS-3 concept consists of a natural geological barrier and engineered barrier systems (EBS), mainly the canister, clay barriers (buffer and backfill), plugs, and closure structures. In the KBS-3 concept the spent fuel is emplaced in canisters which are disposed in the deposition holes. The buffer in the deposition holes fills the space between the disposal canisters and the backfill is used to seal the deposition tunnels where the deposition holes are drilled. The KBS-3 contains two alternatives, one with vertical deposition holes (KBS-3V) and one with horizontal deposition holes (KBS-3H).

The main safety functions of the KBS-3 repository are to isolate the repository and the encapsulated spent nuclear fuel from the surface environment and to contain radionuclides and to retain and retard their dispersion to the environment.The KBS-3 concept is based on UO_2 fuel pellets and the encapsulation of the fuel pellets in zirconium-alloy based cladding. Studies for the release rate of radionuclides are based on dissolution experiments on UO_2. Also, the corrosion rates of the canister materials are linked to the design of the fuel assemblies. (Posiva-SKB, 2017.) The radionuclide release from spent fuel is affected by factors such as (Posiva 2012):

- Radionuclide inventory, affected by the irradiation history of the fuel
- Redox and chemical conditions inside the canister
- The mass transport of water in and outside the canister

To further investigate the suitability of KBS-3 disposal concept and its clay barriers for the disposal of SMR spent fuel, effects of the spent fuel properties on the desired clay barrier properties were reviewed.

Canister

In the KBS-3 concept, the spent fuel is emplaced in copper canisters which are gas- and water-tight containers with load-bearing inserts. Safety functions of the canister include (Posiva-SKB 2017):

- withstand corrosion
- withstand mechanical loads
- maintain sub-criticality

Resistance to corrosion and mechanical loads are taken account of in the design of the canister but they are also linked to the safety functions of the surrounding EBS, especially buffer which should protect the canister from detrimental effects such as the flowing groundwater to reach the canister. The corrosion of the canister can be caused by factors both from the outside and inside of the canister. The mechanical loads to the canister either isostatic loads (especially during glaciation) or loads during rock shear.

The safety function that is most closely related to the properties of the spent fuel is maintaining sub-criticality. Posiva-SKB (2017) states design requirements for the reactivity $k_{eff} < 0.95$ for the canister filled with water and reactivity $k_{eff} < 0.98$ for altered geometries and materials acting to increase the reactivity. To prevent the criticality, the canister should remain water-tight and the properties of the spent fuel (e.g. burnup and enrichment) should be taken into account in the canister and insert design. Fuel enrichment, irradiation history and discharge burnup will be different in many SMR designs and thus should be accounted for in planning the canister loading. This is also indicated by the preliminary estimations of different fuel's k_{eff} values were presented in Section 2. They showed that at least with NuScale and LDR fuel enriched above 4%, burnup credit needs to be accounted for if a KBS-3 EPR canister design would be used. Usage of any canister and spent fuel combination needs to be however evaluated separately and more in depth. Among the safety functions listed above, properties such as thermal conductivity of the canister and other EBS together with spent fuel properties are other important factors in the canister design.

Clay barriers

The buffer and the backfill consist of bentonite which is a natural swelling clay. According to the safety cases for the KBS-3 disposal concept and similar to the canister, these barriers have multiple safety functions, performance targets, and design requirements. Safety functions of the buffer include (Posiva-SKB 2017):

- limit advective transfer
- limit microbial activity
- filter colloids
- protect the canister from detrimental mechanical loads (rock shear load, pressure load)
- resist transformation
- keep canister in position
- retain sufficient mass over life cycle

For the backfill, the safety functions include (Posiva-SKB 2017):

- Keep the buffer in place
- limit advective mass transfer

The clay barriers shall also consist of materials with chemically favourable conditions in the repository (Posiva-SKB 2017).

Many of the safety functions are linked to protection of the canister from corrosion, which would eventually lead to a breach of the canister and leakage of radionuclides. Safety functions to prevent the corrosion of the canisters are especially limiting advective transfer with corroding substances and limiting microbial activity in the buffer (Posiva-SKB 2017). These safety functions are mostly linked to performance targets of the buffer having a sufficient swelling pressure and low enough hydraulic conductivity.

The buffer shall also protect the canister from mechanical loads. Rock shear movements could have detrimental effects on the canister if the buffer would not deform during a rock shear. This property of the buffer is ensured by limiting the buffer strength and stiffness, mainly by the designed dry density of the buffer. Too high swelling pressure would also damage the canister which is why the swelling capacity potential of the buffer should be limited by the dry density of the buffer. The swelling capacity is also linked to the types and amounts of swelling minerals in the buffer material.

Filtering of colloids is linked to the possibility of radionuclides attaching to clay-based colloids being transported to the surrounding environment. The buffer should have a low enough pore size or high enough dry density to prevent this transportation and to filter the colloids.

The safety function which is more closely linked to the spent fuel properties is resisting buffer transformation. The main property of the buffer to resist its transformation is the buffer temperature. Both high and low temperatures (< 0°C) affect the buffer properties but only the high temperatures are considered in the early phase of disposal with high decay heat of the spent fuel. Temperature can have many effects on the bentonite, groundwater, and rock. In a high temperature (> 100°C), the main effects could be mineral transformations in the buffer bentonite reducing its swelling capacity. To prevent such high temperatures in the buffer, the decay heat from the spent fuel and canister should be limited taking account of the thermal conductivity properties of the buffer and rock as well as the distance between the canisters in the disposal facility. Properties of the buffer bentonite linked to the thermal conductivity and transmission of heat from the canister to the surrounding rock are the bentonite type, dry density and water content or saturation degree. Higher dry density and saturation degree lead to higher thermal conductivity.

The buffer shall have sufficient gas transport properties which is linked to the potential of the spent fuel to produce gas, especially hydrogen. Possibility of the gas production by the spent fuel or corrosion processes can lead to a build-up of gas pressure in the buffer. With buffer performance targets of low enough swelling pressure or dry density, the buffer has sufficient gas transport properties for the gas to escape and the pressure to drop. Possibilities for the gas production from the SMR spent fuel is still unknown and should be studied.

As a conclusion, the safety functions and performance targets for the clay barriers in the KBS-3 disposal concept lead to design requirements for dry density which is linked to swelling pressure, hydraulic conductivity, and mechanical properties. High dry density corresponding to high swelling pressure and low hydraulic conductivity is beneficial for heat transfer, limiting radionuclide transport and microbial activity, and filtering colloids. With higher dry density, more clay barrier mass can be installed reducing the detrimental effects of possible mass losses during the repository lifetime. However, an upper limit to the dry density and the swelling pressure should defined to protect the canister from mechanical loads and also to enable gas transport properties in the buffer.

Plugs and closure structures

Plugs are installed at the front end of deposition tunnels to keep the backfill at its place during the operational phase and before the closure structures have been installed. Unlike the plugs, the closure structures such as shafts, boreholes, tunnels etc., have safety functions, including (Posiva-SKB 2017):

- reduce the risk of unintentional intrusion
- avoid the formation of new preferential flow paths
- keep the deposition tunnel backfill in place

Together with other EBS and host rock, properties of plugs and closure structures affect the analysis on the radionuclide migration in a case of a breached canister. In such scenario, properties of the spent fuel could affect the design of plugs and closure structures to ensure that dose limits on the surface are met

3.4 SMR waste storage

In this section, interim storage of Spent Nuclear Fuel in described, the regulatory framework affecting it summarized and key considerations regarding SMR SNF storage discussed.

After spent nuclear fuel (SNF) is removed from a nuclear reactor, it is typically cooled in a water-filled pool. During this time, the radioactivity of the SNF decreases along with its decay heat power. When the fuel has cooled sufficiently, it is typically moved into a longer-term interim storage. In the interim storage, the radioactivity and decay heat power of the SNF continue to decrease, while it waits for final disposal, for example in a deep geological repository. The length of the interim storage period varies. It can be indefinitely long in countries, where a final disposal solution is not yet available, whereas in countries where final disposal is planned to be started soon, the radioactivity and heat might need to be reach a low-enough threshold. In interim storage, the SNF is typically stored either in wet storage in pools, or in casks in dry storage. As wet storage is an active and relatively expensive process, and given the absence of permanent geological disposal facilities, interim dry storage is evolving as an attractive alternative.

3.4.1 Regulatory Considerations for storage

The Nuclear Energy Act (Valtioneuvosto, 1987) and the Nuclear Energy Decree define the safety requirements and dose limits for the production of nuclear energy in Finland. Regulations Y1 (STUK, 2018 a), Y2 (STUK, 2018 b), Y3 (STUK, 2020 a) and Y4 (STUK, 2018 c) of the Radiation and Nuclear Safety Authority in Finland (Säteilyturvakeskus, STUK in Finnish) provide a framework for which nuclear power plants and nuclear waste storage facilities must operate in Finland. More detailed guidance for interim storage facilities and practices is given in YVL D.3. (STUK, 2020 b). Other regulations, such as those related to construction and occupational health and safety, also apply for storage cites.

The Nuclear Energy Act (Valtioneuvosto, 1987) states that a separate decision in principle (DIP) is needed for an interim storage facility, if the site is not at the NPP. For SMR's, or any size plant for that matter, this would mean in practice that either local interim storage is used at each SMR plant, or a separate DIP would be needed for a centralised storage facility.

The general principles of SNF storage consist of confinement of radioactive material, radiation protection, sufficient cooling and maintaining subcriticality (STUK, 2020 b). Safety functions on SNF handling, storage pools and cooling, confinement and isolation of radioactive materials, criticality safety, and monitoring are defined there to meet the safety principles. In general, the safety functions should be met with inherent safety features and passive systems. In addition, redundancy, separation, and defence in depth principles must be followed in the design of the storage facilities.

The storage guidelines apply for both wet and dry storage (STUK, 2020 b). This point is important, since some SMR-LWR vendors are planning to use dry storage for the interim storage of SNF generated in their reactors (Keto, et al., 2024). Therefore, the dry storage option should be regulatory compliant if it is to be used.

The guidelines could have an effect regarding centralised and de-centralised interim storage of SNF. The guide (STUK, 2020 b) states that transfer routes should be kept short and lifts low. This indicates that SMR SNF storage at the nuclear power plant should be preferred, preferably close or at the reactor building. In a centralised waste management strategy this would not necessarily be the case. On the other hand, the guideline also states that spent fuel storages must have all systems that allow handling of damaged or leaking fuel bundles or assemblies. Thus, such systems would be needed even on very small SMR plants with limited SNF storage volumes, increasing the cost of constructing the storage facilities. For a fleet of small SMR power plants, a centralised option could be a more economical option. However, if the same systems used to transfer the SNF from the storage to transport casks can be used for the purpose, these issues become less relevant.

Next, on the spent fuel pools and cooling, they require that the amount of SNF generating heat should be cooled in all situations in the spent fuel pools. This should also be fulfilled, even if the external power or water supply is disrupted. In the initial cooling phase after SNF removal from the reactor, the decay heat might be sufficient to significantly heat the water, leading to decreased cooling of the fuel. Depending on the case, reserve systems maintaining the water levels in the pool should be used or passive cooling by air (if this alternative would be sufficient considering decay heat of the SNF).

The regulation (STUK, 2020 b) also gives regulations on maintenance and condition monitoring. They state that the storage conditions must be so that the condition of the SNF and its storage facilities does not significantly decrease over time. For wet storage, best practices in the Nordic region already exist, but as stated by Keto, et al. (2024), dry storage has not been conducted in the region. Thus, it should be ensured that it can be carried out in such a way, that the regulation is met in the Nordic climate conditions. Nevertheless, maintenance SMR interim storages would probably be conducted in similar manner as in conventional nuclear power plants. However, some designs, such as a high-temperature gas-cooled reactor StarCore (IAEA, 2022) are planned to be automated or remotely operated. In such designs, maintenance-related regulations would still need to be met requiring regular maintenance of any storage facilities on the site (STUK, 2019).

3.4.2 Practical storage considerations

As discussed in the previous subsection, some LWR-SMR vendors are planning to use dry storage for interim storage. This option has not previously been used for interim SNF storage purposes in the Nordic region (Keto, et al. 2024).

The U.S. Nuclear Regulatory Commission (NRC, 2017) gives an overview on dry cask storage methodology. As a summary, a cylindrical dry cask is submerged in the spent fuel cooling pool in a reactor building. Spent fuel is moved from the pool to the cask underwater. After the cask has been filled, it is removed from the pool and dried. It is then filled with an inert gas to prevent the fuel cladding from corroding. The filled and sealed cask are then moved into a storage facility. The benefits of dry storage include passive cooling from air, reduced risk of fuel cladding corrosion, and the ability to scale up storage space incrementally. Dry storage also allows for longer storage periods than that afforded by wet storage. The downsides of it include a high price on the storage casks, difficulties in fuel monitoring and the need to disposal for LILW originating from the casks. The SNF needs to nevertheless be cooled in a cooling pool after it has been removed from the reactor. This time can be longer for dry cask storage than for interim storage in a separate pool due to the fuel having to be cooled enough that the passive cooling of a dry canister is sufficient. This potentially requires a larger initial cooling tank.

Dry casks can be generally divided into three categories. Single-purpose casks are only used for storage of the SNF on the nuclear power plant site. Dual-purpose casks are used both for storage and transport, while multi-purpose casks could, possibly, be used for disposal as well (NRC, 2006). The designs of single- and dual-purpose casks do not necessarily differ, as the purpose depends on licensing (NRC, 2006). The benefit of using a dual-purpose system is that the fuel does not need to be repackaged for transport (NWTRB, 2010).

The design and construction requirements of casks for the dry storage of SNF include containment of radioactive material under expected mechanical loads, providing adequate radiation shielding, maintaining subcriticality and achieving efficient heat dissipation. The most typical cask designs are the welded canister systems and the bolted cask systems (NRC, 2017). In the former, spent fuel bundles or assemblies are inserted into a metallic canister, somewhat like the KBS-3 copper canister. The canister is welded shut and then inserted into a separate overpack, consisting of concrete or steel, acting as a radiation shield. In the latter, the fuel assemblies are inserted directly into a thick metallic cask. A lid is fastened with bolts directly to the cask, hence the name. The casks also usually have handles installed, so that they can be moved around or transported longer distances in the case of the dual-purpose casks. Both designs have a fuel basket inside, which ensures that the inserted assemblies remain in their designed position. Together with sufficient time for the radioactivity to decay and solid neutron absorbers maintain the fuel subcritical. The casks are also designed so that they can be cooled conductively; heat is conducted from fuel to the cask surface, from where it is dissipated to the atmosphere (NRC, 2017). The closed casks can be stored either outdoors or in indoor facilities. In the latter, sufficient ventilation in all conditions must be maintained to ensure cooling of the casks.

Dry storage is commonplace and its safety has been demonstrated thoroughly (i.a. NRC, 2006; NWTRB, 2010; IAEA, 2020; Botch, et al., 2013). However in Sweden and Finland interim storage has been carried out in wet storage (Keto, et al., 2024). The region has cold winters, where temperatures drop below freezing point of water, and rainfall is typical in the fall. These would presumably be the main challenges for outdoor dry storage in the region. Poe and Wise (1998) and Chopra et al. (2014) state that slow degradation in extreme weather conditions must be addressed to ensure safe long-term storage. Especially welds of the welded canister systems should be monitored over time. They also state that freezing and thawing cycles could lead into significant degradation of the canisters consisting of concrete. Capillary water in concrete can freeze near the surface leading into cracks in the material. These cracks could lead into the failure of the canister with extended storage periods, if they are not maintained. If SMR's using dry cask storage for interim storage would be deployed in Finland, it must be ensured that the canisters would withstand the environmental effects, especially the freeze-thaw cycles.

International best practices for possible dry cask storage of SMR fuel in Finland could be studied from countries with similar climates. In Canada, SNF originating from their currently operational power plants is stored at each plant separately. After the initial cooling in pools, the fuel is transferred into dry cask storage (CNSC, 2020) The storage facilities on different power plants differ. On the former Douglas Point NPP fuel was stored in casks outdoors. In Gentilly NPP sealed steel cylinders are emplaced in concrete structures, housing 20 cylinders each. The concrete structures themselves are stored outdoors. NPP's operated by Ontario Power Generation use concrete containers stored in indoor facilities. In their review they state that in their storage facilities, the fuel can safely be stored for a century. Similar practices could also be applied in Finland. Especially indoor storage would remove the concrete degradation due to freeze-thaw cycles.

In other European countries practices also vary. In Germany, interim storage is conducted both on on-cite facilities and also in centralised facilities (BMU, 2020), both in indoor storage. In the United Kingdom interim storage is being carried out in indoor facilities (ONR, 2017)

4. Work package 4 (WP4) Societal engagement on SMRs and SMR waste management

The aim of WP4 Societal Engagement on SMRs and SMR waste management was to advance understanding on the societal engagement related to deployment of SMRs in Finland. The work consisted of two tasks: Task 1: Public opinion on SMR siting and Nuclear Waste Management Strategies (LUT) and Task 2: Resident engagement in pre-zoning phase (VTT).

4.1 SMR insights from Canada

Markku Lehtonen (Universitat Pompeu Fabra, Barcelona, Spain)

As a part of LUT tasks in SMRSiMa project in 2023, specifically “Public opinion on SMR siting and Nuclear Waste Management Strategies”, Markku Lehtonen conducted a research fieldwork visit to Canada,10 April – 7 May 2023. During the visit, he also attended the Reuters SMR and advanced reactor conference in Atlanta, US (1-2, May 2023). Lehtonen met and interviewed 23 academic and non-academic experts, professional and stakeholders in Montreal, Vancouver, Ottawa, Regina, Saskatoon, Toronto, and Atlanta.

Canada has 19 commercially operating nuclear reactors, of the Canadian home-grown CANDU pressurised heavy-water design. All but one of the reactors are located in Ontario. The share of nuclear power in the electricity mix is about 15% nationwide, but over 50% in Ontario, and about 38% in New Brunswick. The other provinces and territories do not currently operating nuclear power plants. Nuclear energy is regulated at the federal level, but the responsibility for energy policy is in the hands of the provincial governments.

The Canadian nuclear community seems confident that the political demand and public acceptance for nuclear is there, both for SMRs and large nuclear power plants (NPPs). A message repeated by many informants was that “all eyes are on Canada”. Thanks to its elaborate and advanced plans and policy frameworks, strong political leadership and near-consensus, and the well-maintained nuclear supply chain, Canada would be uniquely positioned to lead the expected nuclear and SMR renaissance. Indeed one of the key observations from this year’s visit was that especially in Canada, SMRs are increasingly seen as a stepping stone back to the construction of large NPPs.

4.1.1 Canadian collaborative SMR policy for decarbonisation

The federal government established, in 2021, the objective of reducing GHG emissions by 40% below 2005 levels by 2030, and net-zero emissions by 2050. Given the expected electricity demand increase, the generation capacity should increase by a factor of 2.2 to 3.4 by 2050 (CCI 2022, 9-10). These objectives underpin the country’s far-developed SMR-development policies. These have included the multistakeholder processes resulting in the elaboration of an SMR roadmap (2018), an SMR action plan (2020) , a feasibility study and an SMR strategic plan prepared by the utilities of the four provinces (Ontario, New Brunswick, Saskatchewan, and Alberta) currently interested in SMRs, an SMR Leadership Table, as well as a number of other studies, parliamentary hearings and reports.

The policy foresees development along three “streams”: 1) Grid-level SMRs for quick deployment, relying on the existing light-water technologies; 2) Advanced SMRs mainly for industrial heat, but also to foster technological innovation and competence-building through the establishment of nuclear-sector competence hubs; and 3) micro-SMRs for remote communities and for resource-extracting industries, especially in the country’s northern areas.

- **Ontario** Power Generation (OPG) plans to build a first-of-a-kind GE Hitachi BWRX-300 light-water reactor, on its Darlington nuclear site, with expected completion in 2029. In July 2023, OPG announced that the construction of three additional reactors of the same design will follow.

- **New Brunswick**'s provincial government has provided funding for the development of advanced SMRs: the ARC-100 sodium-cooled fast reactor, the Moltex SSR-W high-temperature reactor, and the Moltex Waste-to-Stable-Salt reactor (WATSS), to be deployed at the Point Lepreau site currently hosting the province's only NPP.
- **Saskatchewan** currently has no operating NPPs but has long experience of uranium mining. The provincial power utility (SaskPower) waits for experience from the BWRX-300 first-of-a-kind project in Ontario before deciding whether to build one in Saskatchewan, in the early 2030s. If the experience is conclusive, SaskPower plans to build four BWRX-300, to decarbonise its grid, according to the decarbonisation objectives established for the provinces at the federal level.
- **Alberta** is considering SMRs as a means to decarbonise its oil, gas, and mining industries. The province has recently agreed on collaboration with SMR vendors, to explore the potential of designs such as ARC-100, X-Energy's Xe-100, Terrestrial Energy, and the Korean SMART design.

4.1.2 Funding for SMR development

The federal government has introduced funding and investment tax credits for SMRs, through the Canada Infrastructure Bank (CIB), the Strategic Innovation Fund (SIF), the Enabling Small Modular Reactors Program. It has also provided support for the development of the supply chains. The amount of funding remains relatively modest, reaching (in the April 2022 budget) a total of CAD 120.6 million, over a period of five years. The 2023 budget (Freeland, 2023) included further funding, of which the most noteworthy the CAD 1.3 billion over six years for improving the efficiency of assessments for major project, in collaboration between the Impact Assessment Agency, the Canada Energy Regulator, the Canadian Nuclear Safety Commission (CNSC), and ten other federal departments. CNSC is indeed committed to reforming the licensing arrangements so as to facilitate and expedite SMR licensing. The reform plans include a revision (or abandonment) of the conventional ways of calculating safety zones. Also the provincial governments have allocated funding to support SMR development and deployment.

4.1.3 Licensing

None of the SMR designs under consideration in Canada has yet received a licence. However, 11 designs are either undergoing or have completed a voluntary Pre-Licensing Vendor Design Review (VDR). Remarkably, while Canada has a long and unique history in developing and successfully operating its domestic CANDU heavy-water reactors, no CANDU-based SMR design is among the leading SMR candidates.

4.1.4 Siting and citizen participation challenges: the "Indigenous issue"

Natural Resources Canada (NRCan) is the main coordinator of SMR development and deployment. NRCan also chairs the multistakeholder SMR Leadership Table, which includes as members also the SMR Indigenous Advisory Council, yet most members come from inside the nuclear sector. The relations with the Indigenous communities are indeed a crucial issue shaping SMR deployment, especially for the plans to deploy micro-SMRs to replace diesel generators in remote communities. However, also many of the SMRs planned for grid-scale and industrial purposes would be sited in or near indigenous communities. The government has a legal duty to consult these communities in decision-making on projects that might "adversely impact the indigenous communities. Unlike the highly autonomous provinces, the indigenous communities rely on the federal government in almost all areas of their activity. Due to bad experiences of authoritarian decision-making in the past (e.g. on uranium mining), especially the older generations of indigenous communities are suspicious of nuclear power. While the government and industry underline their commitment to community engagement, many of my informants expressed doubts about the genuineness of this commitment. The matters are further complicated by the fact that 1) views on the desirability of SMRs vary widely both between and the indigenous communities, and 2) the utilities are actively seeking to collaborate with (and recruit) community leaders with a favourable view on SMRs, to help increase acceptance. The diversity of views also underscores the difficulty faced by the government

– which has the obligation to consult – in establishing whether a consensus and community consent for a project has been reached. Matters are not made easier by the fact that the socioeconomic benefits (jobs, economic multiplier effects, etc.) from hosting an SMR are likely to be far more modest than from large NPPs.

4.2 Helsinki metropolitan area and Tampere residents' opinions on a possible small nuclear reactor and nuclear waste management[1]

Matti Kojo, Niina Kiviluoma, Sarah Tornberg, Anni Vainio (LUT), Markku Lehtonen (LUT and Universitat Pompeu Fabra, Barcelona, Spain), Tapio Litmanen, Mika Kari (University of Jyväskylä)

T4.1 Research questions were 1) how do the opinions on public participation and 2) trust in key actors differ between the residents who support and those who oppose small nuclear power, and the answer to this was searched by using data from a resident survey.

The survey was sent to the residents of Helsinki, Espoo, Vantaa, and Tampere, to ask their opinions on a possible small modular reactor (SMR) in their municipality, including questions about themes such as nuclear waste management (NWM) and public participation. The survey was conducted by Innolink's web-based survey for consumer panel in November and December 2022, and was answered by 2014 Finnish-speaking residents aged 18-75. Of the respondents, 46.9% were male and 51.4% female, 1% were other genders, while 1.1% wished not to disclose their gender. The margin of error was 2.1%.

4.2.1 The attitudes towards a possible SMR

The residents were asked how they would react to the introduction of SMR in their home municipality. More than a half (55%) of all respondents responded positively, 23% responded neither positively nor negatively, and 22% responded negatively (Figure 4-1). However, the attitudes diverged significantly between men and women, with 74% of men and only 38% of women holding a positive attitude towards SMRs. Only 11% of men but as many as 33% of women would oppose the introduction of an SMR in their own municipality. In all four cities the majority of the respondents supported the introduction of small nuclear power in their municipalities, with men holding clearly more favourable views than women.

[1] This This section is based on these publications: Kojo, M., Litmanen, T., Kiviluoma, N., & Kari, M. Mitkä periaatteet ohjaavat mahdollisten pienydinvoimaloiden ydinjätehuoltoa? Suurten kaupunkien asukkaat kannattavat keskittämistä. ATS Ydintekniikka 4(52), 30-34, 2023.
Kojo, M., Kiviluoma, N., Lehtonen, M., Kari, M., Litmanen, T., & Tornberg, S.: "Residents' opinions on the options for managing nuclear waste from SMRs: The case of the Helsinki metropolitan area in Finland", The International Conference on Management of Spent Fuel from Nuclear Power Reactors: Meeting the Moment, Vienna, Austria, 10–14 June 2024. Topic: 5. Disposal of SNF, HLW and other waste forms in Deep Geological Repositories (DGR)

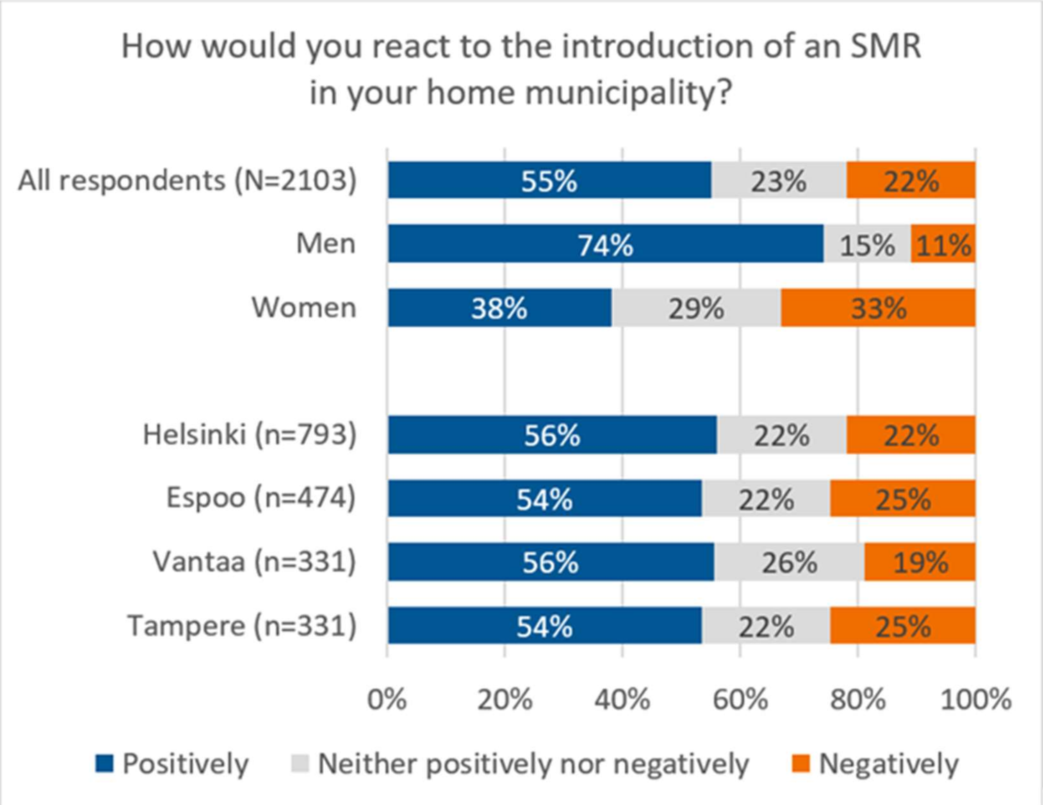

Figure 4-1. Residents' opinions on question "How would you react to the introduction of an SMR in your home municipality?"

4.2.2 Trust in key players involved in the planning and decision-making regarding small nuclear power plants

The residents were asked "to what extent do you trust the following entities in the planning and decision-making regarding small nuclear power plants?"

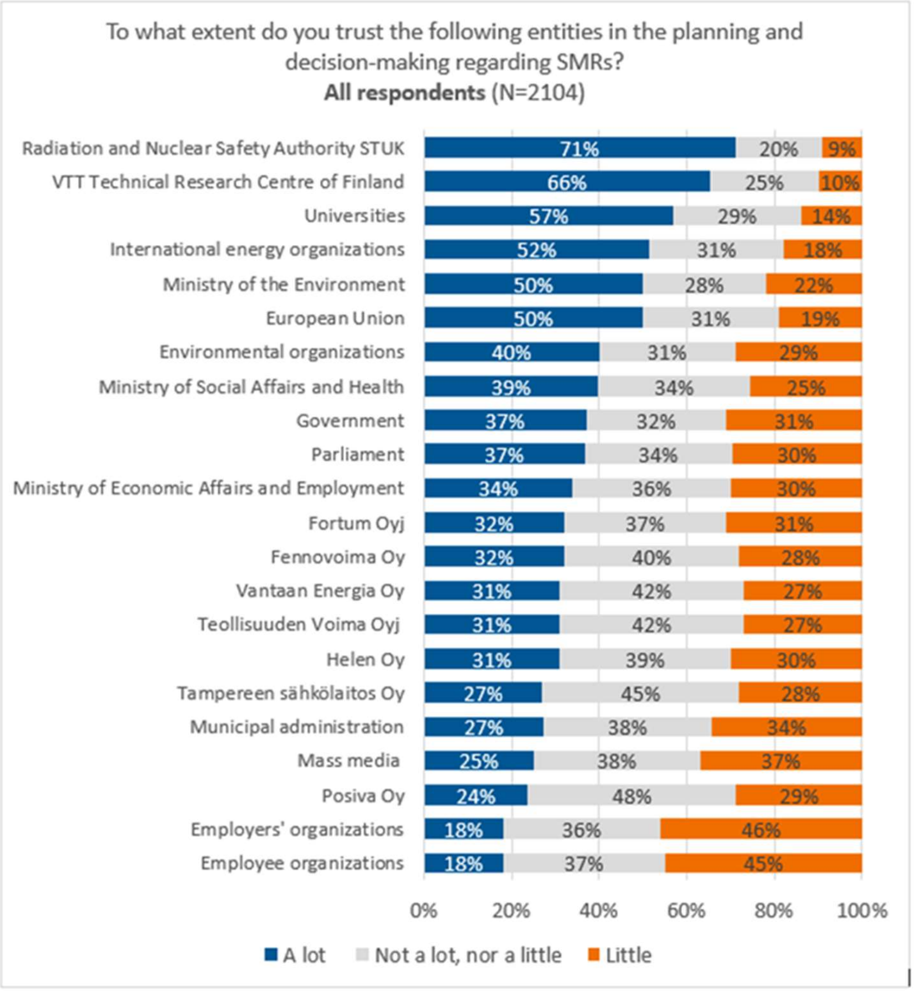

Figure 4-2. All respondents' views on the question "to what extent do you trust the following entities in the planning and decision-making regarding small nuclear power plants?" (N = 2104)

As shown in Figure 4-2, the Radiation and Nuclear Safety Authority (STUK), Technical Research Centre of Finland VTT, and the universities were the most trusted key actors among all respondents. These remained amongst the most trusted entities when compared amongst SMR supporters (Figure 4-3), opponents (Figure 4-4), and those who neither support nor oppose SMRs (Figure 4-5).

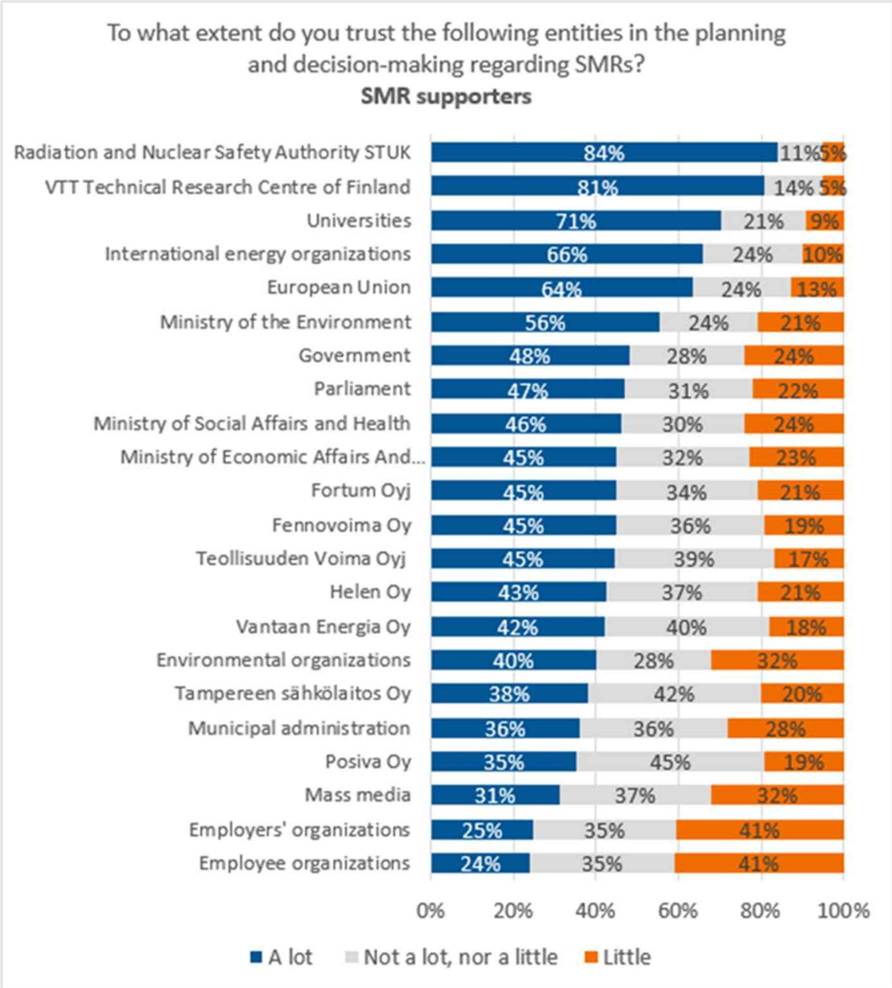

Figure 4-3. Views of those who support the idea of having an SMR in their municipality on the question "to what extent do you trust the following entities in the planning and decision-making regarding small nuclear power plants?"

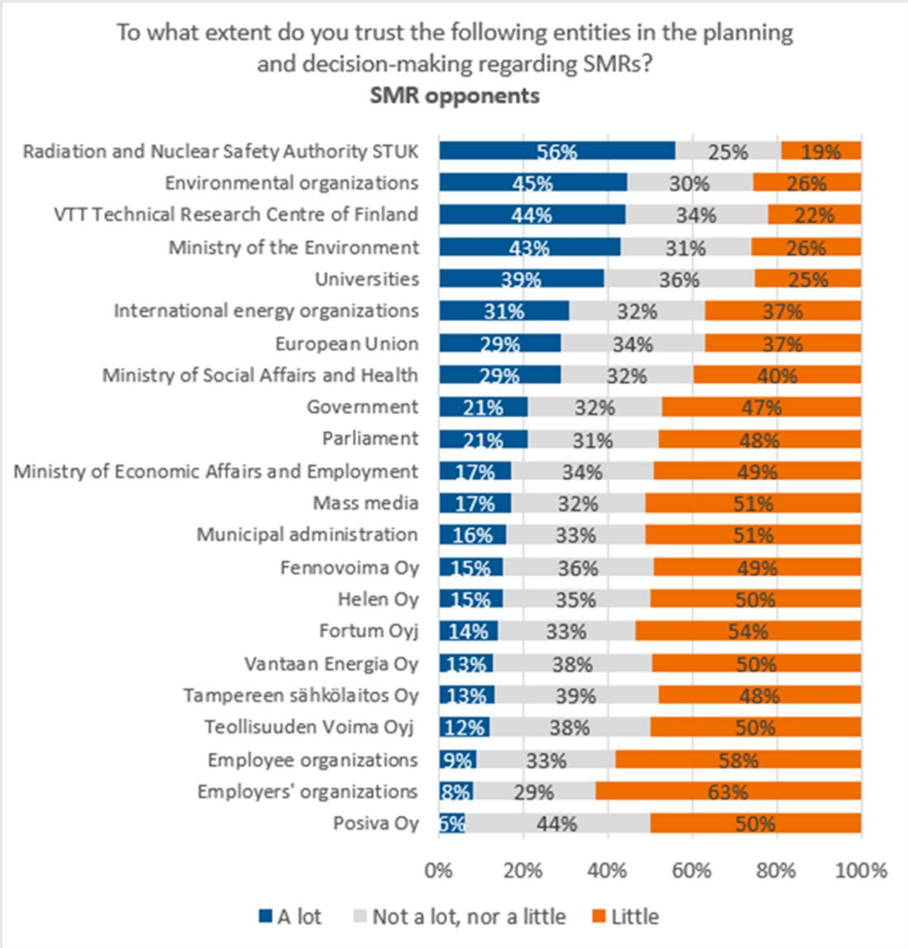

Figure 4-4. Views of those who oppose the idea of having an SMR in their municipality on the question "to what extent do you trust the following entities in the planning and decision-making regarding small nuclear power plants?"

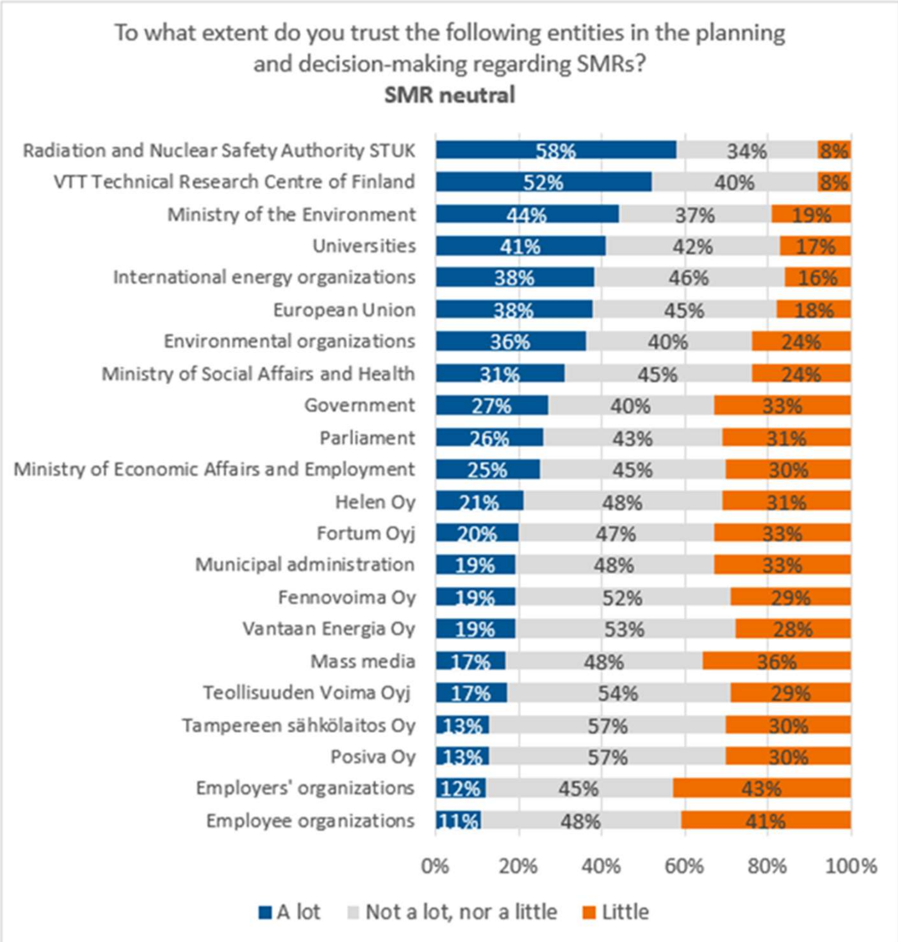

Figure 4-5. Views of those who neither support nor oppose the idea of having an SMR in their municipality on the question "to what extent do you trust the following entities in the planning and decision-making regarding small nuclear power plants?"

The Ministry of Economic Affairs and Employment was moderately trusted by SMR supporters (45 %), while SMR opponents and those being neither in favour nor against SMRs did not find the ministry very trustworthy.

Notably, the nuclear waste management company Posiva was not found to be a trusted entity actor: merely 35% of SMR supporters and 6% of the SMR opponents trusted the company. However, amongst all respondents, including the supporters and opponents of SMRs, more than 40% expressed no opinion on Posiva's trustworthiness. Among the SMR neutral respondents, 57% had no view on whether or not Posiva was trustworthy. This could be due to Posiva being poorly known among respondents. By contrast, STUK is an authority well known by the general public. Power companies were not considered highly trusted. However, the fact that many respondents expressed neither trust nor mistrust towards Tampereen sähkölaitos Oy and Vantaan Energia Oy can be partly explained by the fact that all respondents and not only the residents of these municipalities were asked about their trust in these local actors.

Trust in mass media appeared low in all of the four groups, with SMR supporters having highest (31%) trust in media. It should be noted that different media outlets, such as newspapers and broadcasting companies were not specified in the survey, which could explain low trust in media actors (see Finnish Energy 2023, 43).

A notable difference between SMR supporters and opponents appeared in the general level of trust. SMR supporters appear (Figure 4-3) to have higher trust than SMR opponents in the key actors. In a similar manner, SMR opponents (Figure 4-4) consistently mistrusted most of the key actors. Among those who neither supported nor opposed the possibility of hosting an SMR in their municipality (Figure 4-5), STUK and VTT were considered the most trustworthy.

4.2.3 Public participation and communication

The residents were asked about how they would like to participate in planning a possible SMR and how the municipality and the SMR company should communicate on the plans. The vast majority (87%) of the respondents agreed with the statement “If a small nuclear power plant is planned in my municipality, the residents must be informed about the project” (Figure 4-6). Of those supporting SMRs, 89% agreed with this statement, while 87% of the SMR opponents agreed. Of the SMR opponents, 75% agreed that the residents should have the opportunity to participate in the collaborative planning of a possible SMR, whereas 62% of the SMR supporters agreed with this statement. Of those who opposed SMRs, 71% agreed with the statement “If a small nuclear power plant is planned in my municipality, a consultative municipal referendum must be organised.” More than half of the SMR supporters and opponents (66% and 67%, respectively) agreed that the city council must have the right to approve or reject the project, implying support for a municipal veto (Figure 4-6).

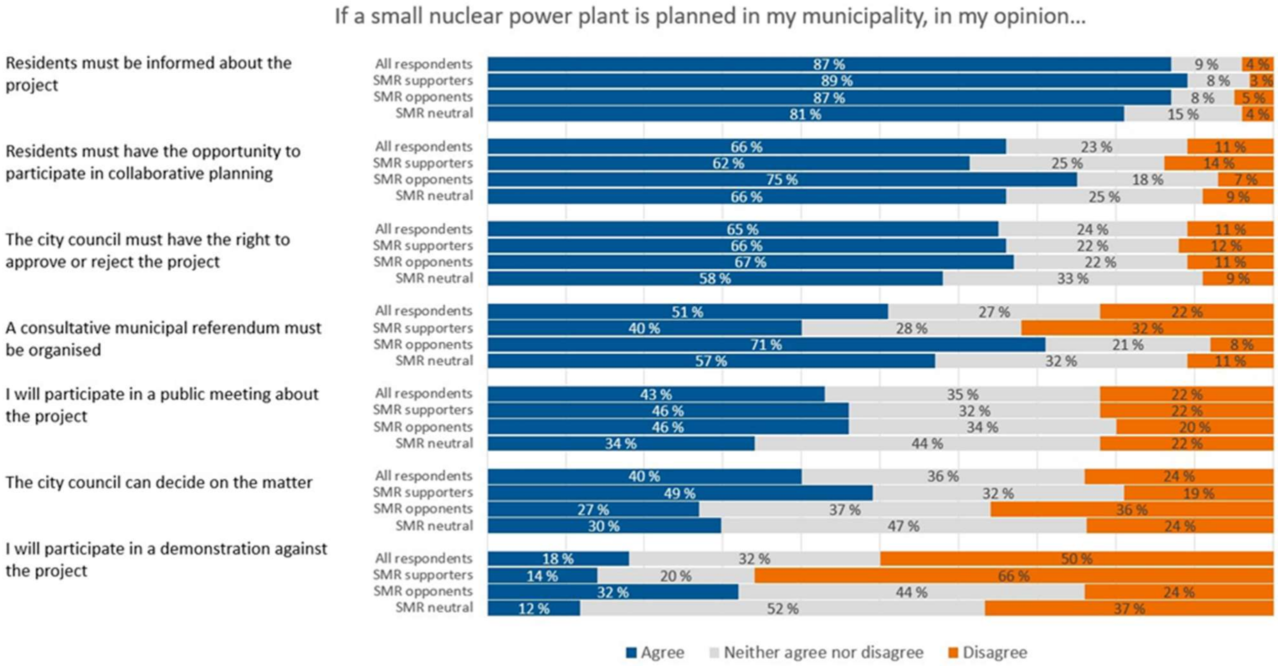

Figure 4-6. Views on statements regarding public participation and communication, among those who suppoer and oppose the idea of hosting an SMR in their municipality

4.2.4 Distance from a possible SMR

When considering how close to their own home the respondents would accept a possible SMR, the most popular (31%) option was at a distance of more than 10 kilometres (Figure 6-7). In total, 41 % of all respondents would accept an SMR within either 10 km or more than 10 km away from their home. All in all, men would generally accept an SMR closer to their residence than women, with 13% of men accepting an SMR within a distance of 0,5 kilometres, and 17% within a 5 kilometre range from their home. Only 3% of the women would accept an SMR within a distance of 0,5 kilometres, whereas 10% would accept one within a distance of 5 kilometres. The clear differences between men and women therefore appeared also on the question of distance from home.

An earlier resident survey, collected in 2021, also inquired residents' views on the acceptable distance of a possible SMR from their home, yet the questions and answer options were slightly different (Kojo et al. 2023, Kojo et al. 2024) (Figure 4-7).

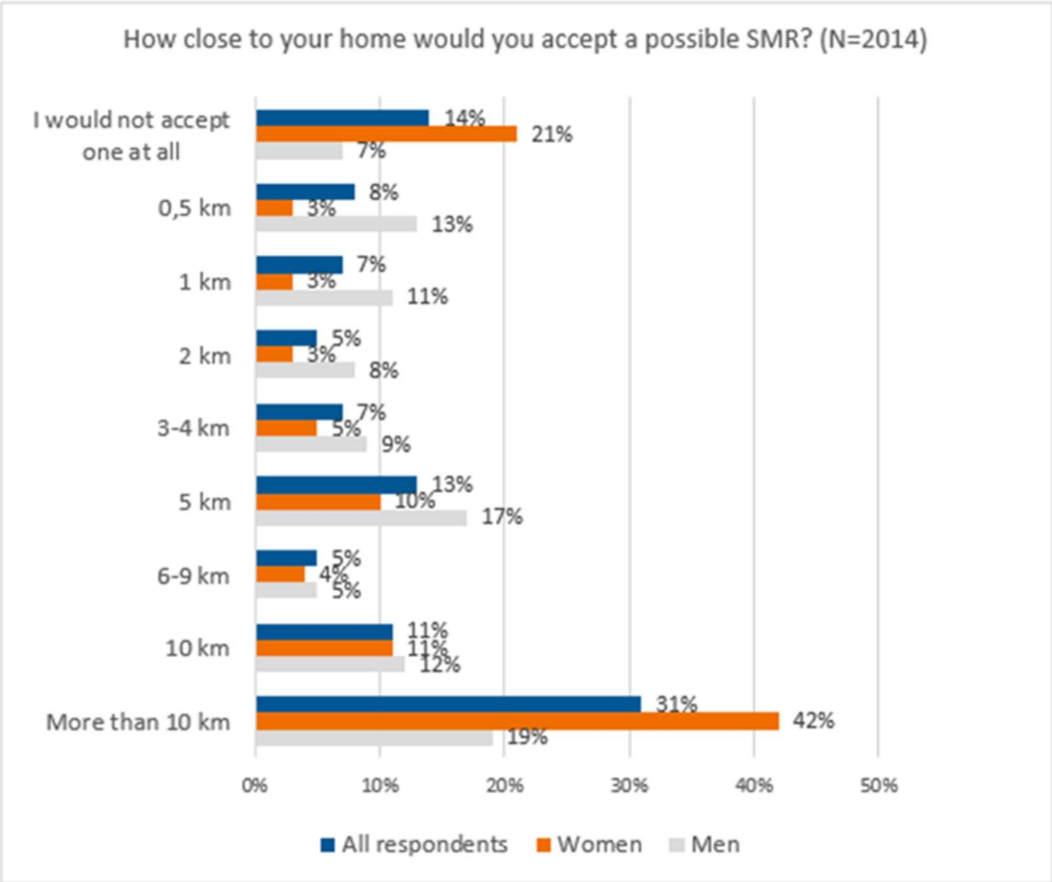

Figure 4-7. Residents' opinions on how close to their home they would accept a possible SMR. All respondents, men, women

4.2.5 What are the residents' opinions on alternative strategies for the management of SNF from possible SMRs in urban areas?

The preferred option for the management of spent nuclear fuel has been, from the mid-1990s, final disposal in a deep geological repository in Finland, with the waste producers carrying the responsibility for the planning, implementation, and costs. Until the early 1990s, Finland participated in the international efforts to close the nuclear fuel cycle. The Nuclear Energy Act forbids the import and export of nuclear waste, with the exception was the spent fuel from the FiR 1 research reactor, which was returned in 2021 to the United States. As the discussion on the possible introduction of SMRs in Finland gathers speed, there is a growing need to think about the principles for the management of nuclear waste that SMRs would produce. The timing is opportune, because the reform of the Nuclear Energy Act is underway. The possible introduction of SMRs in various regions of the country can lead to a situation in which decentralised nuclear power generation results in decentralised NWM. This will happen if the key actors fail to agree on a centralised solution. The companies would most likely strive for voluntary cooperation in the final disposal of SNF, if for no other than cost reasons, but as past experience has shown, this is not necessarily possible, even if the government supports cooperation between the involved companies. Public opinion is an important aspect to be considered in the elaboration of an agreement on the organisational principles for NWM.

When asked about opinions on the statement ”Nuclear waste from small nuclear power plants can be safely disposed of in the Finnish bedrock,” 41% of the residents agreed and 27% disagreed (Figure 4-8) About a third (32%) neither agreed nor disagreed with the statement.

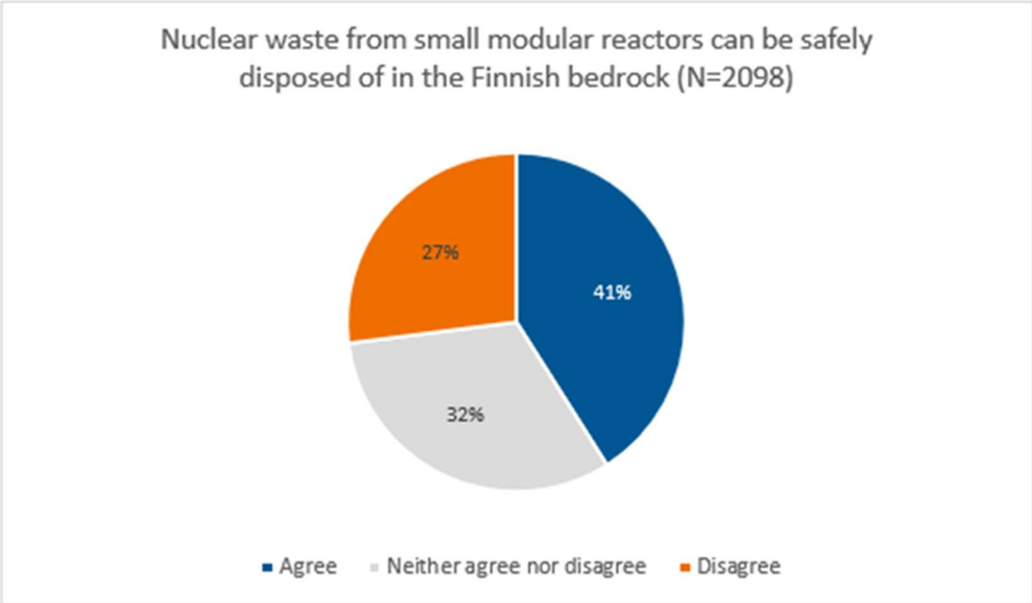

Figure 4-8. All respondents' opinions on the statement "nuclear waste from small nuclear power plants can be safely disposed of in the Finnish bedrock." (N=2098)

As shown in Figure 4-9, the results of the 2022 resident survey show contrasting answers to the question on the principles of NWM. On the one hand, the majority (58%) of the respondents favour a centralised solution. On the other hand, the respondents and especially women emphasise the moral obligation of an SMR municipality to also take its responsibility by disposing of the nuclear waste within its borders. (Figure 4-9).

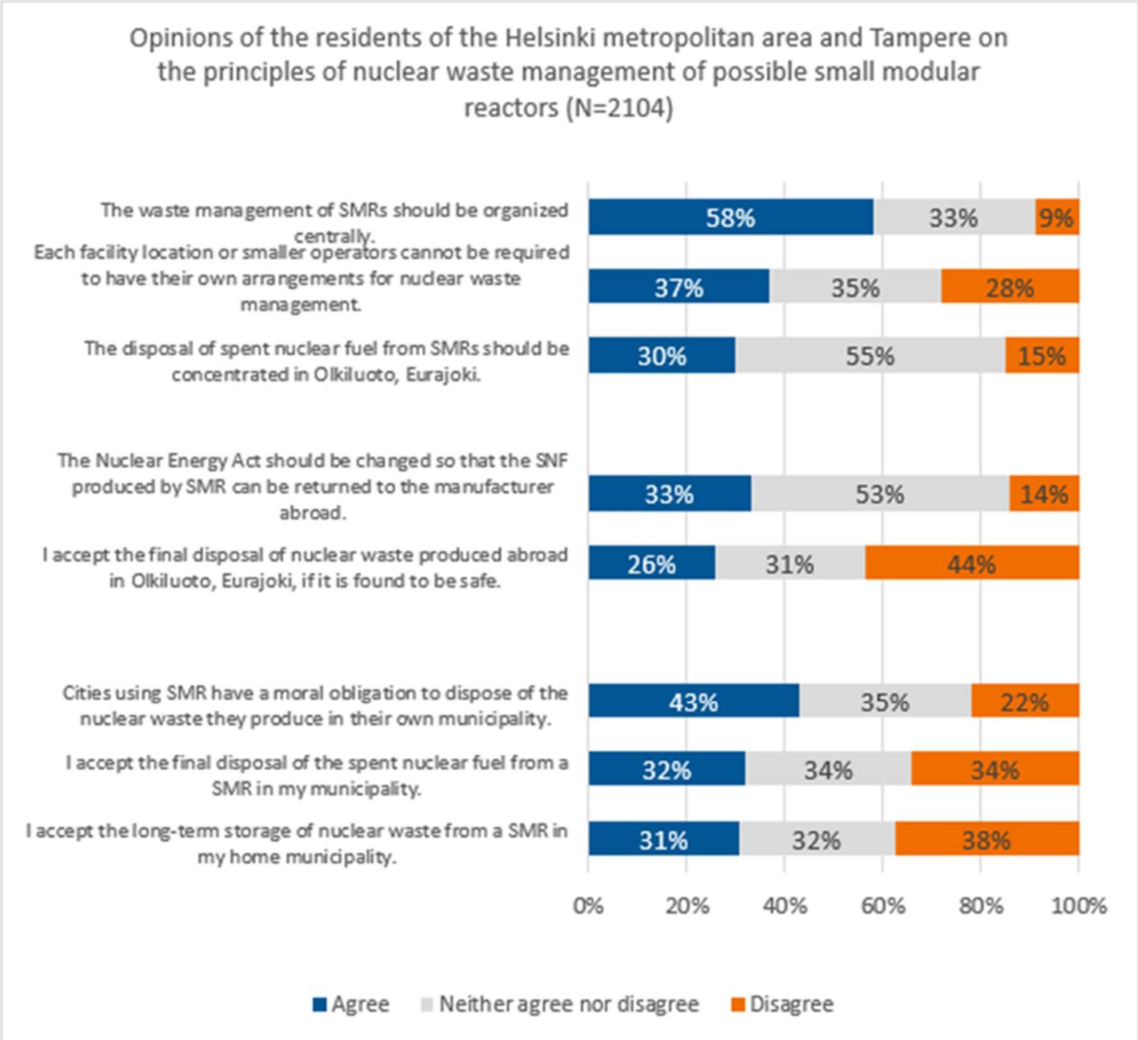

Figure 4-9. Opinions of the residents of the Helsinki metropolitan area and Tampere on the principles of nuclear waste management of possible small nuclear power plants. (N=2104)

Further complexity arise from the finding that only 32% of the respondents would accept the disposal of spent nuclear fuel in their own municipality, and that 33% of respondents supported the idea of returning nuclear waste to the foreign SMR manufacturer. It is also worth noting that the proportion of respondents who could not or did not want to express their position was in all examined statements at least 25%. This is partly due to the fact that SMRs are still a rather new issue for the general public. The key players in the SMR field should publicly outline their scenarios for the NWM, including possible siting options.

4.3 Preliminary roadmap for addressing societal engagement issues related to SMRs in district heating

Nadezhda Gotcheva, Merja Airola (VTT)

Based on scoping review of public documents, interviews (3) with representatives of different key stakeholders and survey results, VTT and LUT have co-developed a preliminary roadmap for addressing societal engagement issues related to SMRs in district heating.

Stakeholder/public/societal engagement as a concept is premised on the notion that those groups who can affect and/or are affected by an issue [e.g., physical location of district heating SMR plant in proximity to residential areas] should be given the opportunity to comment and input into the development of decisions that affect them. The engagement process is basically about developing relationships between different stakeholders, developing trust, communication of risks and possibilities, information flow, understanding, respecting and considering needs, concerns, hopes, and future prospects. In nuclear industry projects the future stakeholders deserve special consideration due to the long-term lifecycle of the nuclear facilities and the responsibilities associated with handling the nuclear waste. Roadmaps for stakeholder engagement are largely missing – most of the strategic roadmaps focus on business and technology aspects. Lessons learned from Canada and US on stakeholder engagement for SMRs should be reflected upon too.

The whole stakeholder landscape is changing with the SMRs: there will be new technology and purposes (heat production), new actors, new ways of working, new risks and opportunities, new requirements, new production and transportation issues, etc. The concept is moving from big nuclear power plant units build in a relatively remote area towards smaller units with a different purpose than electricity production, close to residential areas. This implies a shift from small, relatively remote communities to large cities, with heterogenous, multilingual, multicultural, changing urban population, which brings new considerations for emergency planning zones as well.

Based on the reviewed experiences in Canada, LUT survey results and researchers' workshops regarding the situation in Finland, we developed a preliminary SWOT analysis on societal engagement for SMRs in Finland – this is a living document, which serves a complementary starting point for encouraging discussions among different stakeholders groups on these topics (Figure 4-10).

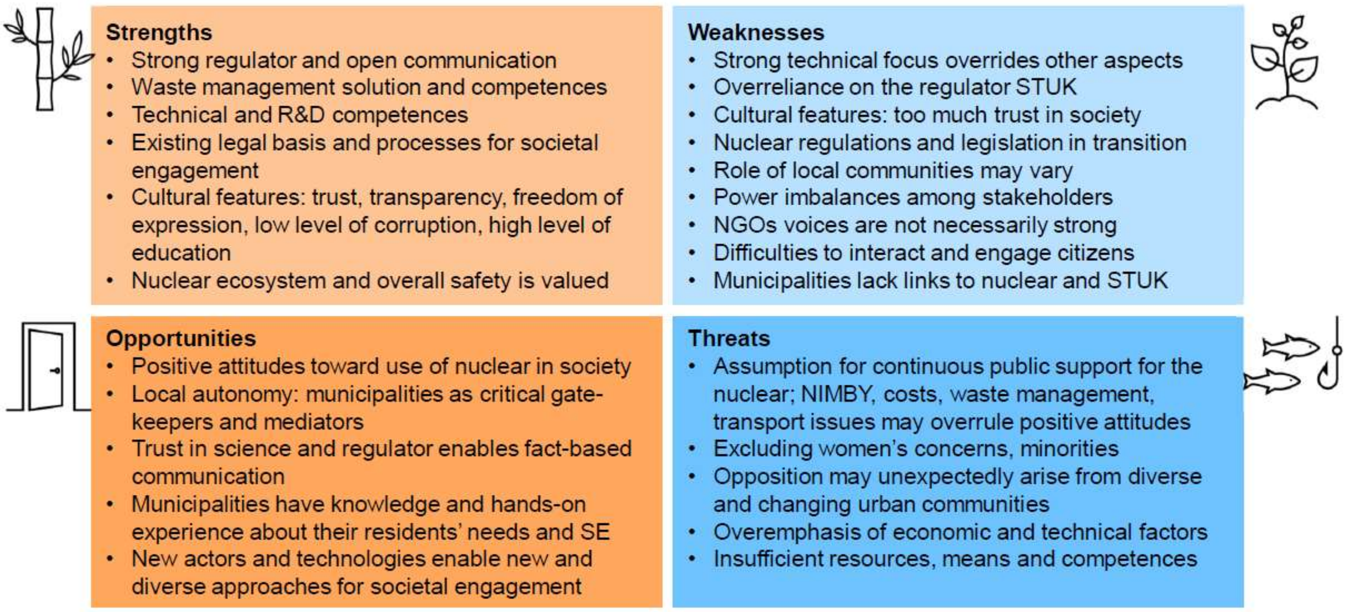

Figure 4-10: Preliminary SWOT analysis for societal engagement in Finland in relation to SMRs

The preliminary roadmap for societal engagement for SMRs in Finland is shown in Figure 4-11. The generic three phases were inspired by the US Department of Energy's concept and roadmap for Consent-Base Siting. The perspective of municipalities has been in focus here because our task was about pre-zoning phase. Since in Finland municipalities have a monopoly on land use planning, their perspective is important. In each phase we encourage stakeholders to ask and discuss what can go wrong and how to prepare. One reason for this is to build vigilance and an overall mindfulness perspective in the whole network of stakeholders in order to develop capabilities, to allocate resources, to cope with the unexpected.

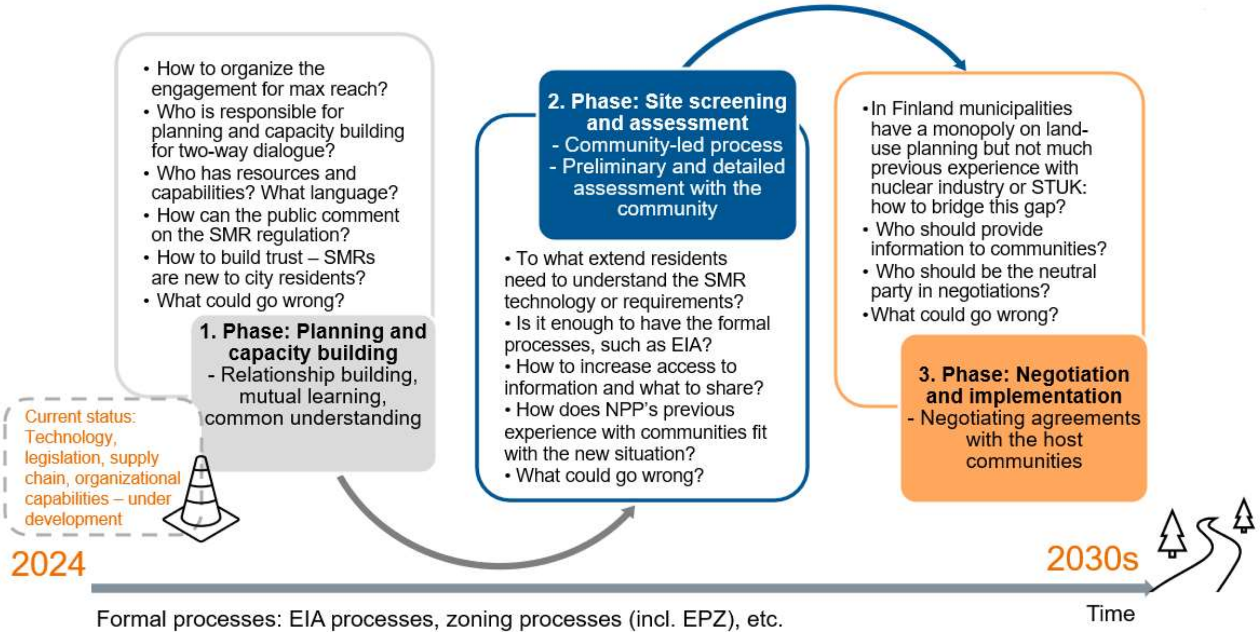

Figure 4-11. Preliminary roadmap for societal engagement for SMRs in Finland.

5. Conclusions

Coarse criticality safety studies for the KBS-3 final disposal canister designed for EPR and similar fuel were performed in WP1 for NuScale and LDR-50 type fuel assemblies. They share the 17 x 17 assembly type, so the EPR canister would be suitable for these, assuming that the axial length of the canister can be adjusted to the length of each fuel assembly type. It has been known previously that burnup credit will be needed in criticality safety analyses with EPR fuel and based on the observations of this study, this will be the case for NuScale fuel with U-235 enrichment above 4 %.

For LDR, the low-enriched, or 2.4 % fuel could be accommodated in the canister with fresh fuel assumption, but for 3.0 % or 3.5 % U-235 enrichment burnup credit would be required. The minimum discharge burnup for NuScale fuel with 4.05 % enrichment was estimated to be roughly 20 MWd/kgU and for 4.55 % enriched fuel 25 Wd/kgU. These are slightly lower numbers than estimated to be for Swedish PWR fuels of 4.0 % enrichment (Agrenius, 2010), i.e. 36.8 MWd/kgU when actinides only burnup credit was taken, and 30.0 MWd/kgU with actinides and fission products credit. At this point, the reader should, however, bear in mind that the Serpent calculations with spent fuel were performed with fuel compositions as such, except for the Gd rods where the spent fuel was replaced with fresh non-Gd fuel.

In WP2 the objective was to continue research on SMR waste management strategies. The work was divided into three main topics. In the first topic SMR plans of two Finnish power companies and one technical university were discussed (Section 3.1). The two power companies, Fortum and TVO, have limited their SMR considerations to LWR-SMR's, excluding SMR's with very small output powers. LUT-university is planning to deploy a HTGR-SMR for research purposes. To study relevant SMR designs for waste management considerations in Finland, the research could be focused on vendors that meet the needs of Finnish stakeholders, such as the ones presented in this report. It should be noted that the list of stakeholders with SMR plans presented in this report is not comprehensive and others could have plans including other types of reactors. As discussed in Section 1.2, Finnish stakeholders are also potentially considering the small district heat reactor LDR-50.

Fortum also identified disposability of SMR Spent Nuclear Fuel (SNF) in KBS-3 -type repository as a topic needing more research. This was addressed in the second main topic of WP2 in Section 3.3, where the objective was to assess Accident Tolerant Fuel (ATF) and SMR SNF disposability in a KBS-3 repository. For ATF, it was identified that they might have beneficial effect on disposability due to their better corrosion resistance. The KBS-3 -type repository is designed for conventional fuel using zirconium-alloy cladding and thus further studies are required to understand whether it could also accommodate ATF. These studies include research on cladding dissolution in final disposal conditions, and its effect on the source term and resulting radionuclide transport.

For SMR SNF, effect of potentially different SNF characteristics on engineered barriers was investigated on a general level. As an example it was concluded that the dry density of bentonite in the buffer affects radionuclide transport through the clay barrier and radionuclide colloid filtering. Thus, changes in radionuclide content and their mobility would also require reassessment of dry density and material requirements for the buffer to ensure that surface doses are below regulatory limits. In addition, the density affects build-up of gas and thermal conductivity in the buffer, and if gas generation rate or decay heat in the spent fuel or its container differs, it has to be ensured that the density is low enough to prevent gas build-up and the buffer also has sufficient thermal conductivity. Properties of different engineered barriers and host rock should taken account of in the safety case analyses for the KBS-3 repository and the definition of the safety functions and performance targets for the barriers. These considerations append the previous discussion of Keto, et al. (2022 & 2023) on how lower burnup allows canisters to be emplaced closer together, while also potentially reducing the amount of spent fuel disposed in a single canister through higher amount of fissile material in the SNF.

As a conclusion, some of the safety functions of the components in the KBS-3 disposal concept are directly linked and some are indirectly linked to the properties of the spent fuel to be disposed of. Properties of the spent fuel, especially its radionuclide inventory, are mainly relevant only in a case of breached canisters when analysing the radionuclide migration. Design requirements of the KBS-3 components should be optimized considering the spent fuel properties along with the properties of and requirements for all EBS and the host rock. As an example, the SMR spent fuel with lower decay heat could enable shorter distances between the canisters. However, more fissile material in the spent fuel would mean that fewer fuel rods could be packed in one disposal canister due to criticality concerns.

In WP4 the aim was to advance understanding on the societal engagement related to deployment of SMRs for district heating in Finland. To address the objective, LUT analysed results of a 2022 resident survey to the Helsinki Metropolitan area and VTT together with LUT developed a preliminary roadmap for societal engagement in the siting phase of SMRs.
In the resident survey of 2022, a bit over half of respondents were prepared to host a potential SMR in their own community, while about a fifth were undecisive and a fifth were against such a proposition. . However, the attitudes diverged significantly between men and women, with men holding a much more positive attitude towards SMRs than women.The vast majority of the respondents emphasized the need to inform the residents, if a SMR is being planned in their municipality.

It is important that residents have the opportunity to participate in the planning of possible SMR projects. Opponents of SMR were more often in favour of collaborative planning and a consultative referendum compared to SMR supporters.More than half of the SMR supporters and opponents agreed that the city council must have a veto right on the topic, that is, the right to approve or reject an SMR project.

The Radiation and Nuclear Safety Authority (STUK), the Technical Research Centre of Finland VTT, and the universities were the most trusted key actors among all respondents. A difference between SMR supporters and opponents appeared in the general level of trust. SMR supporters appear to have higher trust in the key actors than SMR opponents. In a similar manner, SMR opponents consistently mistrusted most key actors. Among SMR opponents, the environmental non-governmental organizations were among the most trusted key actors.

The 2022 resident survey shows contrasting views on the question on the principles of NWM. Whilemost of the respondents favour a centralised solution, the women respondents especially emphasise the moral obligation of an SMR municipality to also take its responsibility by disposing of the nuclear waste within its borders. Further complexity arises from the finding that about a third of the respondents would accept the disposal of SNF in their own municipality, and that about a third of respondents supported the idea of returning nuclear waste to the foreign SMR manufacturer. The key actors in the SMR field should publicly outline their scenarios for the NWM, including possible siting options.

The preliminary roadmap developed in WP4 aimed at enhancing discussion about stakeholder engagement, drawing inspiration also from international experiences. This roadmap, presented in a public webinar, signifies a step towards building a common understanding among stakeholders in Finland. However, further work is needed to refine and expand the roadmap, emphasizing the importance of collaborative efforts among key stakeholders in developing a national strategy for societal engagement for SMR deployment. In conclusion, the societal engagement on SMRs and SMR waste management in Finland cannot be underestimated. It is a long-term, continuous process that requires resources, competences, diverse means, leadership and governance approach.

The results of this report can be used in planning for deployment of SMRs in Finland and in understanding issues related to societal engagement on SMR deployment. The waste management aspects of the work can be used to further assess research and development needs as well as informing Finnish decision makers about legislative and regulatory concerns specific to SMR deployment and waste management.

In this study multiple research topics that need to be addressed in the future were identified. The calculations reported in Section 2, were based on several approximations and simplifications. Some of these could be improved with relatively moderate additional work, such as adding structural elements to the assembly ends and the support grids to their actual positions. Limitations to the acceptable group of nuclides to be included in post-irradiation calculations following the general actinides only or actinides and fission products burnup credit would require somewhat larger effort, as there is not directly such functionality in Serpent. Capability to model full operational history with full-core calculations would also enable more accurate studies. This is expected to be possible with the Serpent – Ants sequence in the near future. However, for real safety case studies, it will require an existing inventory of spent fuel to adequately define the bounding burnup profiles, even though the computational modelling could provide reasonable estimates for indicative studies

In WP2 the stakeholders identified demonstration of SMR SNF disposability in the KBS-3 disposal system as relevant topic. Further assessment during this study revealed that the fission product content of the SNF must assessed more in detail. This can affect the source term and gas generation rate, requiring both transport modelling and assessment of engineered barrier system design parameters. Furthermore, assessment on accident tolerant fuels showed that dissolution rates of the advanced claddings must be investigated again both for understanding the source term and gas generation potential. The stakeholders furthermore identified serial production related topics and economic optimisation of product. Finally, regarding storage of SMR SNF, International best practices for possible dry cask storage of SMR fuel in Finland could be studied from countries with similar climates.

In WP4, the research work conducted so far has highlighted the need to deepen the understanding on the nuances of societal engagement for SMRs in Finland.

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Appendix A

SMR-related questions and answers of Fortum

The questions were asked orally during a meeting on 4.5.2024 with Fortum. Three representatives were present from Fortum, while SMRSiMa-project was represented by Paula Keto (VTT), Sami Naumer (VTT) and Matti Kojo (LUT). The questions, answers and translated answers are presented below:

- Do you have already a planned or preferred vendor for a SMR?
  - *Fortum ei vielä ole valinnut SMR laitevalmistajaa, mutta case studyn kaikki reaktorit olivat kevytvesireaktoreita.*
  - *A SMR vendor has not yet been selected by Fortum, but all SMR's included in their case study were light water reactors*

- Do you have a planned location for a SMR?
  - *Loviisaa ja Torniota on julkisessa ulostulossa mietitty paikkoina SMR:lle*
  - *Loviisa and Tornio have been publicly discussed as sites for SMRs*

- Have you planned how the nuclear waste will be managed from a SMR?
  - *Yhtenä ajatuksena olisi käytetyn polttoaineen loppusijoitus Eurajoelle ja LILW loppusijoitus Loviisaan, mutta muitakin vaihtoehtoja tutkitaan.*
  - *One option would be final disposal of spent nucelar fuel in Eurajoki and LILW in Loviisa. Other options are also under investigation*

- What are the main research needs regarding SMR's that you have identified?
  - *Fortumia kiinnostaa SMR-sijoittamisen yleinen ja paikallinen hyväksyttävyys ja esimerkiksi miten paikalliset näkevät sen, että muussa kunnassa tuotettu ydinjäte loppusijoitettaisiin heidän kuntaan.*
  - *Fortum is interested in societal acceptability of SMR siting and for example how residents see disposal of radioactive waste within their municipality*

- *Kyselytutkimus Torniolaisille aiheesta kiinnostaisi*
  - *A resident survey for Tornio on the topic would be interesting*
  - *Lisäksi oleellista on jos voitaisiin osoittaa joko että SMR-jäte ei merkityksellisesti poikkea nykyisten reaktorien radioaktiivisesta jätteestä, tai jos poikkeamia on*
  - *Another relevant aspect is to show that SMR waste does not significantly differ from waste originating from conventional nuclear power plants or if there are significant differences.*
  - *Miten nämä vaikuttavat loppusijoitettavuuteen?*
    - *Fortum ei ole löytänyt merkittäviä eroja kun palama ja rikastusaste ovat vertailukelpoisia*
  - *How does this affect dipsosibility?*
    - *Fortum has not yet found differences when burnup and enrichment are comparable*

Appendix B

A questionnaire on SMR topics was sent to an Nuclear Energy field Expert from Lappeenranta-Lahti University of Technology (LUT) on 9.11.2023 and answered on 12.1.2024. A summary of the questions and their answers is presented below:

- What is the schedule and the status of the LUT test reactor?
    - Same as before. Pre-feasibility investigations go on.

- Is there up-to date public technical data available on the reactor?
    - See usnc.com.

- Has the site for the SMR been selected?
    - Not yet. Candidates have been identified.

- Have you planned how the nuclear waste will be managed from the SMR?
    - Options have been identified.

- What are the main research needs regarding the selected SMR that you have identified?
    - Economic optimisation of product portfolio.

Appendix C

Summary of the SMR discussions between TVO and VTT

A discussion on SMR topics, between TVO and VTT, was held on 21.12.2023. From TVO three representatives participated in the meeting. From VTT, Paula Keto and Sami Naumer were present. The purpose of the discussion was to answer questions regarding TVO's plans for SMRs on behalf of the SMRSiMa project.

Preliminary questions for TVO were sent before the meeting, which TVO answered. The purpose of the questions was to direct the discussion of the meeting to the topics, that required further detail. The list of the translated preliminary questions and their answers is presented in Table 1.

Question	Answer
1) *Do you have estimates on power output requirements of SMRs for your own needs*	*We follow advanced LWR reactor designs on a general level*
2) *Have you planned a specific vendor for a SMR?*	*No*
3) *Have you planned a site for a SMR?*	*We have investigated siting requirements on a general level*
4) *Have you planned waste management for SMRs?*	*Different options have been considered on a rough level*
5) *How does TVO see the waste management for SMRs in Finland on a general level? Is the usage of the current repository excluded?*	*We do not have an answer for this question*
6) *What are the key research needs regarding SMRs and their waste management*	*Actions aiming for modularity and serial production and their impact on the business case*
7) *Has TVO considered borehole disposal*	*There has not been any discussion on borehole disposal among the SMR workers of TVO*

The questions of Table 1 were further discussed in the meeting. In general, TVO's plans regarding SMRs are on a crude, preliminary planning level. Their plans focus on light water reactors (LWRs) with low enrichment have been mainly considered, but reactors using for example TRISO could also be considered. They have limited their interest into reactors with larger than 50 MW output power, land-based reactors. TVO has considered both single or a low number of larger SMR-reactors and also larger fleets of smaller reactors as possibilities.

Waste management and siting related topics:

TVO has considered SMR waste management on a crude level so far. Topics that they have discussed included for example encapsulation and disposal of potentially shorter SMR spent fuel assemblies. Some ideas that they had come up were to install two shorter canisters in one disposal hole. However, they stated that such plans should be investigated thoroughly before they can be recommended.

When asked about using the current repository for SMR waste, TVO emphasised that no party can be forced to take in new radioactive waste, that has not been included in the former Decisions in Principle. Nevertheless the amount of new SMR plants required to justify construction of a new final disposal site somewhere else was also discussed without a conclusive answer at this stage. TVO stated that Posiva could be interested in selling their expertise if a separate disposal site would be constructed. The LILW cavern currently situated in Olkiluoto is also being planned to be extended for current needs. Technically future extensions could also be possible.

According to TVO, siting of a repository, societal acceptability is very important. It was also discussed that the public mainly worries about drastic accidents, such as nuclear accident on power plants, and less on less spectacular topics, such as nuclear waste management. One consideration is for example that spent fuel is globally in interim storage for example in storage pools, and not permanently disposed in deep geologic repositories.

TVO also stated that transportation of nuclear fuel or spent fuel might not become a large societal acceptance challenge, as it is already commonplace in larger European countries. Thus, transportation in a decentralised waste management strategy would not be a key challenge. VTT however stated, that road regulations, for example road class requirements, would need to be followed in a decentralised fleet, possibly requiring construction of new road infrastructure.

Siting of the SMR power plants and disposal facilities was discussed further. Current regulations regarding emergency planning zones (EPZ) limit SMR siting in proximity of cities, but an upcoming update to the Finnish legislation could change the EPZ to be determined case-by-case.

Business case and other topics:

During the meeting different business and procurement models were also discussed. TVO stated that OL3 was a turnkey procurement model, while other models also have been used for nuclear power plants elsewhere. Similarly for SMRs different models would exist, and it remains to see how for example spare parts of the SMRs are handled and whether it would be possible to “rent” the fuel.

As key research needs of TVO, modularity and serial production related issues were mentioned. Aspects such as concept reviews by the authority for a specific power plant design could make the deployment of SMRs easier. One design could be benchmarked regarding its safety features, which could limit the amount of repeated analysis if the same design would be deployed in multiple areas. Siting related criteria for SMRs could also bring scaling benefits. All requirements for siting, such as seismic or hydrological requirements, could be listed, making site selection for a specific design more streamlined.