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SMRSiMa:
SMR Siting and Waste Management

Waste Management Considerations and Societal Acceptability

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Summary

Small modular reactors (SMRs) are being considered in Finland for the production of low car-bon electricity and heat. Siting of the reactor facilities and management and disposal of the spent fuel and low- and intermediate level waste play an important role in the safe and sustain-able deployment of SMR technology. The deployment process and waste management are guided by a regulatory framework, currently being updated in Finland. In addition, other factors such as applicability of current waste management methods and societal acceptability have an important role in this process.

SMR Siting and Waste Management (SMRSiMa) is a coordinated project between VTT and Geological Survey of Finland (GTK) focusing on waste management of spent nuclear fuel produced in an SMR and in the siting and societal acceptability of an SMR plant and repository. In 2022, SMRSiMa received funding from both the SAFIR2022 and KYT2022 programmes. The work presented in this report focuses on topics linked to the regulatory framework, effect of SMR reactor design and spent fuel properties on waste management and on societal acceptability factors. SMR plant and repository siting is discussed separately in a report by GTK.

The characteristics of the spent nuclear fuel (SNF) play a crucial role in adapting the current disposal methods for SNF produced in a SMR. The method currently in use in Finland (KBS-3V) was originally designed solely for UO2 fuel with specific fuel characteristics. Adapting the method for SMR waste requires that the characteristics of the SNF are defined to a highly de-tailed level, including discharge burnup, decay heat power, photon emission rate (gamma radiation), mobile nuclide concentration, chemical characteristics and post-irradiation reactivity linked to criticality safety. For SMR designs based on current LWR technologies, the spent fuel may differ from that of existing, large LWRs due to the smaller size of the SMR core potentially leading to higher neutron leakage and in other reactor and fuel parameters (e.g., enrichment of the fuel). This report compares some of these basic parameters for number of LWR-SMRs potentially relevant for Finland.

In order to quantify spent fuel characteristics, preliminary 2D calculations were made with two different example reactors (NuScale Power ModuleTM and Finnish heating reactor design LDR-50) with the continuous-energy Monte Carlo code Serpent in the previous phase of the project (Keto et al. 2022). Based on the 2D calculations, the main differences between the SMR and NPP spent fuels was linked to lower burnups in the SMRs. Considering waste management, the lower levels of decay heat and ionizing radiation could make the handling of the waste less demanding. However, 3D calculations were needed to determine the effect of the smaller SMR core size and to address further the potential uncertainties remaining with criticality safety. During 2022, Serpent 3 D calculation were made considering the LDR-50 reactor. Preliminary data shows some difference between the 2D and 3D cases, but since the calculations were per-formed with the start-up core, the results are not fully representative with respect to the total anticipated spent fuel inventory. Furthermore, due to difficulties linked with the heavy calculation process and difficulties in interpretation of the data, the presented results are rather coarse even with the model limitations. Calculations are continued within the next phase of the project.

Considering an SMR that would be utilised for district heating purposes, the location of the site would be closer to a city than normal NPPs. This brings challenges considering the siting from the geological perspective, but also from societal acceptability point of view. Early engagement of stakeholders, civil society and public is required for successful SMR deployment and waste management.

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Preface

This report has been compiled at VTT from April 2022 to January 2023 as part of the SAFIR2022 Finnish Research Programme on Nuclear Power Plant Safety and KYT2022 Finnish Research Programme on Nuclear Waste Management. The objective of the project "SMR Siting and Waste Management, SMRSiMa" was to study further SMR nuclear waste management started in 2021 (Keto et al. 2022) and to study the siting of a SMR plant and repository including also societal and stakeholder acceptability of SMR siting. The siting from the geological point of view is discussed in a separate study by GTK (Hietava et al. 2023). Waste management and stakeholder acceptability are published as part of this report.

The project did not have a named steering group, but the steering took place by the KYT2022 stakeholders in the KYT2022 steering group meeting held at 12.4.2022, in KYT2022 Alternative Technologies, Follow-up group 7 -meeting held at 25.8.2022 and in joint EcoSMR, dECOmm and SMRSiMa Final seminar held at 23.11.2022.

Results of the previous project "SMR Waste Management" (Keto et al. 2022) and the ongoing project were presented internationally by Timothy Schatz in SNETP Forum TS5: Waste minimization and fuel cycle with the title "*Unique Issues in SMR Spent Fuel and Waste management*" and in IAEA meeting (joint presentation with Ville Koskinen STUK) in September 2022 with the title *"Issues in SMR Spent Fuel and Waste Management from (mainly) Finnish Perspectives*". Paula Keto presented the work at OECD NEA workshop on the Management of Spent Fuel, Radioactive Waste, and Decommissioning in SMRs/Advanced Reactor Technologies in November 2022 with the title "*Applicability of Current Finnish Disposal Methods for Spent Fuel from Small Modular Nuclear Reactors*". We would like to thank Linda Kumpula (Ministry of Economic Affairs and Employment of Finland), Ville Koskinen (STUK), Business Finland through EcoSMR project and Tiina Jalonen, Johanna Hansen and Ville Heino from Posiva Oy for contributions and support to be able to present the work in these international venues.

Stakeholder interviews concerning societal acceptability issues were performed between September and November 2022. We would like to thank representatives of Vantaa, Espoo, Vaasa, Jyväskylä, Pyhäjoki and Tampere for valuable input to the project.

The calculations concerning spent nuclear fuel characteristics were performed by Pauli Juutilainen and supervised by Silja Häkkinen and were realized in cooperation with the KYT project KÄRÄHDE. Ville Tulkki as the expert of SMR technology reviewed the report. Paula Keto worked as a project manager of the project and contributed as a waste management and engineered barrier specialist together with Timothy Schatz and Sami Naumer.

We would like to thank all KYT Board members and especially Linda Kumpula and Jaakko Luovanto from TEM, Jaakko Leino and Ville Koskinen from STUK, Annukka Laitonen from TVO and Pasi Kelokaski from Fortum.

Espoo 31.1.2023

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Contents

1. Introduction

The national climate and energy strategy in Finland (MEAE 2022) states that Finland aims to achieve EU-level goals for decreasing greenhouse emissions by 2030 and carbon neutrality within the year 2035. One challenge in this green transition is the relatively fast replacement of fossil fuels for producing energy and district heat with variety of low carbon solutions. Small modular nuclear reactors (SMRs) are considered as one potential source of low carbon energy and heat not only in Finland, but also globally. Licencing of an SMR plant requires that the licence applicant has a plan for implementing a waste management system, in line with the principles of the waste management obligations for spent fuel and radioactive waste defined in the Nuclear Energy Act (Kumpula 2022, IAEA 2023). Plans and preparations for final disposal of nuclear waste are also required by the new EU taxonomy (Complementary Climate Delegated Act to Accelerate Decarbonisation, updated 7/2022) for investments in new nuclear energy production.

SMRs are typically defined as nuclear power plants with electrical power output of less than 300 MW (megawatts) (STUK 2019, IAEA 2020, 2022, 2023) or thermal power of < 1000 MW. However, the actual power output depends on the reactor in question (IAEA 2023) and how many modular reactors are placed in the plant. When talking about SMRs, the features that are also typically mentioned are standardised products (possibly leading to lighter licencing process), serial production in factory and passive safety features (IAEA 2022). The different types of SMR reactors being designed can be divided roughly into the following subtypes: light water-cooled reactors (LWRs, similar to the NPPs in Finland), gas cooled reactors, fast reactors (with liquid metals as coolants) and molten salt reactors (STUK 2019, IAEA 2022). The work presented in this report is limited to LWR-SMRs.

Reform of nuclear energy legislation is currently ongoing and the updated regulations should be ready by end of 2027. According to STUK (2019), the regulations are being renewed considering licencing of SMRs in the future. Liukko et al. (2020) discussed recommendations for the reform and suggest that in the future the waste management for SMRs should preferably be handled by a domestic cooperation. In some cases, this handling may require transfer of waste management and financial provision obligations to another party. Developments of the Nuclear Energy Act from the SMR waste management point of view are discussed further in section 2 of this report.

Other advances towards SMR deployment in Finland have been made during 2022. Fortum launched a feasibility study to explore prerequisites for new nuclear in Finland and Sweden, including both conventional large reactors and SMRs (Fortum corporation business press release 17.10.2022). LUT university announced in December 2022, that they plan to build a gas cooled microreactor for research purposes in cooperation with Ultra Safe Nuclear Corporation (https://www.lut.fi/fi/uutiset/lappeenrantaan-suunnitellaan-pienydinvoimalaa). In addition to academic pursuits, this reactor would also produce district heat for the city of Lappeenranta. Notable with this reactor is that it uses TRISO particle fuel.

In order to plan the waste management for SMR spent fuel and LILW, the general consensus is that the characteristics for the spent nuclear fuel and other nuclear waste generated need to be defined and eventually demonstrated when there are waste streams available (IAEA 2023). Characteristics of spent nuclear fuel form two different LWR-SMR reactors (LDR-50 and NuScale Power module TM) were studied with numerical Serpent 2D model in the preceding KYT2022 on “SMR Waste Management in Finland” (SMRWaMa) project. Since the 2D model cannot be used to simulate the exact volume and surface area ratio typical for small SMR cores, the effect of the core size was studied within this study with the Serpent 3D model. Due to limited project resources, the work focused on the LDR-50 reactor. The modelling method and the preliminary results are described in detail in section 4 of this report.

Brown et al. (2017), Glaser et al. (2017) and Krall et al. (2022) indicate that SMRs may produce higher volumes of radioactive waste than conventional NPPs per unit of energy produced. Perhaps the main reason for this finding are the smaller SMR core sizes and consequent neutron leakage effects. This study included both a water-cooled SMR (NuScale Power module TM) and non-LWR SMRs (molten salt- and sodium cooled SMRs). It should also be noted that there are no standardised methods at industrial scales for conditioning or packaging the non-LWR nuclear wastes into forms suitable for disposal in geological repositories (Krall et al. 2022, Keto et al. 2022). Relative to total power produced the shorter lifetimes of the reactors may also affect the relative amount of decommissioning waste produced (Krall et al. 2022).

The long-term goal of this study is to estimate the SNF and LILW inventories generated by the SMRs relevant for Finland and how the characteristics of the waste streams impact the applicability the waste management methods currently used in Finland. To be able to do precise estimations, generally more information should be available on these reactors. An attempt is made in section 3 to compare basic factors affecting final disposal for six example LWR-SMRs.

The current management method used in Finland for spent nuclear fuel is based on the KBS3V concept developed originally by SKB and later in cooperation with Posiva Oy. According to Johnson et al. (2022), the concept is applicable only for uranium matrix consisting of UO_2 with specific fuel characteristics and using the concept for other type of waste would challenge the existing safety case. The applicability of the KBS-3V method considering the spent fuel characteristics gained as a result of the numerical modelling and literature review are discussed in section 5. Final chapter presents results from a preliminary study on societal acceptability of SMR plants for district heating from the perspective of the local municipalities in Finland. Municipality's role is vital in local land use, planning, as well as informing and engaging residents in climate and energy policy projects. The study summarizes key concepts and literature review related to the nuclear energy in Finland. Insights of experiences and expectations of the municipalities related to SMR plants and social acceptability are presented. The chapter concludes with preliminary implications from the local level perspective addressing social acceptability topics in the situation where the small modular nuclear reactor plant may provide potential application for district heating in the future.

The objectives of the work presented in this report are to 1) discuss the current regulatory framework in Finland considering waste management and especially centralised management option including transfer of waste management obligation, 2) study basic characteristics of selected LWR-SMR affecting waste management, 3) compare results gained with Serpent 2D and 3D numerical model for a LWR-SMR to be able to estimate the effect of small core size on SNF characteristics and thus disposal of the waste, and 4) finally discuss the importance of social acceptability of siting of a SMR plant from the municipalities´ perspective, and factors affecting it.

2. Regulatory framework

This section discusses the management of spent nuclear fuel and LILW generated in a SMR plant in Finland and possible development needs for current nuclear energy regulations.

2.1 Regulations concerning handling, storage and disposal of nuclear waste

According to the Finnish Nuclear Energy Act (990/1987, section 6a), shall all nuclear waste generated in Finland due to use of nuclear energy be handled, stored, and permanently disposed of in Finland. An exemption to this is small quantities of nuclear waste delivered abroad for research purposes or treatment, and nuclear waste generated at research reactors. Also, by virtue of the Nuclear Energy Act (990/1987) section 6b, shall nuclear waste generated outside of Finland not be handled, stored, or permanently disposed of in Finland, with similar exceptions regarding small amounts of nuclear waste delivered to Finland for research purposes or waste possessed by a Finnish authority. Thus, if SMR's are to be used for energy production, prevents section 6 of the Nuclear Energy Act (990/1987) the possibility to transport nuclear waste for handling and/or disposal over the boarders. Depending on the reactor type (LWR-SMR or non-LWR SMR), at least some handling of the waste (e.g. spent nuclear fuel) could be needed outside the country. Another option could also be that some handling (e.g. encapsulation) of foreign SMR SNF would be performed in Finland as a service. In future there may also be a shared repository for European Nuclear waste (ERDO 2021), that could be one option for management of SNF produced in Finland, even though Finland is currently not one of the ERDO working group members. Changes considering Nuclear

Energy Act (990/1987) section 6a and 6b have been under discussion, but the content of the changes cannot be anticipated yet during writing of this report.

2.2 Decision-In-Principle

Construction of a nuclear facility of considerable general significance requires a government Decision-in-Principle as defined in Nuclear Energy Act (990/1987) section 11. Considerable general significance means in this connection "*a nuclear facility in which nuclear materials or waste are fabricated, produced, used, handled or stored to the extent that the amount of nuclear materials at a given moment is more than 50 effective kilograms or the amount of nuclear waste is such that its total activity is higher than 100,000 TBq or the alpha activity higher than 1000 TBq* (Nuclear Energy Decree, section 7)**.** *However, a vehicle or a temporary storage directly associated with transport is, however, not considered a nuclear facility*".

Nuclear Energy Act (990/1987) section 3 and 11 defines the nuclear facilities with considerable general significance to include:

- *"Facilities operated for the generation of nuclear energy having a thermal power higher than 50 megawatts;*
- *Facilities used for the disposal of nuclear waste; and*
- *Facilities operated for purposes other than the generation of nuclear energy and the possession at any given time, of an amount of nuclear material or waste or involving a radiation risk, as defined by a Government decree, that shall be deemed comparable with nuclear facilities as defined in paragraph 1. (342/2008)"*.

Need of a decision-in-principle for a SMR plant would therefore depend on the power output of the plant and whether the SMR plant is considered as a nuclear facility of considerable general significance.

Considering SNF interim storages at a SMR site area or a centralised facility, this means that the need for a decision in principle for an interim spent fuel storage depends on the total activity to be licenced. Currently, all LILW management systems, interim storages and the actual waste streams are licenced as a part of the NPP where the waste is produced. Also, depending on the total activity to be licensed, a disposal facility for the SMR spent fuel and radioactive waste would require a decision-in-principle.

As part of the decision-in-principle process, a supporting statement is required from the municipality where the nuclear facility would be sited. In practice this means that the municipality has a veto right to prevent construction of a nuclear facilities requiring decision-in-principle. Considering facilities that do not require decision-in-principle, similar type of support is required from the municipality through town planning process. Changes considering Nuclear Energy Act (990/1987) and need for decision-in-principle for example for serial produced reactors have been under discussion, but the content of the changes cannot be anticipated yet during writing of this report.

2.3 Regulations concerning organising nuclear waste management in Finland

SMR waste management strategies were preliminary discussed in Keto et al. (2022). Currently there are multiple alternatives how SMR plants could be deployed in Finland, for example:

- Large plant with multiple SMR units for production of electricity and possibly also heat. The capacity of the plant could be, e.g., 500 MW comparable to the capacity of a single reactor in Loviisa NPP or more.
- Single SMR plants deployed across Finland in different municipalities for producing district heat and/or electricity.

In both example cases, the owner, operator or licensee of these kinds of plants could be a power company (e.g. Fortum, TVO or HELEN) or alternatively a newcomer in the Finnish nuclear energy market. In addition, municipalities could be owners or part-owners of the facility. The existing nuclear waste management expertise (or lack of it) of any potential licensee is important when assessing whether waste management can be implemented in both a safe and economically viable manner.

Generally speaking, there are three potential strategies for managing spent fuel and other radioactive waste produced in SMR's in Finland. These are the decentralized, hybrid and centralized nuclear waste management strategies described in more detail in Keto et al. (2022). For example, in hybrid strategy the SNF management and disposal could be done in centralised manner and the management of LILW locally, as it is the case with the nuclear waste produced in Loviisa. How the waste management would be organised in practice is also a matter of ownership base, how the responsibilities are divided between the different actors and the ability of the license holder to take care of waste management.

Assuming that the license holder of the SMR takes care of the waste management by itself or through a separate company (partly or jointly with other licensees as in the case of Posiva Oy), then the current regulatory framework, including the Nuclear Energy Act (990/1987) and the Nuclear Energy Degree (161/1988), can be utilized as such to a large extent. Considering several small SMR plants (e.g. < 50 MWh) that would be owned, licensed or operated different actors across Finland, the question discussed below is could the licence holder transfer its waste management obligation to another party (e.g. to an operator) for organising the waste management in a centralised manner.

Transfer of waste management obligation or financial provision obligation to another party is something that has not yet been done in Finland but will be done in small scale when the waste management obligation of research reactor FiR1 decommissioning waste is transferred from VTT to Fortum. Thus, the current Nuclear Energy Act (990/1987) does not prevent transfer of the waste management obligation to another party as such, and the Nuclear Energy Degree (161/1988) sections 81-83 specifies how the transfer can be applied and granted:

- Nuclear Energy Act (990/1987) section 9: "*License holder whose operations generate or have generated nuclear waste (party with a waste management obligation, jätehuoltovelvollinen in Finnish) shall be responsible for all nuclear waste management measures and their appropriate preparation, as well as for their costs (waste management obligation, huolehtimisvelvollisuus)*".
- Nuclear Energy Act (990/1987) section 30: "*When a nuclear facility, a mine intended for the production of uranium or thorium, a milling facility, or nuclear waste is transferred to another party, the Ministry of Economic Affairs and Employment may, on request, transfer the management obligation (huolehtimisvelvollisuus) to the transferee in part or in full if the transfer of the obligation does not endanger the implementation of the nuclear waste management.*"
- Nuclear Energy Degree (161/1988) section 81: "*An application for the transfer of waste management obligation (huolehtimisvelvollisuus), as referred to in section 30 of the Nuclear Energy Act, must be submitted to the Ministry of Trade and Industry for decision together with the application for the transfer of a nuclear facility, a mine or enrichment plant intended for the production of uranium or thorium, or nuclear waste to another party. The application must be made jointly by the transferor and the transferee.*"
- Nuclear Energy Degree (161/1988) section 82: "*In applying for the licences referred to in section 81, the party with a waste management obligation (jätehuoltovelvollinen) must show how the financial provision (varautuminen) as per chapter 7 of the Nuclear Energy Act will be arranged with respect to the management obligation that is transferred to the transferee, and present plans on how the management of the nuclear waste that is transferred to the transferee will be carried out in accordance with the provisions of the Nuclear Energy Act and this Decree. The decisions on the applications referred to above in section 81(1) shall be given at the same time.*"
- Nuclear Energy Degree (161/1988) section 83: "*The decision referred to in section 30 of the Nuclear Energy Act must contain a condition stating that the decision will not become effective unless financial provision for the cost (varautuminen ydinjätehuollon kustannuksiin) of nuclear*

waste management has been arranged in the way described in chapter 7 of the Nuclear Energy Act."

As stated in the Nuclear Energy Degree (161/1988) section 81, the waste producer and transferee must apply for the transfer of waste management obligation together and the transferee must possess an operating license granted by the government. An important part of transferring the waste management obligation is the financial provision obligation, and therefor shall the financial provisions for the costs of nuclear waste management be presented. In general, the party with the waste management obligation shall fulfil the financial provision obligation by payment for each calendar year to National Nuclear Waste Management Fund (Nuclear Energy Act, Section 36 Financial provision measures). The fund is used to ensure that the society has sufficient funds and expertise to arrange nuclear waste management under all circumstances. The annual fee is determined by The Ministry of Economic Affairs and Employment and the Fund based on the liability of the previous calendar year and the amount of funds in the Fund.

It is in the interest of all parties (nuclear waste producers, waste management organizations, regulator, government, and the public) that a transfer of the waste management obligation is done under mutual understanding. In section 29 of the Nuclear Energy Act (990/1987) is presented how the State can order parties to cooperate:

- Nuclear Energy Act (990/1987) section 29: "*The Ministry of Trade and Industry may order various parties with the waste management obligation (jätehuoltovelvolliset) to undertake waste management measures jointly, if by doing so safety can be increased or costs can be substantially reduced or if any other weighty reason so requires. At the same time, provisions shall be laid down, if necessary, on the distribution of the costs incurred due to the measures to be carried out jointly.*"

Utilizing this or section 31 of the Nuclear Energy Act (990/1987), about the transfer of nuclear waste to the State, are not seen as good practice and should be used as a last resort for implementing nuclear waste management.

After all required prerequisites for a transfer of nuclear waste obligation transfer are met, can the Ministry of Economic Affairs and Employment or the Radiation and Nuclear Safety Authority order the waste management obligation to be expired (*huolehtimisvelvollisuuden päätyminen*) (Nuclear Energy Act (990/1987), section 32. This process can take place in three different cases: 1) transfer of waste management obligation according to section 30, 2) in case of small amounts of nuclear waste disposed outside Finland as described in section 6a, 3) after final disposal (section 33).

As a summary, transfer of waste management obligation and financial provision obligation is in principle already possibly with the current legislation. However, this process will be tried the first time for a relatively small amount of decommissioning waste from a research reactor.

Whether thee transfer process and centralised waste management would be possible in practice remains to be discussed further in Finland, not only from the regulatory framework point of view, but also considering possible business models.

2.4 Other SMR specific considerations

Other SMR specific nuclear waste management considerations that could be possibly considered in reform of the Nuclear Energy Act (e.g. YVL guides) are briefly listed below:

- Many SMR designs rely on dry interim storages, but the current regulations (STUK Y/1/2028 and YVL D.3) consider mainly pool type interim spent fuel storages.
- Spent fuel inventories from different sources, with potentially different characteristics and residual heat. Further discussion is needed whether a centralized interim storage and/or disposal facility can house waste with variety of properties.

- Management of spent fuel and LILW from non-LWR SMRs with potentially very different characteristics in comparison to waste form LWR-SMRs. Can the same facilities be used for both cases?
- What premises, equipment and other arrangements a SMR plant shall have at the plant area (at minimum) to ensure safe handling and storage of the nuclear material and waste generated during operation and decommissioning (as it is currently defined for NPPs by Nuclear Energy Act §7h and YVL D.4-4.1.1-401). For example, assuming a case that there is a delay in licensing of a centralised facility.
- Transport of spent nuclear fuel from SMRs assuming little or no cooling time and requirements for the transport and possibly pre-cooling of the waste before transport might be needed. Possible needs to develop transfer practices fulfilling the requirements of spent fuel with little or no cooling.
- In general, streamlining of the licensing process for serial produced SMRs (same type).
- Siting requirements specific for urban areas, if any (siting requirements from geological point of view are discussed further in Hietava et al. 2023).

3. Comparison of commercial LWR-SMRs and their basic properties affecting final disposal

3.1 Introduction

In this Section six light water cooled small modular reactors (LWR-SMR) are described as with an emphasis on waste management related properties. In addition, a brief description of safety features and plant layouts is presented. Four of the reactors were selected based on their inclusion in the EcoSMR project supporting Finnish industry to create business ecosystem around SMRs (Ecosmr.fi). These example cases include the Rolls-Royce, GE-Hitachi, EDF and VTT developed SMR's. In addition to these, two reactors with mature design and licencing status, the NuScale reactor from the previous report in this study (Keto et al., 2022) and a reactor by KAERI were also selected to the study.

No detailed information for nuclear waste practices for most of the reactors has been presented yet. Thus, in this section a general overview is given on the reactors and properties that could be used in estimating SMR-waste streams summarized. These include both fuel properties and properties related to waste volumes and dimensions.

First, enrichment of the fuel has an effect on spent fuel characteristics. Higher enrichment can lead to a i.a. higher discharge burnup, higher decay heat and different fission product content (Burns et al., 2020 and IAEA, 2003). All of these properties can have an effect on disposal. Different fission product contents also have different half-lives, potentially having an effect on the disposal time required for the waste. Decay heat has an effect on how long the removed SNF has to be cooled down in prior to disposal (IAEA, 2003). Discharge burnup describes how much of the fuel has been utilized, with higher rates meaning more of the fuel has undergone fission (IAEA, 2003). Thus, the higher the rate, the more fission products are again in the SNF. Higher burnups thus lead to decreased criticality, while lower burnups increase it (IAEA, 2003). This could for example have an effect on how much spent fuel could be disposed in one canister, while still maintaining subcriticality. In addition to fuel properties, choice of the reactor coolant also has an effect on the generated waste. In our comparison cases, all reactors are light water cooled, but if different coolant types were used, the waste could be drastically different as was explained in Keto et al. (2022). Some SMRs operate in open (once-through) and some in closed nuclear fuel cycles (IAEA 2009). In the first case the spent fuel is disposed after use as in the case of UO_2 produced in Finnish NPPs and in latter case fuel is reprocessed for re-use (e.g. Mixed Oxide Fuel, MOX, IAEA 2009). All the reactors discussed in this chapter have open fuel cycles.

The waste form and fuel assembly dimensions also affect spent fuel management mainly from encapsulation point of view. The assembly-type affects canister design, as seen in the three different canister designs used for Finnish conventional nuclear fuel from the currently operating reactors (Raiko, 2013). For example, four assemblies of the EPR fuel are planned to be disposed in one canister compared to twelve assemblies of VVER-440 fuel. The length of the assemblies directly affect the length of disposal canisters, again comparing the length of 5.22 m for the EPR fuel and 3.55 m for the VVER-440 fuel. Finally, the more different assemblies of SNF are generated, the more canisters need to be optimised for each assembly type.

3.2 Comparison cases

The first selected reactor is the SMR produced by NuScale Power from USA (IAEA 2020 IAEA 2022). Some design parameters are presented in Table 3-1. The powerplant can be scaled up to 924 MW(e) when a total of 12 power generating modules are used, but smaller configurations can also be used. The reactor itself consists of 37 fuel assemblies and the assemblies themselves contain 17 x 17 fuel rods. According to (IAEA 2022), the length of the assemblies is half of the standard plant fuel, 244 cm (NuScale2020a, 2020b). Uranium dioxide pellets with a maximum enrichment of 4.95% are used as fuel with Gd_2O_3 as a burnable absorber mixed with the pellets.

The NuScale nuclear power plant (NPP) consists of three main buildings: the reactor-, control and turbine buildings. Furthermore, a waste treatment building is on the area. Various configurations on power modules are inside the reactor building, depending on the desired output power. The modules are under a biological shield. In addition to the modules, the building consists of a reactor- and a spent fuel pool, and the reactor refuelling equipment. The reactor and the plant have been designed to aim for passive safety and can remain safe without power, maintenance or water. The safety is ensured with a several independent systems. Firstly, the power modules use a natural circulation and thus no reactor coolant pumps are required or external piping systems. Two natural circulation, closed-loop cooling systems are also used for decay heat removal in cases where feedwater cannot be used normally. Each of the two systems is able to remove all decay heat independently from the other. In case both of the decay heat removal systems fail, valves are opened and water is flowing from the surrounding containment vessel to the reactor vessel to ensure removal of decay heat. Finally, reactor containment vessels consisting of steel surround the reactor pressure vessels and shield them from external hazards and provide heat rejection to the reactor pool.

Refueling of one power module is performed by disconnecting the module from the operational instruments. The reactor is then moved to the refueling area next to the spent fuel pool and refueled. This is done once every 18 months and in total one-third of the fuel assemblies are replaced (IAEA 2022). The spent fuel pool has capacity for 18 years of operational SNF (IAEA 2020). After the initial cooling, the SNF is moved to dry cask storage on the NPP site area, where there is capacity for 60 years of storage, the entire design life to the plant. From there, the SNF is moved to a national SNF management program/repository (IAEA 2022).

The second SMR considered in this report is the Rolls-Royce SMR. The SMR is recently entering the Generic Design Assessment (DGA) process (Rolls-Royce SMR 2022). This PWR SMR is considerably larger than the previous one with a thermal output of 1 358 MW and an electrical output of 470 MW (IAEA, 2022). It can be argued that which such high output, the plant is not considered an SMR as per the typical description discussed in Section 1. However, the reactor and the plant share many other common design features with SMRS with power plant having a repeatable, modular build and emphasis on standardisation (IAEA 2020). The reactor core contains 121 fuel assemblies, which have fuel rods arranged in a 17 x 17 assembly. The fuel is the conventional UO_2 with an enrichment of 4.95%. Gd_2O_3 is used as the poison, while control rods are used for reactivity control. (IAEA 2022).

In the Rolls-Royce SMR design the reactor is cooled with a three-loop, forced configuration. The fuel cycle is 18 months and the NPP is shut down for refueling. The fuel is refueled, and the used fuel is moved to a spent fuel pool. From there the fuel is intended to be transferred to long-term dry-cask storage (IAEA 2020). The plant uses industry proven practices for non SNF waste management and aims to minimize waste generation. More specifically, standardized waste treatment components are used together with a boron free operation (IAEA 2022). However more detailed plans on individual waste management methods and strategies have not been provided in the report.

According to Rolls-Royce SMR (2022), the plant layout is a conventional PWR concept, which has been designed with ASME and European Utility Requirements. The plant consists of a reactor, turbine and a cooling water island. Furthermore, the NPP site has auxiliary and service buildings, such as the interim storage buildings within a berm surrounding the main islands. This berm provides additional protection against external hazards (IAEA 2020).

Third reactor considered in this report is the BWRX-300 produced by GE Hitachi. The reactor is in pre-licensing phase (IAEA 2020). Being suitable for both electricity and district heat production, the BWR reactor has outputs of 870 $MW_{(th)}$ and 270–290 $MW_{(e)}$. The reactor uses a total of 240 GNF2-type 10 x 10 fuel assemblies (IAEA 2019a). The UO_2 fuel is enriched to a maximum of 4.95%. The GNF2 fuel assembly has the same length as the GE14 assembly (GNF 2016) and is therefore 381 cm long (Detkina et al. 2021) According to IAEA (2022) the "reactivity control is provided by control rods loaded with either B4C or Hf neutron absorbers and burnable neutron absorber loaded in the fuel rods." The BWRX-300 NPP contains a reactor-, turbine-, control-, and a radwaste building in addition to other supporting facilities. The reactor itself is situated in an underground section of the reactor building. The reactor building also contains a fuel pool.

In the BWRX-300 safety is ensured with a fully passive approach to safety system. This includes a natural circulation of the coolant, passive cooling systems and a gravity-driven decay heat removal system. Finally, the reactor pressure vessel is surrounded by a containment system, which allows for a dry containment of 72 hours without power.

According to IAEA (2022), the reactor has an open fuel cycle with either a 12 or 24 month refueling cycle. During refueling, either 32 or 72 fuel bundles are removed from the core (IAEA, 2022) and stored within the reactor building's pool. After 6–8 years of storage in the pool, the waste is transferred to dry cask storage outside of the reactor building to wait for final disposal (IAEA 2020). For LILW management, the plan is to minimize waste generation, through proven industry methods. They have stated that gases are treated with charcoal beds and other waste segregated for treatment and disposal (IAEA 2022). However, again no detailed plans on the waste management practices were provided.

Next reactor is a French reactor called NUWARD. The Design contains two independent PWR-type reactor modules, which each have an output of 540 $MW_{(th)}$ and 170 $MW_{(e)}$. The design is currently on a conceptual level (IAEA 2022). The reactors use the typical 17 x 17 fuel assembly, which is in use in most PWRs worldwide that have been shortened (IAEA 2019bhttps://aris.iaea.org/PDF/F-SMR_2020.pdf). It has not yet been publicly defined how much the assemblies are shortened. The fuel rods use UO_2 pellets with an enrichment below 5%. The reactor design does not use boron for reactivity control and relies on control rods and solid burnable poison for it. The two reactor modules are situated within a nuclear island, which is partially underground. The core containments are fully submerged in water. A fuel storage pool is also within the island (IAEA 2022) Turbines are situated within another building outside the nuclear island. The plant also has separate auxiliary buildings (IAEA, 2019b).

Safety in the NUWARD design is ensured with passive features. All systems required for ensuring the safety of the NPP for a minimum of three days are inside of the nuclear island. Cooling during the three days is ensured by the large amount of water surrounding the containment providing passive cooling. The core itself is small and thus in a case of core melting, it can be contained within the containment vessel. Operation of the reactor is boron-free with the usage of control rods and burnable poison. A 24-month fuel cycle is used in the reactor so that half of a core is refueled at a time. Spent fuel can be stored for 10 years on site (IAEA 2019b). Nuward (IAEA 2022) is assessing their waste disposal options utilizing best practices from the industry. No further details on the waste management have been presented as of now.

Fifth reactor considered in this report is the Korean – Saudi Arabian SMART-reactor. The design has an approval for the standard design in Korea. The reactor is an integral PWR and has an electrical power of 107 MW_e and 365 MW_t. Fuel in the reactor up to 5% enriched UO_2. 57 of the standard 17 x 17 fuel assemblies are used with a length of 2 m. Reactivity control is done with both control rods and soluble boron. Furthermore, fuel rods with Gd burnable absorber are used in the reactor. The design uses forced primary circulation (IAEA 2022). The nuclear power plant consists of a power block which includes two reactor containment -, auxiliary- and turbine generator buildings. It also has a seawater intake system, for which the turbine buildings can be coupled to for desalination of the water. The plant also has a compound building for radwaste treatment and a hot machine shop (IAEA 2020). The radwaste treatment building can treat all liquid radioactive waste by solidifying them with mineral exchanger. The plant also treats all gaseous waste by ensuring sufficient holdup times enabling decay time. Solid waste is treated with polymer solidification technology (IAEA 2022). The reactor has a 30-month fuel cycle. Spent fuel generated is cooled down in a spent fuel pool for 30 years (IAEA 2020). The total design life of the plant is 60 years.

The SMART reactor has automatic safety functions. Passive functions include a passive injection system and a residual heat system, which can keep the reactor in a safe shutdown condition for 72 hours and even longer if an emergency cooling tank is refilled. Furthermore, the reactor has a reactor shutdown system, depressurizer systems and a severe accident mitigation system.

Final reactor considered in this report is a SMR for district heating purposes currently being designed by VTT Technical Research Centre of Finland (Leppänen et al. 2021). The reactor is very small with a 50 MW size. The design uses 37 17x17 fuel assemblies with 24 control rods, but a hexagonal VVER-1000/1200 type assemble has also been preliminarily analyzed. The enrichment of the UO_2 fuel is between 2 and 3% with a burnup of 20–25 MWd/kgU. Only control rods, and thus no soluble boron is used for reactivity control. The fuel cycle of the reactor is approximately 36 months.

The plant layout for the design is still in early phases, but it was stated by Leppänen et al. (2021) that one or multiple reactors could be used. The reactor is surrounded by the containment that is submerged in a reactor pool. As the reactor is intended for district heating purposes without electricity generation, no turbine building is needed. The reactor is combined with heat exchangers to the district heating network. The plant can be constructed underground, partially underground or attached to an existing heat producing power plant.

Due to the low operating temperature of 100–300 °C, passive heat transfer can be achieved without valves or other moving parts. If the primary heat removal is lost for some reason, the temperature of the water in the containment raises over the boiling point, condensing on the cool outer wall of the containment. From there heat is transferred to the surrounding water pool. Only when the temperature in the reactor pool reaches the boiling points after several weeks of passive heat transfer, active measures are needed to cool down the reactor.

Main properties relevant to nuclear waste management of the described reactors are presented in Table 3-1. All aspects relevant for nuclear waste management have not been presented in the table, as they might be too complex to present in a condensed format. These include for example plant layout for determining decommissioning waste amounts or systems used in radioactive waste treatment on site. Some of these were presented above in descriptions of each selected reactor.

Table 3-1 Basic information of the SMR reactors compared.

Property	NuScale	Rolls-Royce	GE Hitachi	EDF	KAERI (Korea) and Saudi Arabia	VTT (Finland)
Name	VOYGR	Rolls-Royce SMR	BWRX-300	Nuward	SMART	LDR-50
Reactor type	PWR	PWR	BWR	PWR	PWR	PWR
Fuel	UO_2	UO_2	UO_2	UO_2	UO_2	UO_2
Assembly	17 x 17	17 x 17	10 x 10	17 x 17	17 x 17	17 x 17
Assembly length (mm)	2436		3810		2000	
Number of assemblies	37	121	240	76	57	37
Enrichment (%)	< 4.95	< 4.95	3.4–4.95	< 5	< 5	1.5 / 2.4
Fuel cycle/reloading cycle (months)	18	18	12–24	24	30	24–36
Discharge burnup (GWd/ton)	>45	50-60	49.6	-	< 54	6–18
Circulation	Natural	Forced	Natural	Forced	Forced	Natural
Design life (years)	60	60	60	60	60	
Approach to safety	Passive	Active and Passive	Passive	Passive	Passive	Passive
Thermal capacity (MW(t))	250	1358	870	2 x 540	365	50
Electrical capacity (MW(e))	77	470	270–290	2 x 170	107	-
Licensing status	Licensed/ Licensing ongoing	Certified design in the US	Detailed design	Conseptual design	Detailed design	Design phase
Reactivity control	Control rods, Boron	Control rods	Control rods, burnable absorbers	Control rods, solid burnable absorbers	Control rods, boron	Control rods, burnable absorbers

Out of the six reactors, the LDR-50 heating reactor stands out with a lower enrichment compared to the other reactors. Similarly, most reactors have a discharge burnup in the range of 45–60 GWd/ton, while the LDR-50 reactor has a much lower value of 6–18 GWd/ton. As discussed in Section 0, different burnups can have an influence on decay heat, radioactive nuclide content of the nuclear waste and different post-irradiation reactivity. Some preliminary assessment on spent fuel properties between the NuScale reactor, LDR-50, and a conventional EPR-reactor were made in the previous phase of this study (Keto et al. 2022).

Capacitites of the reactors were also vastly different. The smallest one, LDR-50 had a thermal capacity of only 50 MW and no electrical capacity, while the largest one, the UK SMR had a thermal capacity of over 1.3 GW and an electrical one of almost 0.5 GW. Followingly, reactors with larger capacities would result in larger quantities of spent fuel. It would be beneficial to study the ratio of volume of SNF generated to the output power in order to better understand what size of a reactor would be the most beneficial for minimizing SNF. The studies of Brown et al. (2017) and Krall et al. (2022) indicate that SMRs in general would perform worse on the energy to spent fuel ratio than conventional nuclear power plants.

While most fuel assemblies of the reactors were similar 17 x 17 type assemblies, the BWRX-300 reactor used a 10 x 10 assembly. This has no effect on the disposal strategy, since both assembly types are currently in use in Finland for NPPs. While an assembly length was not determined for all reactors, the length varied between the documented ones. This would require different length of canisters and possibly disposal holes in the final repository. Another option to consider with the shorter assemblies would be stacking two assemblies in one canister. More research should be conducted to ensure that disposal criteria such as subcriticality are met.

4. Spent fuel characteristics calculations and implications to waste management

The reactor concepts listed in Table 3-1 are all very similar to currently operating PWRs and BWRs with respect to the fuel and operating conditions, except for the LDR-50 whose operating temperature and pressure are much lower. Therefore, the spent fuel properties are also very similar with similar discharge burnup and when the impact of larger neutron leakage rate, feature of small reactors, is ignored. This was concluded when the reactor physics Monte Carlo code Serpent (Leppänen et al., 2015) was employed for calculations with 2D assembly geometry (Keto et al., 2022). Even the lower operating temperature of LDR-50 did not have significant impact on the studied features, i.e. decay heating power, spontaneous fission rates or post-irradiation reactivity. However, the 2D assembly calculations can provide an assembly average, which is not as representative for fuel in small cores than in larger ones. This is due to the relatively larger fraction of the core where neutron leakage affects notably.

4.1 Computational models

In order to obtain more accurate information on the impact of the end- and periphery-effects, a 3D full-core model of LDR-50 was calculated over the first cycle of the first core loading. The applied start-up core model had been constructed as part of the LDR-50 development, including control rod driving scheme iteration and adjustment of U-235 enrichment for the assemblies that are loaded as fresh but irradiated over only one or two cycles. The three-cycle 2.4 wt-% enriched assemblies comprise the bulk of the equilibrium core, but for the initial core such assemblies were positioned only in the outer corners. Other assemblies had enrichment 1.4 …1.8 wt-%. Gadolinium absorber was added to part of the assemblies either in 4 or 8 rods in the assembly and Gd content varying between 1 … 9 %. The core consists of 37 assemblies. A cross section of the core is depicted in Figure 4-1.

The full-core calculation was performed over the first cycle, or 580 effective full power days. A burnup step of 10 days was used, defined by the control rod repositioning interval. Additionally, follow-up calculations were performed for the corner assemblies simulating the remaining two cycles, or up to 1730 days. The assemblies were surrounded by similar assemblies with fresh fuel. The purpose of these calculations was to observe, whether the radial differences in rod burnups even out towards the end of the irradiation.

For comparison, following calculations were also performed:

- follow-up calculation up to 1730 days for the corner assemblies surrounded by equal fresh fuel assemblies in 3D
- 2D full-core calculation and the follow-up calculations for the corner assemblies alone, surrounded by similar fresh fuel assemblies (radially infinite outside the assembly of interest)
- 2D assembly calculations for each of the assembly types with average operating parameters, e.g. the power normalization set at the average power density 10.7 W/gU
- 2D assembly calculation with and without control rod presence in a 2.4-wt-%-assembly.

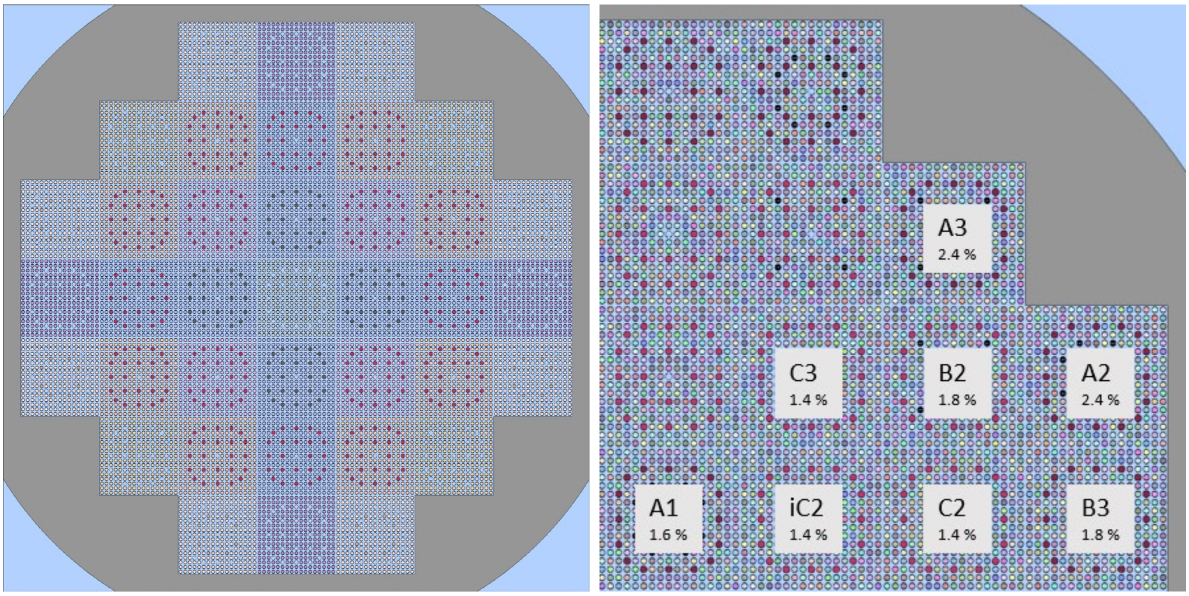

Figure 4-1. Left: a cross-sectional view on the LDR-50 core applied in the calculations. The different colours represent various fuel types. The double-circle patterns of red and dark blue dots represents the control rods in the inner core assemblies. The right figure shows the 1/8 symmetry slice of the core with assembly enrichments and identification labels.

4.2 Results

As an introductory illustration, the Figure 4-2 displays the power distribution in the reactor core at around halfway of the cycle. The plots coarsely show the impact of leaking neutrons in the axial ends and the radial peripheries of the core. With respect to Figure 4-1, the assemblies A2 and A3 are of the highest interest as they represent the enrichment characteristic to the assemblies irradiated over all three cycles. Naturally, they are likely moved closer to the central core after the first cycle. Figure 4-3 presents the calculated assembly burnups after the first cycle, suggesting that for other assemblies than the A2 corner assembly, the burnup distribution is rather even.

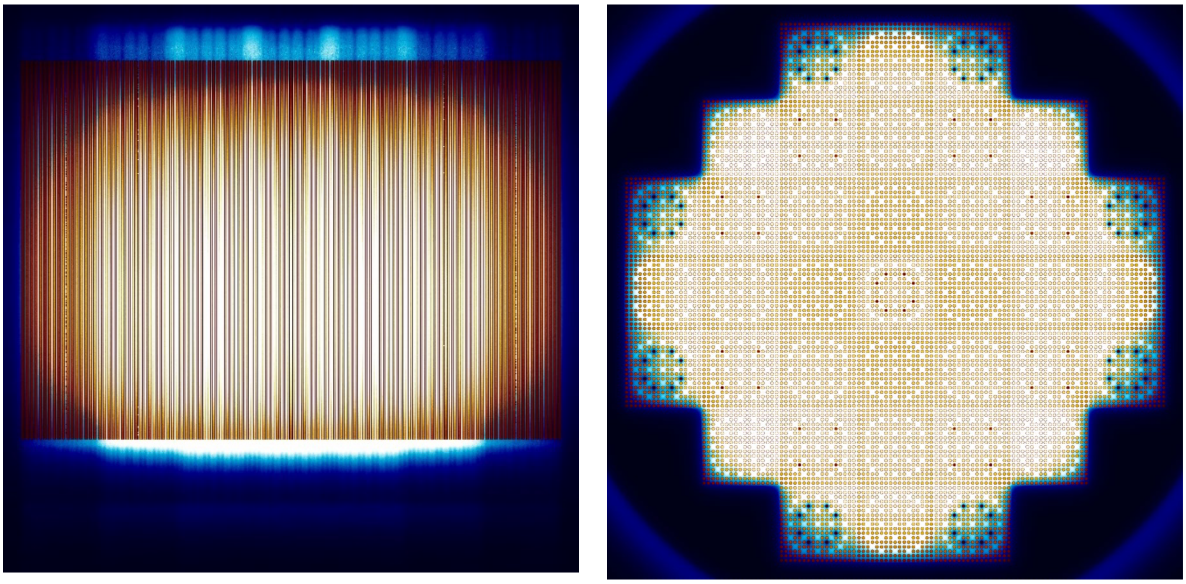

Figure 4-2. Power distribution at mid-cycle.

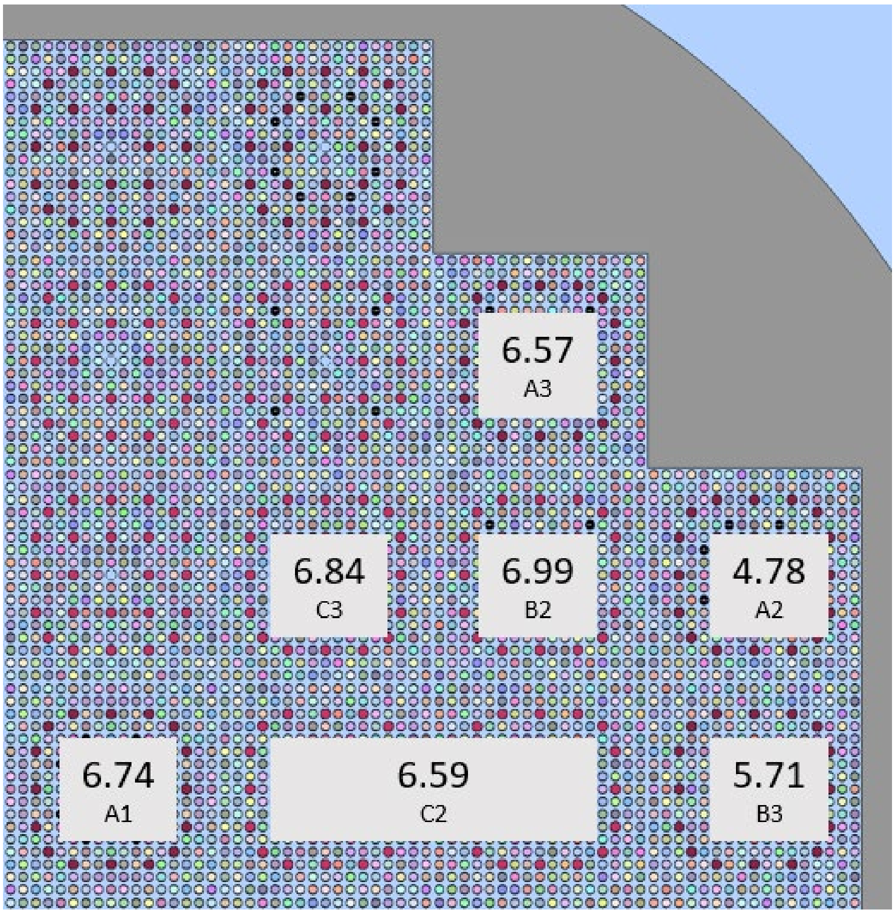

Figure 4-3. The calculated average burnup (MWd/kgU) for each assembly (except for C2 assemblies that are combined) after the first operating cycle.

Moreover, the rod-wise variation in burnup is very significant in the A2 assembly, as the burnup of the innermost corner rod was 10.5 MWd/kgU, but only 1.5 MWd/kgU for the outermost corner rod at the axial midpoint. With the full-core 2D calculation, the largest and smallest non-Gd-pin burnups in A2 were 7.3 and 2.1 MWd/kgU.

The impact of 2D approximation with respect to full-core modelling on decay heating power after the irradiation expectedly depends on the assembly position in the core. Based on the calculated model and the comparisons, the 2D model seemed to mostly underestimate the heating power for the inner assemblies up to 15% over the first 200 years after irradiation. When the outer assemblies are considered, the 2D model estimated as much as 45% higher heating power. These results are presented in Figure 4-4 and Figure 4-5. Outside these figures, for the C3 assembly the 2D calculation suggested up to 12% smaller decay heat. The relative difference showed increasing trend towards the end of the calculated period.

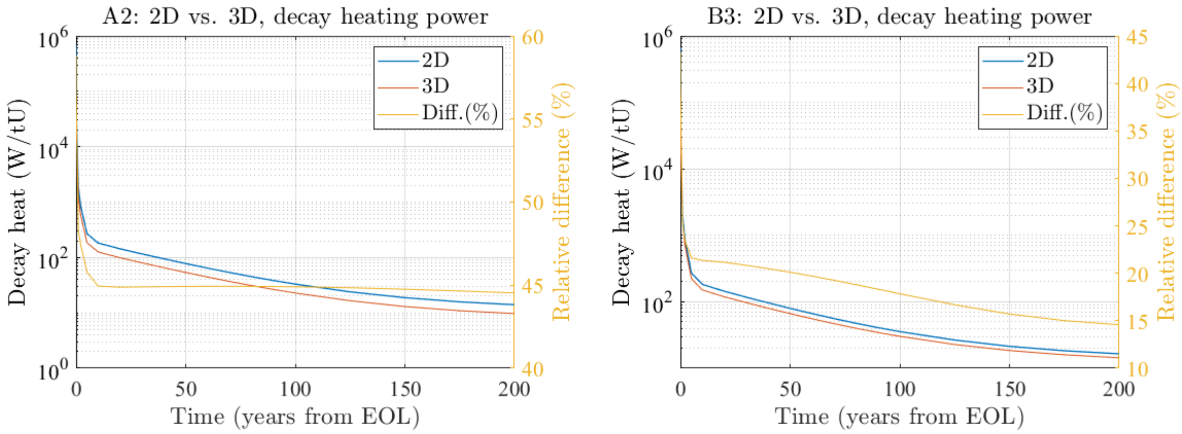

Figure 4-4. Comparison between decay heating powers calculated with 3D full-core (reference) and 2D assembly models for the peripheral assemblies A2 (left) and B3 (right).

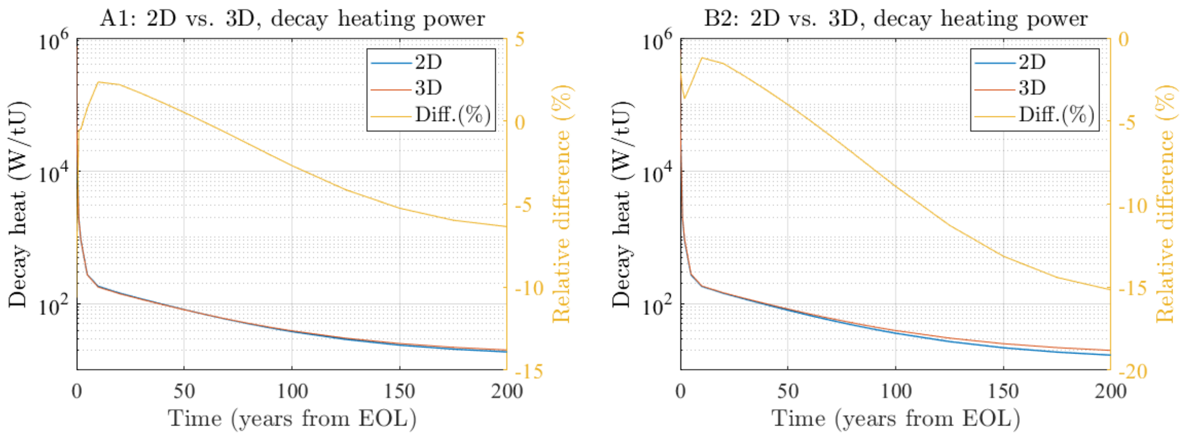

Figure 4-5. Difference of the predicted assembly decay heating power between the 3D full-core (reference) and 2D assembly calculations for the central assembly A1 (left) and an inner-core assembly B2 (right).

4.2.1 Full-core 2D calculation

As listed above, a full-core 2D calculation was also performed over the first cycle. For the A2 and A3 assemblies the calculation was continued to 1730 days corresponding the full 3-cycle irradiation in the configuration, where the irradiated assembly was surrounded by the respective fresh fuel assemblies. Such an approach was supposed to somewhat replicate the move of the peripheral assemblies to the inner core, although the concept of all adjacent assemblies consisting of fresh fuel is not completely accurate. The model should, anyway, provide some indication about the behavior of fuel depletion in xy-directions.

Based on the model, the spent fuel decay heating power is overestimated by more than 20% when an infinite lattice assembly calculation is used. However, the discrepancy should be considered with some scrutiny, since the models also contain issues deteriorating the comparability. First, the full-core model was calculated with cold shutdown temperatures for fuel and other materials. According to a quick check with comparative 2D assembly calculations, the cold model underestimates decay heating power by up to 6% during the first 200 years. Second, the burnup history was modelled in irradiation days for the core calculation and its follow-up, whereas burnup steps were applied in the assembly calculation. For the latter, the burnup of 16 MWd/kgU was used as the starting point for the decay calculation. The calculated average burnup for the full-core & follow-up -model was 16.2 MWd/kgU. The results are illustrated in Figure 4-6.

Figure 4-6 also shows the pi-wise distribution of the burnup at the moment of discharge. It suggests that notable differences still exist. For comparison, the smallest and largest pin burnup values for the 2D assembly calculation were 15.3 and 17.0 MWd/kgU, respectively. The burnable absorber pins are not included in this comparison.

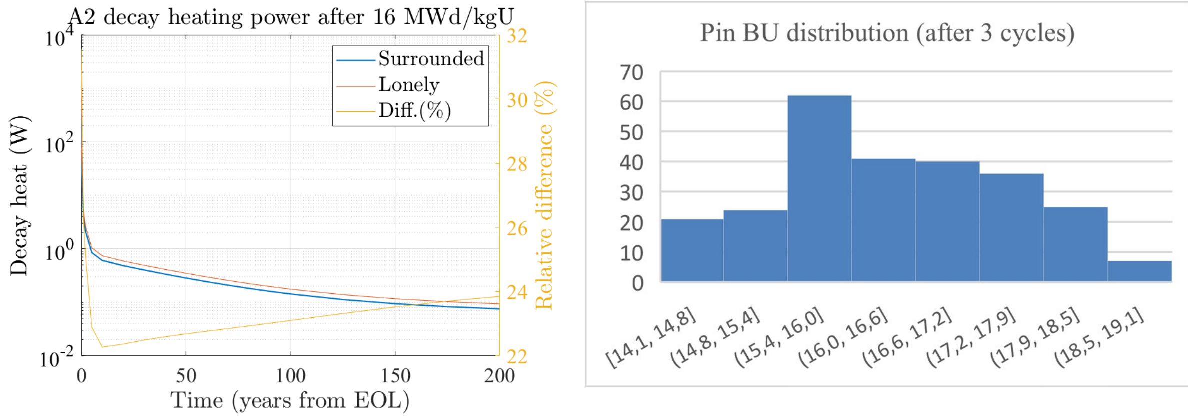

Figure 4-6. Left: comparison of decay heating power with two models. 'Surrounded' refers to the model where the A2 assembly was part of the full-core 2D calculation over the first cycle and after that irradiated between fresh assemblies to 1730. The 'Lonely' curve corresponds to the mere 2D assembly calculation in infinite lattice from the start. Right: the pin-wise burnup distribution of the 'Surrounded' model in the end of its irradiation.

4.2.2 Impact of control rods on criticality safety

The active use of control rods in LDR and e.g. in NUWARD is a special feature compared to typical PWR designs, where the reactivity control is mainly managed with soluble boron and burnable absorbers in the fuel. The presence of a control rod hardens the neutron spectrum and reduces the fuel depletion in its vicinity (Jutier et al. 2017). The harder neutron spectrum leads into larger inventory of Pu-239 and other fissile transuranic nuclides. It has an increasing effect on the post-irradiation reactivity and has to be taken into consideration in criticality safety analyses, if burnup credit is utilized.

A 2D burnup calculation was run for a 2.4 wt-% enriched LDR fuel assembly with and without control rods inserted. The difference of the post-irradiation multiplication factor k_{eff} is depicted in Figure 4-7. The 7 GWd/tU roughly represents irradiation over one cycle only and 20 GWd/tU irradiation through all planned 3 cycles. The results remind that the impact of the control rods is not automatically positive for the post-irradiation reactivity with Gd assemblies, as the keff after discharge at 7 GWd/tU is slightly higher for the assembly subject control rods over irradiation.

The calculations were performed in the same infinite lattice geometry as the burnup calculation, which is not representing any realistic storage or transport configurations. Therefore, the actual values of k_{eff} (showing notable supercriticality) are not the matter of interest but the difference between them. Another issue to note is that the control rods were either present or absent through the whole irradiation. The former of these options is not very likely to happen for a large part of the assembly, particularly in the case of 20 GWd/tU discharge burnup, so the curves represent somewhat extreme options. Furthermore, the average discharge burnup is less interesting in criticality safety analyses than the segments of lower burnup yielding higher reactivity. Such segments are typically in the axial ends, highlighting the importance of 3D modelling.

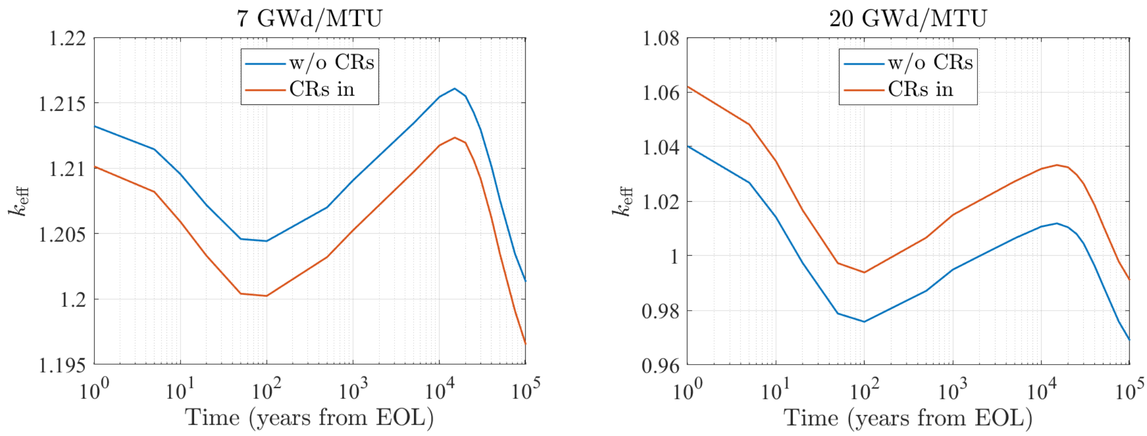

Figure 4-7. Multiplication factor k_{eff} calculated after discharge at 7 (left) and 20 GWd/tU (right) burnup. For the simulated 2.4 wt-% U-235 assembly, the latter is closer to realistic discharge burnup.

5. Societal acceptability of Small Modular Reactor Plants for district heating: A preliminary study of perceptions of Finnish municipalities

5.1 Introduction

In the current climate and energy crisis, Small Modular nuclear Reactor (SMR) plants are considered as one of the solutions for producing carbon neutral energy. Replacement of fossil fuel central heating systems is especially relevant for Finland as a Nordic country. Cities and energy companies are committed to achieve carbon neutrality in energy usage by 2030 and they are seeking means to achieve this goal.

As in safety-critical industries in general, ensuring the safety of an SMR plants is of utmost importance. As stated by the Radiation and Nuclear Safety Authority of Finland (STUK), the overall safety of the SMR facilities must be assessed properly to ensure safety of the people, environment and property. In the production of district heating, the plant has to be located relatively close to the population areas. The size of the protection zone and contingency area must be considered as necessary, based on the risk the facility poses to its environment (STUK 2019).

Recently, the public opinion in Finland regarding the use of nuclear has become more favourable (Nurmela 2022). Public support is pivotal to the growth of the nuclear power sector, therefore the issues related to social acceptance of SMRs should be given serious consideration (Sam-Aggrey 2014). Although SMRs seem to offer one potential solution for energy production in the future, the social and political challenges, including assumptions about levels of risks in terms of policy and regulation, marketability, and social acceptance must be addressed in regions where the nuclear power is already prevalent (Boldon et al. 2019).

This chapter presents results from a preliminary study on societal acceptability of SMR plants for district heating from the perspective of the local municipalities in Finland. Municipality's role is vital in local land use, planning, as well as informing and engaging residents in climate and energy policy projects. The study summarizes briefly key concepts and literature review related to the nuclear energy in Finland. Insights of experiences and expectations of the municipalities related to SMR plants and social acceptability are presented. The chapter concludes with preliminary implications from the municipality perspective addressing social acceptability topics in the situation where the small modular nuclear reactor plant may provide potential application for district heating in the future.

5.2 Key concepts

This chapter presents a few key concepts addressing societal aspects of the use of nuclear energy.

Social acceptance of energy technologies and applications has been studied in multiple theoretical and disciplinary perspectives and paradigms, as well as in multiple contexts over the years (Upham et al. 2015). The concept used to define the perspective of the public seems to vary and the concepts and frameworks of *social acceptance and social acceptability* are both used in nuclear energy and nuclear waste related studies.

Social acceptance can be defined as “a favourable or positive response (including attitude, intention, behaviour and use) relating to a proposed or in situ technology or socio-technical system, by members of a given social unit (country or region, community or town and household, organization)” (Upham et al. 2015). There are three principal dimensions of social acceptance that highlight different aspects: **community acceptance** includes procedural and distributional justice and trust; **market acceptance** customers, investors and intra-firm and **socio-political acceptance** includes acceptance of the technologies by the public, key stakeholders, and policy-makers (Wolsink, 2018).

Social licence to operate (SLO) refers to a local community’s acceptance or approval of a project or a company’s ongoing presence, beyond formal regulatory permitting processes (e.g., public hearing and rights for written interventions). According to the European Commission (2023), SLO derives from the acknowledgement that stakeholders may threaten a company’s legitimacy and ability to operate through boycotts, picketing or legal actions Concept of Social Licence to operate has been developed by Thomson & Boutlier (2011) and they categorise SLO by four dimensions (See also: Lehtonen et al. 2020):

1) **Economical legitimacy** including citizens’ perception that the costs and benefits of the project are shared equitably;

2) **Interactional trust** highlighting the competence, sincerity and responsiveness of the company and relevant state authorities in relation to citizens;

3) **Socio-political legitimacy** referring to procedural justice where legal and regulatory measures ensure transparency, access to information and participation, and

4) **Institutionalized trust** meaning the full mutual trust between the community and organisations.

Citizen engagement has various definitions that highlight the interaction between citizens and their governments, for example that city officials are encouraging citizens to discuss, assess policies and contribute to projects. In addition, it can be defined as efforts done by local government to involve citizens in all aspects of decision-making and governance, also known as public participation (Viitanen & Kingston, 2019). In nuclear domain **public participation in risk-related decision-making** is highly relevant. A study related to nuclear waste management is classifying public participation is six ladders highlighting in more detailed the different degree of participation: the public right to know, informing the public, public right to object, public participation in defining interests and determining the agenda, public participation in assessing risk and recommending solutions, and public partnership in the final decision (Di Nucci et al. 2017).

Social acceptability can be defined “the quality of being satisfactory and able to be agreed to or approved of”. Therefore it is a p**recondition for agreeing to something but does not automatically create acceptance.** It refers to considerations regarding whether an object is suitable to be accepted, even before it has materialised, have not been built yet. (Lundheim et al. 2022) This implies that social acceptability and social acceptance are different phases of the same process: acceptability before the implementation and acceptance after the implementation of a new technology.

In the nuclear industry community, **partnership and stakeholder confidence** have been institutionalised internationally e.g., in the activities of the Forum on Stakeholder Confidence (FSC) of the OECD Nuclear

Energy Agency. In Finland, this topic is addressed in regulatory frameworks via mandatory Environmental Impact Assessment procedures, multi-stakeholder expert committees, and national commissions of public debate (Lehtonen, 2020).

The key concepts highlight the social nature, dynamics and complexity of social acceptability and acceptance processes. On the other hand, informing and engaging residents in local decision making is formal regulatory requirement and normal part of the work for the municipalities. In this study the concept of social acceptability is used because SMR plants are yet not implemented. The focus is on the community level and the municipalities´ perceptions of the factors affecting social acceptance, experiences and means to inform and engage residents that can be applicable in the SMR plant context.

5.3 Overview of studies on social acceptability and nuclear in Finland

This chapter provides a brief overview of the Finnish studies related to social acceptability in nuclear domain in Finland in order to better understand the contextual societal factors affecting the implementation of SMR plants.

Trust has been identified as a key contributor to successful stakeholder engagement. Trust is diminished with the appearance of lack of transparency or excluding the public from certain deliberations related to the introduction of SMRs. Hence, the manner, in which the nuclear industry and the regulatory bodies introduce SMRs will be key to gaining the trust and acceptance of the public as it pertains to SMR technology (Sam-Aggrey 2014).

In Finland, the relationships between nuclear energy companies and Finnish society, when compared to other countries, has been viewed as more positive with less controversy. In Finland (and Sweden) there are long tradition of engaging with local communities and trust in experts and scientist is relatively high (Charnley-Parry et al. 2017). This is aligned with the findings of country-specific culture related to nuclear communities in Finland that emphasises the culture being built on high trust and low accountability (NEA 2019).

According to Strauss (2010), strong principles of local self-government make municipalities in Finland able to hold an absolute veto right on the siting of nuclear facilities. In early planning stages for hosting a nuclear facility, municipalities elaborate their land use plans, which aim at attracting businesses to the region and facilitate the licensing process. As Strauss indicates, in this context a transparent, open and democratic process could be undermined by “the absence of an unbiased facilitator, reluctant authorities and an unbalanced set of consultation practices in the licensing procedure”. The author concludes that public participation in nuclear facility licensing procedures requires “an accountable, open-minded authority that is responsible for, present and approachable during the conduct of public consultation.”

Recent survey results indicate the **positive attitudes toward nuclear in Finland are increasing** and the climate change have long been one of the key factors behind the popularity of nuclear power: 60 per cent of respondents has a positive attitude towards nuclear power and 11 per cent had a negative attitude (Nurmela, 2022).

Furthermore, recent survey on Finnish citizens´ attitudes towards energy confirms that same**. Overall support of nuclear has risen to 83 percent**. Support for nuclear energy has increased in all groups of citizens, regardless of gender, place of residence, age and political opinion. 65% of the respondents consider that the use of nuclear should be increased although the responses are highly varied between men (86% in favour) and women (45% in favour). Half of the respondents consider that nuclear waste can be safely disposed of in Finland's bedrock (Year 2021 39% agreed). 68% of the respondents have a positive attitude towards the use of small nuclear power in district heating. Furthermore, STUK and energy researchers/research institutes are considered to be reliable source of information (Energiateollisuus, 2022).

According to another recent survey conducted in the capital area of Finland, **almost half of the Finnish-speaking residents of the Helsinki metropolitan area were in favour of the commissioning of a small nuclear power plant in their own municipality**. 31 per cent of the respondents had a negative attitude, while 23 per cent said they did not have a positive or negative view. The survey highlighted the need for residents to communicate and have the opportunity to participate in project planning. On the other hand, there were certain groups that had the most negative attitudes towards SMRs: women, and age groups 30–39. Moreover, 24 per cent said they would take part in a protest if a SMR is planned in their own municipality. 57 per cent of respondents was in favour of holding a consultative municipal referendum (Kojo et al. 2022).

Waste management of SMR plants is an important factor affecting public opinion. In the context of **nuclear waste management,** the learning from the Finnish case studies show that whilst trust and confidence among decision makers and citizens in expert and industry are notable, there is a relative weakness of **a critical civil society – specially in a limited level of public participation and NGO involvement** (Litmanen et al., 2010). Findings also expose that local acceptance is not higher in the communities with experience of the nuclear waste repository due to the minor role given to the municipality than in the greenfield community (Vilhunen et al. 2022). Furthermore, studies confirm that siting procedures of nuclear waste repositories require **inclusive approaches, early access to information, stakeholder involvement and openness to unforeseen results** (Di Nucci et al. 2017). Studies in Finland indicate that ensuring empowerment and encouragement potential host communities to undertake review and information activities is not so heavily applied although the institutional arrangements ensure that the candidate municipalities have an economic incentive to host a facility (Kari et al. 2021).

Possibilities of addressing and enhancing social acceptability of SMR plants in Finland is relative good; the trust in authorities and scientists is relatively high and the public opinion is increasingly positive toward the use of nuclear energy as one means to address the climate change. On the other hand, studies indicate varying public opinion among residents and reveal need for strengthening the municipalities' role in enhancing public participation.

5.4 Method and research context

Major cities in Finland have published ambitious climate neutrality target years and are preparing for transition to climate neutrality. Cities of Espoo, Vantaa, Tampere, Jyväskylä and Vaasa were selected as case cities. Selection was based on their interest in SMRs, size, location in different areas in Finland and their use of coal/wood/peat in energy production. All the case cities have committed to the goal of reaching carbon neutrality by 2030 although they all have different strategies for attaining it. (See also: Examples of Finnish cities carbon neutrality targets and suggested means to reach them in Huovila et al. 2022, 3-4). In addition, Pyhäjoki was included due to their recent experiences related to societal acceptability topics and resident engagement that could be applicable to SMRs.

Municipalities' role as stakeholders in the siting and addressing the social acceptability in their communities is vital. Their role is determined by laws and regulations. Municipalities are responsible for providing residents with statutory basic services including fundamental rights and participation in civic activity (Suomi.fi- portal). In general, the local municipalities' role becomes important regarding land use in general planning and zoning areas for possible SMR plants. In addition, Environmental Impact Assessment (EIA) includes public hearings and events in potential host municipalities to encourage citizens to participate.

Espoo and Tampere have decided to investigate the usage of SMR plants as one means to produce district heating. None of the cities had yet conducted a survey for the residents to study resident opinions about SMR plants nor there has been extensive public discussion over the topic. Figure 5-1 below briefly summarises the basic information related to case cities' energy strategies and approach to SMR plants.

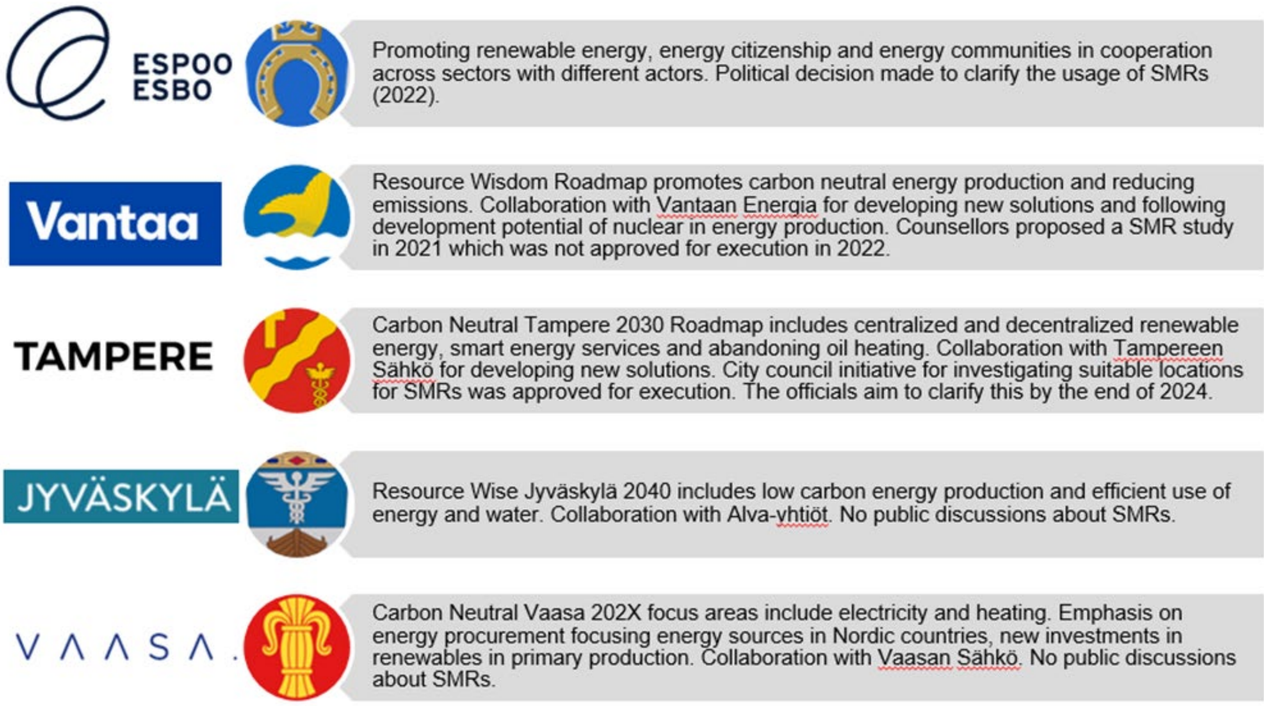

Figure 5-1. Cities' energy strategies.

For the purpose of this study, representatives of cities Espoo, Vantaa, Tampere Jyväskylä, Vantaa, as well as Pyhäjoki community were interviewed. Six interviews including eight interviewees were conducted between September and November 2022. Interviews lasted 1,5 hours. Interviewees were managers and experts in sustainable development, built environment, environmental and master planning/zoning. Interviews were semi-structures and the themes covered following topics: city´s energy strategy, approach to SMRs and perceived societal acceptability factors, experiences in social acceptability and resident engagement in energy and climate change related projects. Pyhäjoki interview was about experiences and learnings related to societal acceptability and resident engagement. Interviews were voluntary, open and reflective, and the topic was seen as interesting. Interview data was thematically analysed, and main findings summarized.

5.5 Results: Municipalities experiences and expectations in addressing societal acceptability issues

In general, there is significant need for information related to what are SMR plants about, what are the benefits, impacts, risks and options, and timelines for possible implementations. From the resident's perspective, the meaningfulness in everyday life needs to be considered and articulated including alternative solutions. It was noted that the acute energy crisis and climate change is possibly increasing the acceptability of the SMR plants for district heating.

5.5.1 Experiences

Regarding the role of **municipalities to inform and engage the residents** in the energy and climate related projects, there was an emphasis that city municipalities should have **an active yet neutral position** between different **stakeholders to maintain trust and credibility in the community.** It was suggested that cities could be acting as mediators between different stakeholders and examples were given for collaborating and organizing meetings for residents together with different stakeholders including NGOs, energy companies and resident associations.

It was noted that reaching and engaging residents is a big challenge in the cities and there is no one fit for all solutions to tackle the issue. Openness and transparency in communication was highlighted in multiple ways. Benefits and risks for the public need to be clearly and understandably communicated, and technical jargon should be avoided. Information should be **objective and neutral** – preferably not coming from an interested party such as energy companies but rather from impartial scientific and research entities. In addition, if something cannot be told to the public for some confidentiality or other reason, there is a need to explain reasoning behind it. This related also to maintaining the trust to the municipalities and avoiding assumptions that they are hiding something or taking a side of an interest partner. Interviewees highlighted **the inclusive approach to information sharing and resident engagement** including following topics:

- Using multiple channels to communicate the information is important to reach various representatives of the public and different age groups. Information has to be clear, understandable, accessible, regularly updated and provided in sufficiently early phase. Examples were given about using regularly local new papers, organizing events for residents and streaming them, as well as transparent and updated information portals where the resident can follow how the cities targets are being achieved.
- Role of social media in informing and engaging resident has increased and it can be useful and flexible way in reaching variety resident groups. On the other hand, the importance of being cautious and addressing possible buzz on social media platforms needs to be considered. Multiple examples were given how different projects have been negatively affected, and even cancelled by the reactions in the social media including distribution of mis- and disinformation.

Language challenges cannot be underestimated in public information sharing and engaging. Although the official languages in Finland are Finnish and English there are resident groups in the cities who do not speak or understand Finnish or Swedish (or English), and there are people who use sign language. Language consideration implies an inclusive approach as well to ensure the information reaches various groups of people, who have different needs, capabilities and limitations. An Example of providing information to the residents via schools was mentioned as one mean to tackle the challenge.

5.5.2 Expectations

There is yet not relevant information about the SMR plant available which makes planning and zoning areas for possible SMR plants impossible. Municipalities also need political decision to investigate the topic in their area; only in Espoo and Tampere this has happened. Municipalities need information for example about criteria and boundary conditions related to location, safety and security, nuclear waste management of the plant. It was noted that residents´ fears and concerns need to be heard and addressed and the voices of opponents should not be suppressed to maintaining trust and respectful interaction. For residents, it does not necessary matter if the NPP is big or small – a nuclear facility in the vicinity of a city is a nuclear facility even, if the probability of accident is low.

Related to planning differences possibly affecting social acceptability were mentioned. There might be more opposition if a new location is needed versus the plant is located in the existing district heating production area. Workplaces are considered to be more preferable places compared to homes. In general, if SMR plants are perceived as something wanted versus something residents are forced to have in their area matter as well as how the SMR plants are introduced; if residents have negative perceptions in the beginning, it is difficult to change afterwards with the facts.

Training, collaboration with energy companies, research organisation and regulators, using change agents within the cities, recruitments (including consultants for impact assessment needed for the planning) were given as examples how to build competences related to SMR plants. Objective knowledge and competence building is needed also for informing and engaging the residents in a hasty manner. It was highlighted that planning and zoning processes may take a long time. Specially if citizens' complaints can prolong the process.

Need for efficient, early phase, inclusive information sharing, and engagement methods are vital for addressing social acceptability topics. It was considered that formal regulatory processes included in EIA and master planning and zoning processes are not considered to be enough. There is a need for creating genuine possibility for changes based on residents' feedback and development ideas. New approaches of informing and engaging are needed taking into consideration, how you ask residents affects the answers you gain. A big challenge remains: how to gain residents' attention in real life events and in social media platforms? How to reach and engage resident groups in novel ways? How to anticipate and address the social media downsides, like polarized discussion and mis- and disinformation which can jeopardize the project and create mistrust toward municipalities?

Due to novelty of the topic, there is yet no guidelines or practices how to collaborate in the region or in the national level. Furthermore, nuclear related regulations and STUK as a radiation safety regulator bring new aspects and connections to the city municipalities. There are unforeseen risks, uncertainties, and open questions. What will be the first city to implement the SMR plant and face the risks? Who is taking a lead of informing and engaging the residents within the city organisation and in the region? Nevertheless, there is a need for national, regional and internal co-ordination and collaboration between the cities.

5.6 Discussion and conclusion

In agreement with the existing literature, the need to build and maintain trust through transparent communication with the public was evident. It is important to build capabilities for informed, evidence-based decision-making and start discussing social acceptability issues in advance, before the plans and reports are ready. Residents should not be left with the impression that things are planned in behind the closed doors.

In addition, the rights of the public (to know, to be informed, to object, to define interests and determining the agenda, to assess risks and recommend solutions and to participate in decision-making) were well considered. This was evident in the awareness of importance of inclusive approach towards citizens' participation and communication. Regarding economic legitimacy, the objectivity and neutrality of the information provided was highlighted to allow proper consideration of various factors and not to overshadow decision-making by business interests. Municipalities also need information for own capacity building – for internal discussions and sharing of insights, while more technical and detailed information should be planned for the purposes of zoning and citizen engagement. In essence, we consider the expressed need for information and raising awareness by representatives of Finnish municipalities as a positive finding. Especially from sustainability and future generations perspectives, the role and responsibilities of municipalities in making informed decisions seem to be well recognized.

Perceived risks are important aspects of building social acceptability in a safety-critical domain. This is a long-term issue as well, as a potential SMR plants and the nuclear waste will be handed over to the next generations to handle. Essentially, ensuring safety and potential benefits for the society are the most important aspects in short-term and long-term. Finally, there should be awareness how the relationship between the city / municipality and the licensee applicant is build and developed: trust needs to be built in the process, but too close relations pose risks on economic pressures and the ability to make decisions independently.

6. Summary

Deployment of SMR technology is considered important for achieving the carbon neutrality goal of Finland before 2035. Safe and sustainable waste management is however a prerequisite for deployment of SMR technology.

Regulatory framework concerning nuclear energy is currently under reform in Finland. One of the goals of the reform is to update the Nuclear Energy Act (1987/990) so that it takes better into account new developments in the nuclear technologies, including SMRs. Considering current NPPs in Finland, the licence holder producing the waste is responsible for the waste management and is therefore the party with the waste management and financial provision obligations. One question raised by discussion around SMRs is whether these obligations can be transferred to another party, for example considering various small district heating plants with separate license holders and sites. Based on review of the current legislation, this is already possible, but not yet a process that has been tried in Finland. The preferable option is to apply Nuclear Energy Act (1987/990) section 30 relying on good cooperation between the different parties. Further development of business models is however also required before centralised or hybrid waste management models could be applied in large scale.

The need for a government decision principle for a nuclear facility to be used for interim storage or in final disposal of spent nuclear fuel or LILW depends on the total activity of the waste, the limit being higher than 100,000 TBq or alpha activity higher than 1000 TBq (Nuclear Energy Decree, section 7). It is therefore likely, that in a centralised or hybrid waste management model for SMRs a decision-in-principle is needed, at least for interim storage and disposal facility for SNF. In addition, support from the municipality is a prerequisite for this type of facilities. The current final disposal site for SNF (ONKALO) is licensed for the SNF from the currently operating NPP units OL1-3 and LO1-2 and not for any additional waste from SMRs. The prerequisite for using ONKALO for any SMR waste is that the repository would be licensed for the new waste as well and that municipality of Eurajoki would support this plan.

Some of the current regulations, including ban to handle waste outside Finland (Nuclear Energy Act, section 6a), may be able to limit deployment of some SMR technologies relying e.g. on reprocessing of the SNF. There is also other issues that may be relevant for SMR waste management that need to be considered in the regulation reform and in updating of YVL guides. For example, placement of waste with very different inventories and characteristics into a same final repository.

The basic characteristics of six different LWR-SMR reactors were compared as examples within this report including VOYGR (NuScale), Rolls-Royce SMR (Rolls-Royce), BWRX-300 (GE Hitachi), Nuward (EDF), SMART (KAERI and Saudi Arabia) and LDR-50 district heating reactor (VTT). In general, the capacities of the reactors vary significantly with the Finnish heating reactor having the lowest output power and the Rolls-Royce SMR the highest. All of these reactors rely on UO_2 fuel and have similar enrichment rates (a little less than 5%), excluding the heating reactor with significantly lower enrichment rate (1.5/2.4%). For most of the example cases the discharge burnups varies from 45–60 GWd/ton, but again the Finnish heating reactor has significantly lower burnup (6–18 GWd/ton). Differences considering for examples decay heat, fission products and risks linked to criticality safety need to be taken into account in final disposal, especially considering centralised spent nuclear fuel interim storages and final disposal repository. There are also small differences in the waste assembly forms between the example reactors meaning that there would be differences in the detailed encapsulation designs between the example cases (inner parts of the canister and canister height). Based on the analysis, even the basic comparison shows that there will be differences in the basic SPF characteristics between the LWR-SMRs. This may result in some challenges when defining the waste acceptance criteria (WAC) for the spent nuclear fuel deposited to a centralised repository.

In order to quantify spent fuel characteristics, preliminary 2D calculations were made with two different example reactors (NuScale Power Module^{TM} and Finnish heating reactor design LDR-50) with the continuous-energy Monte Carlo code Serpent in the previous phase of the project (Keto et al. 2022). Based on the 2D calculations, the main differences between the SMR and NPP spent fuels was linked to lower burnups in the SMRs. Considering waste management, the lower levels of decay heat and ionizing radiation could make the handling of the waste less demanding. However, 3D calculations were needed to determine the effect of the smaller SMR core size and to address further the potential uncertainties remaining with criticality safety. During 2022, Serpent 3 D calculation were made considering the LDR-50 reactor. Preliminary data shows some difference between the 2D and 3D cases, but since the calculations were performed with the start-up core, the results are not fully representative with respect to the total anticipated spent fuel inventory. Furthermore, due to difficulties linked with the heavy calculation process and difficulties in interpretation of the data, the presented results are rather coarse even with the model limitations. Calculations are continued within the next phase of the project.

Social acceptability is another vital prerequisite for deployment of SMR technology. Municipalities have veto right in relation to siting of the plant in their area and their role in addressing the social acceptability topics in their communities is important. Insights of experiences about informing and engaging residents in climate and energy policy projects and expectations of the municipalities related to SMR plants and social acceptability were studied via municipality interviews. Results highlight the need for objective, transparent information and internal, regional co-ordination and communication and collaboration between the cities and the stakeholders. In addition, efficient and inclusive early phase information sharing, and resident engagement methods are needed in order to address the social acceptability of the SMR plants in a proactive manner.

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