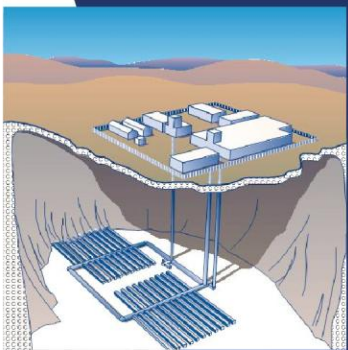

Joint Study on the Potential Impacts of Small Modular Reactors on Multinational Cooperation at the Back End of the Fuel Cycle: Appendices 1, 2, 3, 4, 5 & 6

MCM Project Ref: 2207

27th November 2025

ERDO

MCM

Document Authorisation

Project ID	2207 – Potential SMR Impacts on Multinational Cooperation		
Project Name	Joint Study on the Potential Impacts of Small Modular Reactors on Multinational Cooperation at the Back End of the Fuel Cycle		
Version	2.0		
Description	Final report for publication.		
Date	27th November 2025		
	Prepared by	**Checked by**	**Approved by**
Name	Jake Kinghorn-Mills (MCM) Neil Chapman (ERDO) Leon Kegel (ERDO) Charles McCombie (ERDO)	Roger Thetford (MCM) Tara Beattie (MCM)	Alastair Clark (MCM) Ewoud Verhoef (ERDO)
Signature	*N/A – Internal*		

Preface

This document presents detailed underpinning material for the accompanying *Joint Study on the Potential Impacts of Small Modular Reactors on Multinational Cooperation at the Back End of the Fuel Cycle* report. It is designed to be used as a supplement. The report references each of the six appendices contained herein, by number, when relevant.

This joint study project is an evaluation of how the challenges of managing radioactive wastes from Small Modular Reactors (SMRs) may affect the drivers for multinational radioactive waste management (RWM) solutions. The project is evaluating technical, strategic, economic and planning issues associated with SMR fuels and wastes. It includes an assessment of how a shared or a commercial multinational repository project could be impacted in terms of concept, design, economics and scheduling if a number of users were to require disposal of SMR fuels and wastes.

Any specific SMR vendors and SMR designs in this document have not been named as a result of any involvement in the project. They have been named based on references in the open literature. Furthermore, the down-selection of specific SMR designs has been conducted in a purely data availability-led process which is fully outlined in the document. This study does not advocate or endorse any specific SMR design but uses specific data available in the open literature to enable a more realistic understanding of the size and scale of SMR deployment and radioactive waste generation so as to better understand the potential impact on the back end of the fuel cycle.

Any specific countries in this document have not been named as a result of any involvement in the project. They are either named in regard to a scoping review of the open literature to understand global interest in SMR deployment, or are named as examples to illustrate the size and scope of typical nuclear power capacities, radioactive waste inventories, nuclear skills and expertise, radioactive waste facilities, etc.

It should be noted that the specific technologies and national plans included or referenced in this document reflect the SMR landscape at the time of initial drafting; April 2024.

Contents

Appendix 1: Potential Global SMR Deployment

As shown in Figure 1, globally, there is a large gap between the power provided by nuclear power reactors and the expected demand for sustainable, low carbon power, even after taking into account the deployment of planned conventional nuclear power plants.

Policy makers and energy providers are expecting SMRs to fill a significant part of the global power generation capacity gap (~66 GWe by 2035 and around ten times this at over 660 GWe by 2050, as shown by the orange part of Figure 1), with action required in the near-term.

The expected SMR contribution to the ~66 and ~660 GWe nuclear capacity requirements in 2035 and 2050 is shown in Figure 2 and Table 1. The increase from effectively zero to ~32% of the capacity gap in 2035 and rapid increase to ~57% over the following 15 years (peaking at ~67% in 2040) places an enormous reliance of the global energy market on SMRs and illustrates the drivers for the scale of SMR Research and Development (R&D) efforts being observed at this time.

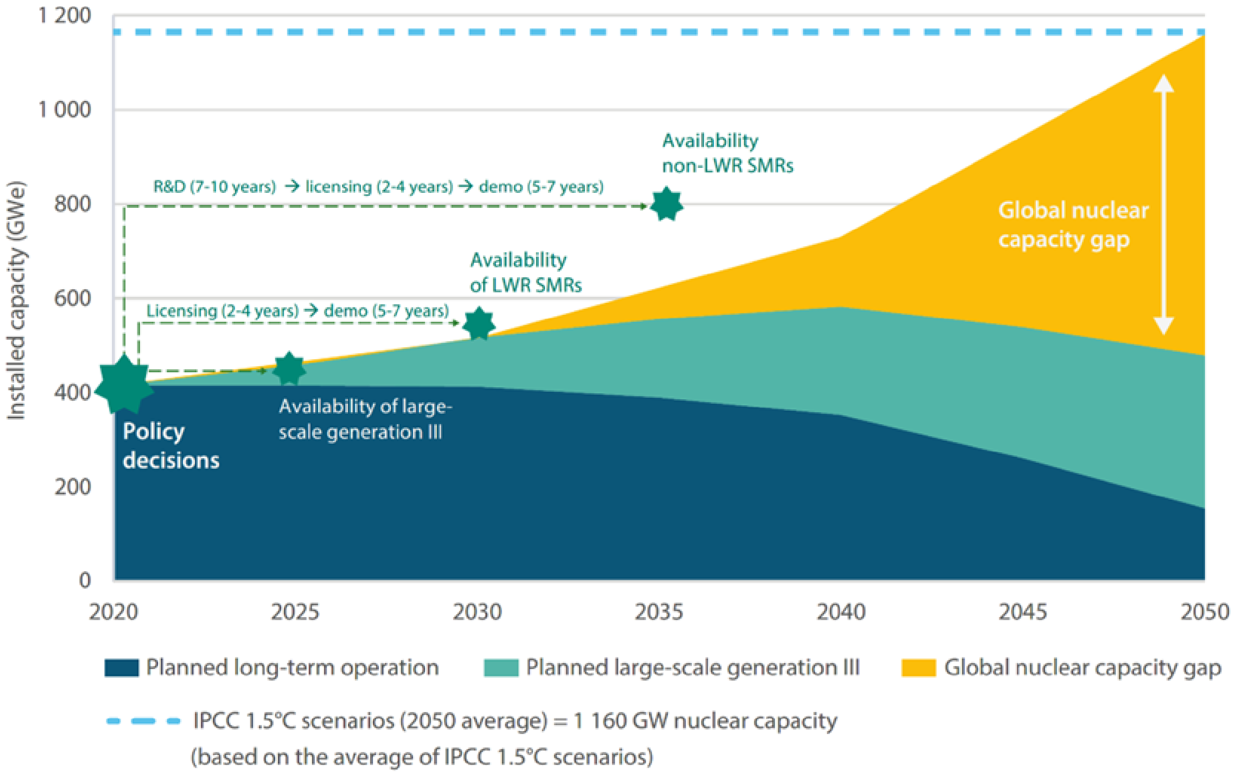

Figure 1: The global nuclear power capacity gap expected as a result of the shut-down of nuclear power plants in the upcoming decades and assumptions in regards to the role of nuclear made by the Intergovernmental Panel on Climate Change (IPCC) for global energy generation scenarios which limit average global warming to less than 1.5°C. LWR stands for Light Water Reactor. Diagram copied from the Organisation for Economic Co-operation and Development's Nuclear Energy Agency (NEA) [1].

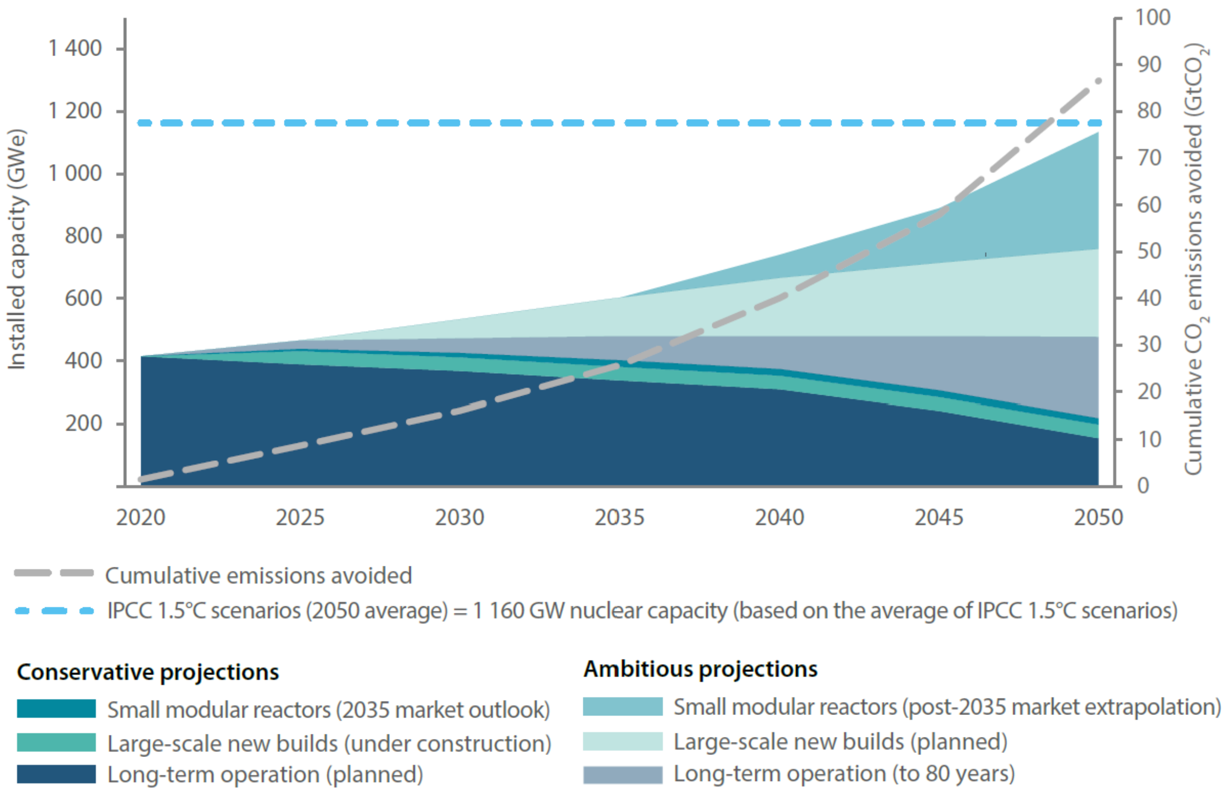

Figure 2: The potential contribution of nuclear power generation in the pursuit of net-zero global emissions. Diagram copied from NEA [1], where the SMR 2035 market outlook is a high-case assumption [2].

Table 1: Estimated global SMR deployment, where all values are approximate given they are drawn from Figure 2 and Figure 1.

	SMR Power Generation by Year (GWe)					
	2025	**2030**	**2035**	**2040**	**2045**	**2050**
SMR (2035 market outlook) *(drawn from Figure 2)*	4	14	21	21	21	21
SMR (post-2035 market extrapolation) *(drawn from Figure 2)*	-	-	-	75	175	375
Global nuclear capacity gap *(taken from Figure 1)*	-	-	66	144	396	665
Potential SMR contribution for closing the nuclear capacity gap *(calculated based on above rows)*	-	-	32%	67%	49%	57%

Appendix 2: Global Interest in SMR Vendors & Designs

This Appendix presents a scoping review of the current global SMR end-user landscape, based on published financial or strategic commitment, e.g., collaborative development agreements or direct funding of SMR vendors. It aims to establish the current strategic interest in specific SMR technologies and vendors. It follows a regional approach, covering countries with published interest in SMR deployment.

The aim of this review is to systematically identify the most likely near-future deployable SMR technologies to better focus the scope of this study. This summary is presented in Appendix 2: Section 9. However, the field is changing and expanding rapidly; this outline summarises interest based on the available literature as of December 2023.

1. European Union

1.1. Belgium

The Belgian government recently agreed to close all seven of the country's nuclear power reactors. However, the government plans to dedicate €100 million, over four years, to investigate the potential for SMR deployment, and to verify whether sustainable nuclear energy is technically feasible for Belgium [3]. Belgian engineering company Tractebel Engie is working with EDF and other partners on the PWR-based NUWARD SMR project [4], but the Belgian government wants the funding to be used to research SMRs that do not use water as a coolant.

If Belgium chooses to explore lead-cooled SMRs, it is expected that lessons learned from the Multipurpose Hybrid Research Reactor for High-tech Applications (MYRRHA) accelerator-driven research reactor could be applied. Although Myrrha is not an SMR, it shares some principles of Generation IV reactors, e.g., compactness, a novel coolant, use of the fast neutron spectrum. It is managed by SCK-CEN at their site in Mol.

The development experience for MYRRHA is considered to be similar to the development pathway required for innovative SMRs, although the objective remains fundamentally different. "Innovative SMRs will produce electricity," explains SCK-CEN Director-General, whereas "with MYRRHA, we need those fast neutrons to demonstrate that we can convert highly radiotoxic waste into waste that is no longer toxic, gives off less heat, and for the most part has a shorter lifespan. With that process, transmutation, we can reduce the ecological footprint of a future geological repository" [5].

In November 2023, the SCK-CEN Director-General announced that the first SMRs in Belgium could be online by 2040. A Belgian-Italian-Romanian consortium has been established, with support from the US company Westinghouse Electric Company LLC to develop and "deploy globally" lead-cooled fast reactors. The consortium aims to begin with a small reactor to demonstrate the technological and engineering aspects of a commercial SMR. This test plant will also be built at SCK CEN's facility at Mol [6].

1.2. Bulgaria

In Bulgaria, in January 2021, the government approved plans to build a new nuclear power plant at the existing Kozloduy site and announced discussions with external partners for the potential roll-out of SMRs [7].

In November 2021, the US-based Fluor Corporation signed a memorandum of understanding (MoU) with Bulgarian Energy Holding EAD, related to the potential construction of new SMR units in Bulgaria. Fluor and Bulgarian Energy Holding agreed to co-operate on evaluating Bulgaria's existing coal-fired fleet for potential nuclear SMR re-purposing projects using SMR technology being developed by US company NuScale Power, in which Fluor is the majority investor. They will also assess the Bulgarian supply chain and other related services [8].

Bulgarian Energy Holding EAD is a group of companies engaged in electricity generation, supply, and transmission; natural gas supply, transmission, and storage; and coal mining. The company is wholly owned by the Bulgarian government, is the largest state-owned company in the country and operates Kozloduy, the country's only nuclear power plant, which has six reactor units.

"The necessity of implementing safe and reliable clean energy power at Kozloduy is well understood in Bulgaria and eastern Europe," said Valentin Nikolov, Chief Executive Officer of Bulgarian Energy Holding. "Coupled with NuScale's small modular nuclear reactor technology, we can achieve European and Bulgarian policy goals in a more diversified power market, improve the security of energy supply and add sufficient value for the national gross domestic product."

1.3. Czechia

The Czech government sees SMRs as potentially useful in an emerging hydrogen market and as a source of heat for centralised district heating systems [9].

In September 2022, Rolls-Royce SMR signed a MoU with Czech nuclear engineering and manufacturing firm Škoda JS. The aim is to explore areas of collaboration for the Rolls-Royce SMR plant, for deployment both in Czechia and broader central European regions. Under the MoU, both companies will work together to understand how the capabilities of Škoda JS, in areas of nuclear engineering and manufacturing, can support the deployment of Rolls-Royce SMR power plants across Europe. State power company ČEZ Group has already signed SMR agreements with reactor developers NuScale, GE Hitachi, Rolls-Royce SMR, EDF, Korea Hydro & Nuclear Power, and Holtec International. A MoU between Holtec and ČEZ, will enable continued exchange between the parties for evaluation of SMR-160 deployment feasibility at the Temelín site.

ČEZ has announced ambitious plans to deploy a pilot SMR as early as 2032, an additional two to follow between 2035 and 2040 and SMRs with a total capacity of over 1 GW after 2040. In July 2023, the president of Czechia backed the 2032 date, and stressed the role of nuclear power in the country's future energy mix.

ČEZ said the announcement of plans for a first SMR unit follows the signing of an agreement in September 2022 with the region of South Bohemia for the establishment of the South Bohemia Nuclear Park, where a pilot SMR project will be developed. In December 2022 ČEZ announced that it began geological surveys for first SMR at the Temelín site to determine the precise geological conditions, along with other factors that could affect the project. The geological surveys will use 30-metre-deep boreholes to examine the composition of rock at the site.

Beyond the Temelin site, ČEZ has tentatively identified two preferred sites for its two follow-up SMRs: the coal-fired generation sites at Detmarovice and Tusimice. Both sites will undergo "further intensive exploration and monitoring works" before it is clear whether they are suitable locations for SMRs.

In December 2023, The Czech government approved a Ministry of Industry and Trade roadmap that provides an overview of possible sites and investment models for the deployment of SMRs in the country, mostly at existing coal sites. A government statement said, based on the roadmap, SMR technology will be included in state energy and development policy. The roadmap recommends speeding up the process of site selection and preparation so construction of the first SMRs can begin in the first half of 2030s.

1.4. Denmark

No official governmental plans currently exist for SMR deployment in Denmark. However, SMR R&D activities are being developed by private companies such as Copenhagen Atomics and Seaborg Technologies. Seaborg has developed a power barge design which uses two of its modular, compact molten salt reactor (CMSR) units. Seaborg Technologies signed an MoU with Samsung Heavy Industries in April 2022 to progress with barge manufacturing [10].

In March 2017, the public funding agency Innovation Fund Denmark awarded Seaborg with a grant to "build up central elements in its long-term strategy and position itself for additional investments required to progress towards commercial maturity." This is the first Danish investment into nuclear fission research since the country introduced a ban on nuclear power in 1985. In December 2020, the American Bureau of Shipping issued a feasibility statement regarding the reactor's use on barges. This is the first stage in the Bureau's five-phase New Technology Qualification process. Seaborg aims to deploy the first full-scale prototype power barge by 2025.

1.5. Estonia

To secure and increase its energy generation capacity, and to reach climate targets, Estonia is planning to deploy its first nuclear reactor; an SMR, within approximately ten years.

In April 2021, the Estonian government officially approved the creation of a nuclear energy working group (NEWG), headed by the Estonian Environment Minister, to investigate the possibility of introducing nuclear energy in Estonia. The NEWG will analyse technologies and projects under development in other countries, assess whether the development of a nuclear power plant should be carried out by the state or the private sector, and determine options for private-public co-operation. Nuclear energy labour and expertise need also need to be fulfilled. A separate sub-working group is evaluating suitable sites for SMRs and is co-operating with a number of international groups interested in reactor deployment.

The results of the NEWG research are expected to provide the Estonian government with a factual basis for assessing whether nuclear energy is applicable in Estonia. If positive, the option would be passed to the Estonian national assembly for approval. After approval, the formation and roll-out of the following is expected to take place:

- a regulator (2024);
- regulations (2024-2026);
- a National Detail Special Plan and Location selection process (2024-2027);
- a technology selection process (2024-2025);
- preparation of building plans and permitting (2025-2026).

The Estonian government has issued tenders to revise the nuclear law that was drafted 10 years ago but was never formally used. It has also issued a tender for a human resource development strategy for the future nuclear regulator.

Fermi Energia, established in 2019, is supporting nuclear innovation and SMR deployment in Estonia. Fermi Energia said it had raised more than the €2.5 million it needed to start the official planning process for the deployment of an SMR. The investment was intended to kick-start a planning process with the Estonian government to analyse the building of an SMR and determine potential locations for a first plant. Initial plans expect the SMR site to be ~100 km east of Tallinn, on the coast of the Gulf of Finland. Fermi Energia is also taking steps to train the nuclear specialists the country will need. It has put in place scholarships for students to study nuclear engineering overseas and is supporting nuclear-related education programmes in local universities and schools.

"For Estonia, only SMRs as currently developed in the UK, the US and Canada are suitable," said Mr Kalev Kallemets, Chief Executive Officer of Fermi Energia. In July 2019, the company launched a feasibility study on the suitability of SMRs for Estonia's electricity supply and climate goals beyond 2030, following a financing round from investors and shareholders. It selected four SMR designs to be included in the feasibility study: Moltex Energy's SSR-W300, Terrestrial Energy's IMSR400, GE Hitachi's BWRX-300 and NuScale Power's VOYGR Module.

Fermi Energia signed several co-operation agreements and MoUs, e.g., with Swedish utility Vattenfall (May 2021), with Laurentis Energy Partners of Canada (a subsidiary of Canada's largest energy company; Ontario Power Generation (OPG), April 2022), and with SMR developer NuScale Power (August 2022). This collaboration will include the provision of expertise to support the development of SMRs in Estonia, including feasibility studies, planning, construction, deployment, operation and sustainability [11]. Fermi Energia's SMR initiative also involves Belgian engineering company Tractebel, the Finnish energy company Fortum, US-based GE Hitachi Nuclear Energy and the UK's Rolls-Royce.

As each nuclear power plant operation and its decommissioning generates radioactive waste and spent nuclear fuel (SNF), Estonia has investigated US-based company Deep Isolation's horizontal borehole disposal solution for the geological disposal of SMR SNF. Deep Isolation believe a deep horizontal borehole solution in Estonia could be constructed at about a quarter of the cost of a more conventional mined deep geological repository (DGR). Furthermore, as the geology near the earmarked Estonian SMR site appears suitable for disposal, the costs and risks associated with transporting radioactive waste long distances are expected to be avoided [12].

In March 2023, Fermi Energia announced that US-based GE-Hitachi's BWRX-300 was chosen as its preferred SMR design due to the use of proven technology, existing components, and the experience that can be gained from a construction project that has begun in Canada for OPG [13]. In April 2023, four possible sites for Estonia's first commercial nuclear site were identified. Detailed analysis will follow and will depend on the technological choice, how much land is needed, and how major the socio-economic impact will be [14].

1.6. Finland

Nuclear energy plays a key role in Finland's energy sector and is a central part of the government's plans to achieve carbon neutrality.

In June 2022, the Finnish government adopted an action plan to help Finland achieve carbon neutrality by 2035. In this plan, SMRs, built in serial production and replacing fossil fuel electricity and heat production, are recognised as the key mechanism for reducing carbon emissions. In October 2022, Finnish nuclear operator Fortum started a two-year programme to explore the potential for SMR and conventional large reactor deployment in Finland and Sweden. Based on this programme, in March 2023 Fortum signed an MoU with UK-based SMR developer Rolls-Royce. This aimed to explore opportunities for the deployment of SMRs, e.g., the decarbonisation of stainless steel manufacturer Outokumpu's industry operations. Fortum has also signed nuclear-related co-operation agreements with EDF, Swedish SMR developer Karnfull Next, and Finland-based energy company Helen. In June 2023, Fortum signed an agreement with Westinghouse to study the possibilities for the development and deployment of AP300 SMR projects in Finland and Sweden. In August 2023, the Finnish government announced that will initiate reforms for the utilisation and regulation of nuclear energy that will enable SMR implementation [15].

After reviewing the Finland 2023 Energy Policy, The International Atomic Energy Agency (IAEA) stated that Finland is a robust case for considering SMR demonstration projects and urged the government to complete the update of nuclear legislation allowing the implementation of SMRs. The IAEA referenced the presence of sparsely populated areas; small and remote communities; harsh winters and a heavy reliance on heating; combined with a long-standing and robust technical culture of safety, societal acceptance of nuclear technology and regulatory excellence.

Finish research organization VTT has produced several reports analysing management plans and disposability issues for future inventories of SMR SNF and other radioactive wastes.

1.7. France

Announced in October 2021, the "France 2030" plan includes a €1 billion programme to demonstrate SMR technology and hydrogen production using nuclear electricity; €70 million is dedicated to the completion of the preliminary design of the NUWARD SMR supported by the French EDF-CEA-TechnicAtome-Naval Group consortium. In June 2023, the NUWARD consortium signed a framework co-operation agreement with Tractebel to further joint efforts for the development of

NUWARD's SMR technology. The first target of "France 2030" is to enable SMR emergence in France by 2030.

EDF announced that the NUWARD SMR design will be the case study for a European early joint regulatory review led by the French Nuclear Safety Authority (ASN). Also participating in the review process will be Czechia's State Office for Nuclear Safety (SUJB) and Finland's Radiation and Nuclear Safety Authority (STUK). This review will be based on the current set of national regulations from each country, the highest international safety objectives and reference levels, and up-to-date knowledge and relevant good practice. Through technical discussions, this collaboration will help ASN, STUK and SUJB increase their respective knowledge of each other's regulatory practices at the European level and improve the ability to anticipate challenges of international licensing for the NUWARD SMR, so that it can meet future market needs. NUWARD is envisioned as a 340-MWe European pressurised water SMR plant consisting of two 170-MWe reactors and is in the conceptual design phase, where the current focus is on selecting major technical features while producing a plant that can be competitive.

1.8. Hungary

In June 2023, Hungarian energy minister Csaba Lantos stated that Hungary could consider deploying one or more SMR plants, but not earlier than 2029 – 2030. Potential SMR units will not be deployed at the existing Paks nuclear site in southern Hungary, but "somewhere where energy demand is growing". SMR deployment could be realised somewhere in eastern Hungary next to rivers with smaller yields, but other locations are also under consideration [16, 17].

1.9. Italy

The president of the Italian Nuclear Association (AIN) has stated that Italy needs to develop a national energy policy that includes restarting its nuclear power programme as it seeks to reduce dependence on fossil fuels and imports from Russia. He called for a national law that "supports, encourages and promotes" the participation of Italian companies in international SMR and advanced reactor projects, adding that "Italian industry and academia are already there, but autonomously, without the political support of the state, which is massive in other countries".

In May 2023, the Italian parliament voted in favour of a return to nuclear power, backing the government's plan to include nuclear in the country's energy mix as part of its decarbonisation efforts. The energy plan says Italy could have a nuclear capacity of 35 GW from seven plants by 2050 and also considers Generation IV SMRs.

France's NUWARD consortium has signed an agreement with Italy-based Ansaldo Energia, committing to co-operation in the development of SMR technologies.

1.10. Netherlands

The Dutch government is planning for the construction of two new nuclear power plants and is looking at the role that nuclear can play in the production of green hydrogen, according to a draft national energy system plan. The plan outlines €50 million for supporting building new nuclear power plants in 2023, €200 million in 2024, and €250 million in 2025. Cumulative new nuclear support is anticipated to reach €5 billion by 2030, although the power plants will not be online by then. If SMRs are chosen, the lead time is expected to be reduced, but development of the technology will take longer than it would for conventional large-scale plants. Commissioning of SMRs is not expected until "after 2035".

UK-based Rolls-Royce SMR has signed an exclusive agreement with the Dutch development company ULC-Energy to work together to deploy the Rolls-Royce SMR design in the Netherlands. Additionally, Dutch construction company BAM Infra Nederland has agreed to collaborate with ULC-Energy and Rolls-Royce SMR on the deployment of a fleet of Rolls-Royce SMRs in the Netherlands. The two companies said they believe nuclear energy can accelerate the transition to a clean, affordable, and reliable energy system in the Netherlands.

Amsterdam-based ULC-Energy intends to develop nuclear projects deploying modern, modular reactors based on proven technology. Its aim is to accelerate decarbonisation in the Netherlands. A September 2022 study found that a nuclear generating capacity of about 9 GW would be an optimal step towards this goal, including large-scale nuclear and possibly SMRs.

The province of Limburg in the southeast Netherlands began setting up a nuclear energy alliance in March 2023, aimed at exploring the potential for SMR deployment in the 2030s and beyond. The alliance will consist of private sector organisations, governmental and regulatory bodies, scientific institutions and potential financers. It will focus on the use of nuclear energy for the industrial sector and plans to conduct research and share information on SMRs in the province. One of its aims will be to study which locations in Limburg could be suitable for SMR deployment [18].

1.11. Poland

The implementation of nuclear power production is one of the important objectives of the framework for the energy transition in Poland [19]. The Polish government is aiming for construction of its first nuclear power plant, made up of 6 reactor units, each with an electricity generation capacity of 1.0 – 1.6 GWe, totalling 6 – 9 GWe. The government aims to have initiated construction by 2033, with operations commencing by 2043.

There are also plans to use SMRs for district heating and industrial process heat applications. The transfer of operational experience from prototype plants to be launched in other countries would be required, ensuring the reliability and efficiency of the SMR designs under consideration are confirmed before deployment in Poland.

In June 2022, Polish state-controlled energy group Enea and US startup Last Energy signed a letter of intent for the joint development and potential deployment of Last Energy’s 20 MW SMRs in Poland. The two companies will initially co-operate on the development, construction and further distribution of SMRs. The letter also allows for the possibility of establishing a Poland-based joint company, responsible for the implementation of Last Energy's SMR technology in the country. After confirming the economic and technological viability and obtaining relevant certificates, the companies will decide on the scope of further co-operation based on market analyses and the needs of the Enea Group. In July 2022, Wroclaw-based energy efficiency specialist DB Energy signed an agreement with Last Energy for the potential construction of ten SMRs with a total capacity of 200 MW.

Large players in Poland’s energy and heavy industry sectors including Orlen, Synthos, KGHM and ZEPAK have also shown interest in the development and deployment of SMR units for industrial use. Chemical producer Synthos has established a subsidiary which has the right to develop projects using GE-Hitachi's BWRX-300 design and is working with chemical producers PKN Orlen and Ciech on the potential for using energy from the BWRX-300 to replace coal at their plants. Synthos is also working with power company ZE Pak to examine whether BWRX-300s could replace coal at the Pątnów power plant.

In December 2021, GE Hitachi, BWXT Canada and Polish chemical producer Synthos Green Energy (SGE) signed a letter of intent to co-operate in deploying BWRX-300 SMRs in Poland. SGE, together with its partners, aims to deploy the first BWRX-300 in 2029 and to have at least ten of the reactors in operation by the early 2030s.

In September 2022, Romanian utility Nuclearelectrica and Polish copper and silver producer KGHM Polska Miedź SA signed a non-binding MoU for co-operation in the development of SMRs. The agreement includes the exchange of technical, economic, legal, financial and organisational experience and know-how. It includes “a comprehensive approach to all SMR project development activities”, from site selection to decommissioning, in order to develop robust, safe and cost-effective SMR projects in Romania and Poland. SMR control room simulators will be built in Poland and Romania to train operators and nuclear specialists. Both companies have previously signed agreements with NuScale Power. Prior to this, in February 2022, KGHM signed a definitive agreement with NuScale Power to initiate work towards deploying a first NuScale VOYGR SMR power plant in Poland as early as 2029. The first task under that agreement was to identify and assess potential project sites, develop project planning milestones, and develop cost estimates.

Also in September 2022, KGHM announced that it is had initiated a process to initially identify four or five potentially viable sites to deploy its first SMR in Poland, with a decision to be made within five years. KGHM has already applied to the Polish National Atomic Energy Agency for a safety assessment of the SMR technology it has earmarked and a review of its location study. The environmental impact assessment (EIA) for a selected site may take up to two years with SMR construction expected to take another three years [20].

In January 2023, EDF signed an agreement with Polish operator and trader of renewable energy Respect Energy to co-operate on NUWARD SMR projects. In February 2023, Rolls-Royce SMR signed a memorandum of intent with Polish industrial group Industria that could lead to the deployment of SMRs in central and southern Poland in the 2030s [21].

In April 2023, The Polish government announced that it had updated its energy strategy until 2040, increasing targets for low-carbon power generation. This strategy aims at accommodating the deployment of both SMRs and large-scale conventional reactors [22].

In July 2023, Poland's Ministry of Climate and Environment approved KGHM's plans to build an SMR in Poland based on work already performed as part of its application for a decision-in-principle. The decision-in-principle is the first in a series of administrative permits needed for nuclear power facilities in Poland. With governmental approval, KGHM can now apply for a number of further permits, such as those for siting and construction. A decision-in-principle is formal confirmation that the company's investment project is in line with the public interest and the state's policies [23].

A project to develop SMRs in Poland has moved forward with a co-operation agreement signed between the Polish energy giant Orlen and two US government financial institutions in April 2023, where the latter plan to lend up to $1 billion to support the development and deployment of twenty SMRs designed by GE Hitachi Nuclear Energy.

In May 2023, Poland's nuclear regulator PAA issued a "general opinion" to OSGE that confirms the design of GE Hitachi Nuclear Energy's BWRX-300 SMR meets nuclear safety requirements. In June 2023, Poland's General Directorate for Environmental Protection initiated an environmental decision process for the proposed deployment of a BWRX-300 SMR plant in southwest Poland. Later that summer, a transboundary consultation process began with Czechia, Slovakia and Austria expressing a willingness to participate in the process. Following that year, in December 2023, OSGE was granted a decision-in-principle from Poland's Ministry of Climate and Environment, for the construction of up to twenty-four SMRs at six potential sites distributed across Poland [24].

1.12. Romania

Romania's 'Energy Strategy 2016-2030, with an Outlook to 2050' [25] recognises that, after 2035, Generation IV reactors and SMRs will be introduced, enabling an increased share of energy with low emissions. In November 2021, Romania announced the potential roll-out of SMRs in the country by 2028 [26].

The US Trade and Development Agency (USTDA) awarded a grant to Nuclearelectrica in early 2021 for a study to identify and assess several sites across Romania, including locations where existing coal-fired power plants could be replaced with SMR plants [27]. In March 2022, Romania announced its intention to work with Last Energy to develop an SMR at the central Mioveni site.

In May 2022, NuScale Power signed an MoU with Romania's state nuclear power corporation Nuclearelectrica to conduct engineering studies, technical reviews, and licensing activities at a site in Doicesti, that is the preferred location for the deployment of what could be the first SMR in Europe. This is a key advancement of an agreement signed in 2021 under which NuScale and

Nuclearelectrica – the operator of Romania’s only nuclear station at Cernavodă, are taking steps towards deploying a six-module, 462 MW NuScale VOYGR power plant.

In June 2022, The US government, working with NuScale Power, announced it would provide $14 million in support for a front-end engineering and design study for Romania's deployment of a first-of-its-kind SMR plant. Nuclearelectrica and NuScale Power will co-operate with USTDA on a series of engineering and design activities and studies, as well further technical analyses of the Doicești site. The study is expected to take 8 months and cost $28 million in total, with additional contributions from Nuclearelectrica and NuScale Power. It will provide Romania with site-specific data and identify potential Romanian services, manufacturing and assembly suppliers [28].

Romanian state-owned nuclear operator Nuclearelectrica and Polish organisation KGHM signed an MoU in September 2022 to facilitate co-operation in the development of SMR technology for potential deployment in both countries [29].

In May 2023, the USA and Romania launched the first NuScale Energy Exploration (E2) Centre outside the USA, at the University Politehnica of Bucharest, supporting Romanian plans to deploy the first SMR in Europe. The E2 Centre will be used to educate and train the next generation of nuclear engineers in operating advanced civil nuclear reactor technologies, while establishing Romania as a regional educational and training hub for the next stage of civil nuclear deployments across Romania and Europe. In the same month, the Biden administration built on the plans announced in June 2022 by committing to “early stage” funding of up to $275 million (€254 million) for the deployment of a NuScale Power VOYGR power plant at the previously identified coal plant site. The funding is expected to support procurement of long lead materials, phase two front-end engineering and design work, site characterisation, regulatory analyses, and the development of schedules and budgets [30].

1.13. Slovakia

In June 2023, The Ministry of Economy and Slovenské elektrárne signed a memorandum of co-operation with a range of partners in the energy field to support the development of SMRs in Slovakia, including an application for funding from the USA's Project Phoenix. According to the Ministry, SMRs should not replace existing Slovakian nuclear resources. Instead, they should replace coal-fired power plants and provide another source of stable and carbon-free energy, enabling self-sufficiency for Slovakia. Project Phoenix will provide direct US support for coal-to-SMR feasibility studies and related activities in support of energy security goals for countries in Central and Eastern Europe. A feasibility study to be co-funded by a grant under Project Phoenix will assess the suitability of SMRs in Slovak conditions and to propose the necessary steps for their possible future construction.

In July 2023, Westinghouse announced the signing of memorandums of understanding with Slovak state-owned nuclear company Javys for the potential deployment of its AP1000 and AP300 designs.

1.14. Slovenia

At the strategic level, Slovenia supports the further exploitation of nuclear energy for electricity production, including through the deployment of a new conventional nuclear power plant or SMRs. For this purpose, in December 2023, a public consultation process was initiated focused on a draft resolution on the long-term peaceful use of nuclear energy in Slovenia entitled "Nuclear energy for the future of Slovenia". The resolution acknowledges that The National Assembly of the Republic of Slovenia supports all procedures and the use of all experience for the optimal construction of nuclear new buildings as soon as possible and emphasises the importance of R&D in the field of nuclear energy, including the possibility of using advanced reactors and SMRs.

1.15. Sweden

In June 2022, Swedish utility Vattenfall announced that it would begin work on a pilot study to determine the feasibility of deploying at least two SMRs at the site of the Ringhals nuclear power plant. Vattenfall said the study is focusing on Ringhals in southern Sweden because more electricity generation is expected to be needed in that region. The study will assess the conditions for proceeding with a decision to build at least two SMRs next to the existing Ringhals plant. Provided that the pilot study concludes that it would be profitable, and all other conditions for a future investment decision are met (in particular, new regulations for nuclear power), it is possible that an SMR will be operational by the early 2030s.

Vattenfall is also co-operating with Finland’s Fortum and, together, they are planning to build SMRs that could come online at some point between 2030 and 2035. In June 2021, Vattenfall signed an agreement with the Estonian nuclear energy start-up company Fermi Energia that is studying the deployment of SMRs in Estonia. The agreement was signed in order Vattenfall to become a minority shareholder of the company with a seed investment of €1 million ($1.2 million).

In line with a framework agreement from June 2016 by the Social Democrats, the Moderate Party, the Green Party, the Centre Party and the Christian Democrats, ten new nuclear reactors are authorised for deployment at existing nuclear sites, to replace existing nuclear power plants as they retire. Replacement of Ringhals 1 and Ringhals 2 which were shut down in 2020 and 2019 is therefore allowed within the existing legislation, where the existence of grid infrastructure at the site is beneficial for new nuclear. There is public acceptance for both existing and new nuclear power at Ringhals and Forsmark, and a “proposal to amend Sweden's legislation on nuclear power” which would “remove the current law limiting the number of reactors in operation to ten, as well as allowing reactors to be built on new plant sites, rather than just existing sites” was recently presented by the Swedish Prime Minister and Climate and Environment Minister [31].

In March 2023, Swedish internet provider and telecom company Bahnhof announced that it is considering building a nuclear reactor to power a new data centre. The company is putting together plans for an SMR on an industrial site in the Hjorthagen area of Stockholm which would provide electrical power for a new data centre and 30,000 households, along with heat for homes and offices.

Swedish SMR project development company Kärnfull Next has announced plans for its first nuclear new build site in Nykoping, southeast Sweden, a site that the company wants to turn into an “SMR campus” by the mid-2030s. Kärnfull Next is working with reactor companies and utilities including GE Hitachi, developer of the BWRX-300 SMR, and Finnish state energy company Fortum, to develop and package ready-to-build projects [32]. The company has signed an MoU and has attained prospecting rights to explore the potential for commercial nuclear energy production at an industrial site owned by nuclear technology company Studsvik. A feasibility study began in May 2023, and preliminary results suggest that the Studsvik site has favourable conditions for commercial SMRs.

2. Other European Countries

2.1. Norway

In July 2022, Norsk Kjernekraft was established as a company with the objective of building and operating SMR plants. It said it would work with three municipalities to investigate the technical, financial and safety aspects of building one or more SMRs in the areas. A proposal to Norway’s Ministry of Oil and Energy was submitted in November 2023, as the first formal step towards the assessment of the construction of a power plant based on multiple SMRs in the municipalities of Aure, northern Norway, and Heim in central-west Norway. According to a preliminary plan, the plant will be built in a common industrial area in the border area between Aure and Heim and it could be operational within 10 years. The facility would consist of several SMRs which together could produce around 12.5 TWh of electricity annually, and would correspond to an increase in Norway's power production of about 8% [33].

In March 2023, Norsk Kjernekraft signed an agreement with Rolls-Royce SMR to work together to increase acceptance of nuclear power in Norway, and to potentially establish future projects that “could lead to the deployment of Rolls-Royce’s small, modular nuclear power plants in Norway”.

Norsk Kjernekraft also signed a letter of intent with Finland's TVO Nuclear Services (Tvons) in June 2023, to collaborate on examining the possibility of deploying SMR plants in Norway. In July 2023, a letter of intent was signed with Seaborg, to investigate the possibility of establishing Seaborg's CMSR technology in Norway.

2.2. Turkey

Turkey is prioritising renewable energy in its clean energy transition, but the Turkish government has plans to integrate nuclear energy as part of its energy mix. Investment in SMR technology is being considered as a replacement for coal and lignite power plants [34].

In March 2020, Turkey's state-owned EUAS International ICC signed an MoU with Rolls-Royce SMR to evaluate the technical, economical and legal applicability of SMRs. In addition, they will consider the possibility of joint production of SMRs.

2.3. Ukraine

Ukraine is considering ambitious plans to deploy up to 20 SMRs to contribute to the strengthening of the country's energy security and to replace thermal generation units destroyed during the war with Russia. In November 2022, Estonian SMR developer Fermi Energia and Ukrainian energy company Eco-Optima signed an agreement to study the potential deployment of an SMR in Ukraine. In March 2023, Ukraine's state nuclear company Energoatom, which owns and operates Ukraine's fleet of 15 commercial nuclear power plants, and Rolls-Royce SMR signed an MoU to explore the deployment of SMRs.

Energoatom and Holtec International have signed an agreement for the potential deployment of up to 20 SMRs with the first pilot project connected to the grid by March 2029. The agreement sees Energoatom and Holtec jointly developing a plan for the expedited construction and commissioning of Holtec's SMR-160 plants in Ukraine, and for establishing a manufacturing facility in the country to produce equipment required to build the plants. In September 2023, Energoatom signed an agreement with Westinghouse for the development and deployment of its AP300 SMR design, with the first units potentially going online within a decade.

2.4. United Kingdom

In 2015, the United Kingdom (UK) launched the first steps of its national programme to support SMR and advanced reactor designs through an open competition, inviting vendors to submit proposals to meet the country's energy needs and industrial potential. In July 2019, the UK government committed £18 million as part of the Industrial Strategy Challenge Fund to support the development of the UK SMR design proposed by a Rolls-Royce-led consortium [35].

A UK Energy White Paper [36] highlights the role of nuclear power in the UK's 2050 climate neutrality pledge. At least one additional nuclear power plant is to be built by 2024, and support is offered for SMRs and advanced reactors, as well as for nuclear fusion. According to the advanced nuclear innovation plans, £385 million has been assigned to an Advanced Nuclear Fund, with up to £215 million for investment by the early 2030s. This money will be used to develop a domestic SMR design that could potentially be built in factories and then assembled on site.

An additional £40 million will be invested in developing regulatory frameworks and supporting the UK's supply chain. As the first major commitment of the programme the Generic Design Assessment (GDA) [37] was opened to SMR technologies. Managed by the Office for Nuclear Regulation (ONR) and the Environment Agency (EA), the GDA is a voluntary process that allows regulators to begin consideration of the generic safety, security and environmental aspects of designs for nuclear power plants prior to applications for site-specific licensing and planning consents. Any reactor deployed in the UK must meet robust and independent regulatory requirements, which include meeting design safety requirements via the GDA process. Given the potential role that SMRs could play, alongside conventional nuclear plants, as a low-carbon energy source to support a secure, affordable decarbonised energy system, the UK Government will continue to progress work on key policy and market enablers, including finalizing regulatory access, siting, and financing for SMRs.

In November 2022, Rolls-Royce SMR was chosen as the preferred nuclear technology provider for the newly formed Solway Community Power Company, which is planning to bring new nuclear power to West Cumbria in northwest England. Solway Community Power Company aims to act as a catalyst to speed up the process of bringing a Rolls-Royce SMR to the area, most likely on a site at Sellafield owned by the Nuclear Decommissioning Authority (NDA).

Rolls-Royce SMR has recently completed a siting assessment review into the potential options for deploying SMRs, with the focus on four potential locations in England and Wales. Of these, four potential land parcels were prioritised: land neighbouring the Sellafield site; Trawsfynydd and Wylfa, both nuclear sites in North Wales; and Oldbury in England. The Trawsfynydd site could be suitable for a range of SMR technologies, with the potential to generate up to 1 GWe, as was announced in May 2023 by the Cwmni Egino which is owned by the Welsh government [38].

UK government support in SMR implementation continued in July 2023, with grants of £157 million (€182m, $205m) as part of its launch of a new body, Great British Nuclear (GBN), to support the nuclear power industry. GBM is tasked with helping deliver the government's commitment to provide a quarter of the UK's electricity from nuclear energy by 2050. GBN's official launch in July 2023 was supported by a competition for organisations to bid for development funding for their SMRs [39].

Current SMR projects include Rolls-Royce SMR proposals looking at constructing reactors in Oldbury and Berkeley in England and Balfour Beatty's proposals with Holtec Britain to develop plans for an SMR-160 in the UK. Once the initial stage of the SMR selection process is complete, GBN will select those technologies which have met the criteria before entering detailed discussions with those companies.

In October 2023, GBN announced it had selected six companies as the most able to deliver operational SMRs by the mid-2030s and to advance to the next phase of the competition. EDF, GE Hitachi Nuclear Energy International LLC, Holtec Britain Limited, NuScale Power, Rolls Royce SMR and Westinghouse Electric Company UK Limited were invited to bid for UK government contracts in the next stage of the process. It was hoped that contracts would be awarded by summer 2024 [40, 41].

3. Asia-Pacific

3.1. Australia

There is increasing interest from government, industry and wider society in introducing nuclear power to Australia. In August 2022, Peter Dutton, leader of the opposition party, initiated a formal internal process to examine the potential for advanced and next-generation nuclear technologies to contribute to Australia's energy security and reduce electricity prices.

SMR Nuclear Technology Pty Ltd, based in Sydney, is a leading proponent of both nuclear power and SMR use and has published various material suggesting how an SMR nuclear power programme could be implemented in Australia to replace the predominantly coal-fired generation systems [42]. Support for developing an SMR programme has also come from the mining organisation Minerals Council of Australia (MCA). Australia satisfies ~10% of global uranium demand and the mining industry sees considerable potential in a domestic nuclear power programme. An MCA report [43] explores the possible use of NuScale Power's VOYGR Module, GE-Hitachi's BWRX 300 and Terrestrial Energy's IMSR400.

SMR Nuclear Technology suggests that SMR plants with outputs of 50 to 900 MW are particularly suitable for the Australian power system. They base their assessment and proposals on the version of the NuScale Power VOYGR module which has received design approval from the US Nuclear

Regulatory Commission (NRC). They note that up to twelve 77 MWe modules can be accommodated in one power plant to provide a gross output of 924 MWe and expect implementation up to operation to take 7 years, including 4 years for community consultation, site selection, feasibility studies, environmental and development approvals and arranging financial facilities. If SMRs are used to re-power retiring coal-fired power stations, much of the supporting infrastructure, such as transmission connections, cooling water supplies and administration and maintenance buildings could be reused.

SMR Nuclear Technology challenge Commonwealth Scientific and Industrial Research Organisation (CSIRO) cost estimates and suggested in September 2022 that a unit cost for a 12 VOYGR module unit SMR plant would be ~AUD 5.1 billion, with electricity generation costs of AUD 16.6 / MWh. The Australian Energy Council is, however, sceptical about both cost and time estimates for the NuScale Power VOYGR module and advocates a cautious assessment of how SMRs would fit into an evolving Australian grid system [44].

SMR Nuclear Technology notes that a 924 MWe NuScale plant would produce 120 m^3 of LLW and about 1,500 kg of SNF per year. They note that several countries, including Australia, are looking at deep boreholes for geological disposal. The MCA report used the UK government Waste Transfer Pricing model for new nuclear build to assign an additional AUD 1/MWh to the Variable costs of SMR generation to account for SNF and Intermediate Level Waste (ILW) management.

In April 2022, a meeting of the Australian Nuclear Association heard the suggestion [45] that the pre-project activities phase of the IAEA Milestone Approach to introducing nuclear power could be used in parallel to cover the nuclear infrastructure issues that Australia will face both for the AUKUS nuclear submarine acquisition programme and any future consideration of SMRs.

3.2. China

China is leading SMR development with its ACP100 design. In July 2021, construction started on a demonstration project at the Changjiang nuclear power plant, managed by China National Nuclear Corporation (CNNC), who said that the project will be the world's first land-based commercial SMR [46]. The multi-purpose 125 MWe pressurised water reactor (PWR), referred to as the Linglong One, is designed for electricity production, heating, steam production or seawater desalination. The construction is expected to take about 5 years. The ACP100 will be deployed nationally, with power plants comprising two to six ACP100 SMR units being envisaged at several locations in China. A floating version, the ACP100S, is also under development.

3.3. Indonesia

In 2018, the National Atomic Energy Agency (BATAN) launched a roadmap for developing a detailed engineering design for an experimental power reactor (Reaktor Daya Eksperimental, RDE) using a High Temperature Gas Reactor (HTGR) with a capacity of 10 MWth [47, 48]. Besides the experimental reactor, BATAN is also planning to deploy small HTGRs (up to 100 MW) in Kalimantan, Sulawesi, and other islands to supply power and heat for industrial use. A prototype unit was planned for West Kalimantan and, in March 2023, the USTDA awarded a grant to PLN Indonesia Power for assistance in assessing the technical and economic viability of a proposed nuclear power plant in West Kalimantan. The assistance includes work on a site selection plan, power plant and interconnection system design, preliminary environmental and social impact assessment, risk assessment, cost estimate and regulatory review. Indonesia Power selected NuScale Power to carry out the assistance in partnership with a subsidiary of Fluor Corporation and Japan's JGC Corporation. The proposed 462 MWe facility would utilise NuScale Power’s SMR technology [49].

Indonesia is also active in floating SMR development. In August 2020, the Indonesian Nuclear Society hosted a webinar on "the world's first floating nuclear power plant and its possible use in archipelagic countries", with support from Rosatom’s regional centre in Southeast Asia to showcase Russian SMR technologies and the advantages of floating nuclear power plants [50].

In September 2023, Pertamina NRE (a subsidiary of Persero, the country’s largest energy company) signed an MoU with Seaborg to investigate the deployment of its CMSR power barge. A study will assess the feasibility of power supply to the grid, directly to industry, or for the production of alternative fuels, such as hydrogen, ammonia and methanol. The World Nuclear Association (WNA) reports that Seaborg's design is for modular CMSR power barges equipped with two to eight 100 MWe CMSRs, with an operational life of 24 years. The low-enriched fluoride fuel salt is not yet commercially available, so Seaborg recently announced the initial power barges will be fuelled with low-enriched uranium (LEU) [51].

Further developments in floating SMRs were also reported in 2023, with PT ThorCon Power Indonesia (a subsidiary of USA-based ThorCon) signing an agreement with the Nuclear Energy Regulatory Agency (Bapeten) to start a safety, security and safeguards consultation in preparation for licensing a demonstration 500 MWe floating ThorCon TMSR-500 [52]. ThorCon intends to establish an SMR assembly line in Indonesia and to license, build and operate its first 500 MWe demonstration power plant at Kelasa Island in the Province of Bangka-Belitung by 2029. The estimated cost of a two-unit (1 GWe) plant is $1.2 billion.

Also in 2023, four Danish companies (Copenhagen Atomics, Aalborg CSP, Alfa Laval and Topsoe) signed an MoU with an ammonia fertiliser producing company (Pupuk Kalimantan Timur) and Pertamina New and Renewable Energy to study the legal and regulatory context for building a facility on the east coast of Borneo (province of East Kalimantan) to produce one million tonnes of ultra-low emission ammonia fertiliser annually [53]. Copenhagen Atomics would supply 25 of its thorium molten salt SMR units, providing 1 GWe to power the new facility, which is hoped to be operational in 2028.

3.4. Japan

The Ministry of Economy, Trade and Industry (METI) promotes a green growth strategy to achieve carbon neutrality by the middle of the century and the current government is developing a clean energy strategy to achieve this. Depending on the political feasibility of renewed progress on nuclear power, following the 2011 Fukushima disaster and the effective shut-down of the entire national nuclear power programme, the new strategy is expected to have some focus on SMRs, with the aim of technology demonstration through international co-operation by 2030 [54].

However, the decade of problems with the domestic nuclear power programme are considered by some to have put Japan at a distinct disadvantage in making progress on SMRs, with most of the activity being investment in projects outside Japan. Both JGC Holdings Corporation and IHI invested directly in the NuScale Power SMR project in 2020 and, in April 2022, the Japan Bank for International Co-operation (JBIC), wholly owned by the Japanese Government, decided to invest $110 million in NuScale Power.

The Japan Atomic Energy Agency (JAEA) and Mitsubishi Heavy Industries are participating in TerraPower’s project to build a mid-size next-generation demonstration reactor by 2028 in Wyoming, with funding from USDOE.

In addition, Hitachi is currently developing the BWRX-300, a 300 MWe boiling water reactor (BWR), in collaboration with General Electric in the USA, and Mitsubishi Heavy Industries is working on the demonstration of a small PWR-type SMR.

The increased interest was reflected in a meeting and joint statement issued in early 2023 by METI and the USDOE on co-operation on advanced reactors and SMRs.

3.5. Myanmar

In 2023, the government of Myanmar signed an intergovernmental agreement with Russia’s Rosatom, which includes training a workforce for building and running an SMR. A Nuclear Technology Information Centre in Yangon is a joint project between Rosatom and Myanmar's Ministry of Science and Technology. A further MoU was signed in October 2023 outlining how the development of nuclear infrastructure will be carried out in accordance with IAEA approaches and recommendations, as well as Rosatom’s best practices [55].

3.6. Philippines

The Philippines is an archipelago comprising thousands of islands where off-grid deployment of SMRs would be advantageous. The Philippine Department of Energy (DOE) discussed SMR technology with the Republic of Korea and, in 2019, a site survey was conducted by Korean Hydro and Nuclear Power (KHNP) in accordance with an MoU signed with the Philippine DOE [56].

In December 2021, the power utility Manila Electric Company (Meralco) said it was open to considering the deployment of SMRs as part of its long-term energy investment strategy and, in January 2022, Rosatom and the Philippine DOE agreed an action plan to explore the potential for deploying SMRs supplied by Russia [57].

In November 2022, the US Vice President visited Manila and opened talks with President Marcos and Vice President Duterte Carpio to promote security and economic ties between the two nations. During the visit Kamala Harris offered a “clean energy partnership” to help build SMRs. A deal would provide the legal basis for exports of nuclear equipment and material from the USA [58].

In May 2023, President Marcos of the Philippines visited the USA and met government representatives and staff from NuScale Power. It was announced that NuScale is expected to invest $6.5 - 7.5 billion to provide 430 MWe of power by 2031, using its VOYGR Modules, in addition to the commencement of siting studies in the country [59].

3.7. Republic of Korea

The Republic of Korea has recently changed its position on nuclear power, which was to have been phased out. Under President Yoon Suk-yeol. The country is now looking at a continued and expanded nuclear power programme. Major industrial companies such as SK, Samsung, Doosan and Hyundai are involved in pursuing SMR possibilities. While the Republic of Korea clearly wishes to be a major provider of SMR technologies, it is not currently clear to what extent it might also be an end-user.

In May 2022, SK Innovation announced a wide-ranging partnership with TerraPower, with a focus on SMRs. At the same time, Samsung C&T, the construction and trading arm of Samsung Group, together with Doosan Group and GS Energy Group, signed an MoU to explore the deployment of NuScale Power’s SMR technology. Doosan Enerbility states that SMRs are a central part of its plans to invest $4 billion in new energy technologies over the next five years, including the supply of equipment for NuScale Power’s SMRs. The Republic of Korea companies will advise NuScale on component manufacturing, plant construction and plant operation [60].

The GS Energy power company signed an MoU with Uljin County in North Gyeongsang Province to consider using NuScale Powers’ VOYGR module to provide heat and power to the planned Uljin Nuclear Hydrogen National Industrial Complex. Six modules would be deployed, with construction planned to start in 2028 [61].

Hyundai Engineering has also set its sights on SMRs and other next-generation nuclear systems. It has set up a dedicated team of about 70 design and project management personnel with a goal of cultivating its own SMR technology. In April 2023, they signed an MoU with Ultra Safe Nuclear Corporation (USNC) of the USA and SK E&C to conduct joint research and development for the commercialisation of Hydrogen Micro Hubs over the next five years, using Ultra Safe’s 5 MWe HTGR Micro-Modular Reactor (MMR) [62].

Samsung Heavy Industries (SHI) and Seaborg have agreed to develop FNPPs, applying existing shipbuilding technology to build a new type of reactor. In early 2023, SHI announced it had completed the conceptual design for the CMSR Power Barge and obtained the basic certification of the design from the American Bureau of Shipping. The company plans to commercialise the CMSR Power Barge by 2028 in a partnership with Seaborg and KHNP.

KHNP also entered a partnership with TerraPower and Korea's SK Group in April 2023 to support the demonstration and commercialisation of the Natrium reactor and integrated energy system [63].

In a parallel development for the use of floating reactors, HD Korea Shipbuilding & Offshore Engineering (KSOE) and KEPCO Engineering & Construction (KEPCO E&C) received approval in principle from the American Bureau of Shipping for the design of a power barge. This would use either TerraPower technology or the BANDI-60 SMR design that has been under development since 2016. This is a block-type PWR with a power output of 60 MWe [64].

The Republic of Korea has made progress on its 100 MWth System Integrated Modular Advanced Reactor (SMART), which is being developed by the Korean Atomic Energy Research Institute. Smart Power successfully submitted an SMR Licensing Advisory Report in July 2020. The design has been promoted for export, most notably to Saudi Arabia, and has not been viewed as an option for domestic development [65]. Korea Atomic Energy Research Institute (KAERI) also plans to build a demonstration 70 MWth light-water SMR with multiple applications, including large merchant ships, icebreakers and submarines.

In June 2022, plans were announced to develop the "i-SMR" ('i' for innovative), which will be manufactured as a module for easy transportation to secure economic feasibility.

In early 2023, nine Korean industrial organisations agreed to co-operate in the development and demonstration of SMRs for marine use, particularly the development of SMR-propelled vessels. Together, they will develop an MSR suitable for use in marine vessels [66].

The ambitious plans of the many Korean organisations involved in SMR development were brought together in July 2023, when a public-private partnership comprising 42 state-run and private entities was created to advance Korea's SMR sector. The alliance aims to establish plans to revitalise the country's SMR industry within the next year. It includes 11 government and public institutions, including the Ministry of Trade, Industry and Energy (MOTIE), KHNP and the Korea Energy Economics Institute, as well as 31 companies, including GS Energy, SK Inc, Samsung C&T, Daewoo E&C and Doosan Enerbility [67].

3.8. Singapore

In March 2022, the Singapore Energy Market Authority (EMA) issued a forward look [68] "Charting the Energy Transition to 2050", which evaluated scenarios for how the energy sector could develop.

One scenario was that continuous advancements in SMRs had significantly improved their safety performance and pilot SMRs that commenced operations abroad from the late 2020s were demonstrated to be safe for deployment in small and dense cities. As a result, several commercial SMR designs and units were progressively developed and deployed globally from the late 2030s. By the 2040s, Singapore had assessed that nuclear energy was viable and began to develop domestic generation capacity.

The recommendation is that Singapore has a holding position, where the global deployment capacity of SMRs and nuclear fusion will suggest when these options are sufficiently mature for Singapore to adopt.

3.9. Thailand

Thailand does not currently use nuclear power. The US Vice President Kamala Harris visited Bangkok in November 2022 and offered USA support to Thailand in the development of nuclear power as part of the US Net Zero World Initiative. The assistance would include the offer of technical assistance to deploy SMRs. The White House did not give a timeline for the programme of assistance [69]. As with the Philippines, Thailand does not have a 123 Agreement with the US, which would need to be developed to permit the transfer of technology.

During the November 2022 visit, Kamala Harris unveiled a Foundational Infrastructure for Responsible Use of SMR Technology (FIRST) programme to build Thailand's capacity for SMR deployment. FIRST was established in 2021 by the US State Department to provide assistance to partner countries seeking to develop nuclear programmes to support their clean energy goals. The FIRST programme will work with experts from government, academia, industry, and national laboratories to explore options to advance Thailand's goal of net-zero emissions by 2065 via SMR deployment [70].

4. Central Asia

4.1. India

India has 22 operating nuclear reactors, with a further 8 units under construction. The Indian government is committed to growing nuclear capacity as part of its massive infrastructure development programme, which includes plans for a three-fold rise in nuclear installed capacity by 2032, to 22,480 MW. Commentators in the country have been saying that the government should look at using SMRs [71] and the topic is currently under active discussion [72]. In November 2022, India's Minister of State, Jitendra Singh, called for Indian private-sector companies and start-ups to take part in the development of SMR technology as part of a new national roadmap for clean energy transition. The Minister said that technology sharing, and the availability of funding are the 'two crucial links' for ensuring commercial availability of SMR technology within the country [73]. The Indian 220 MWe pressurised heavy water reactors (PHWRs) are in the small reactor category. The Nuclear Power Corporation of India (NPCIL) is now focusing on 540 and 700 MWe versions of its PHWR and is offering both 220 and 540 MWe versions internationally. These small established designs are relevant to situations requiring small to medium units, though they are not state of the art technology [74].

In May 2023, the National Institution for Transforming India (NITI Aayog) and Tata Consulting Engineers Limited issued a joint report "The Role of [SMRs] in the Energy Transition" as a contribution to the international debate during India's Presidency of the G20 group of nations. The report took a global look at SMRs, rather than being specific to India. Among its findings it noted that: "SMR technology developers need to consider the new forms of [SNF] and nuclear waste that may get generated during SMR operation, anticipate any new issues in their processing and provide for such requirements in their designs, plant layouts and project planning".

In June 2023, the Indian Prime Minister and US President Joe Biden met and discussed nuclear power development in India, including discussion on developing next generation SMR technologies in a collaborative mode for the domestic market as well as for export. A month later, at a meeting in Paris, the Indian Prime Minister and the French President Emmanuel Macron issued a joint statement saying that the two countries had agreed to work on establishing a partnership on low and medium-power modular reactors or SMRs and AMRs.

By August 2023 the government was increasingly positive with respect to SMRs. A Minister of State told parliament that India is considering steps for development of SMRs, to fulfil its commitment to a clean energy transition. He noted that the government is exploring the options of collaborating with other countries and taking up indigenous development of SMRs, and the provisions of the 1962 Atomic Energy Act are being examined to allow participation of private sector and start-ups [75].

4.2. Kazakhstan

In December 2021, Kazakhstan Nuclear Power Plants (KNPP, a branch of the government's Samruk-Kazyna National Welfare Fund) signed a memorandum of co-operation with NuScale Power to investigate the deployment of SMRs in Kazakhstan [76]. In 2019, NuScale had submitted a 'technical and price offer' to KNPP. In February 2022, Kazakhstan's Energy Director of the Department of Nuclear Energy and Industry said that the government was evaluating six suppliers: NuScale, a US-Japanese GE Hitachi consortium, KHNP, CNNC, Rosatom and EDF. It was reported in June that the Kazakh Energy Ministry has excluded the USA and Japan from the list of potential suppliers of technology for the nuclear power plant project as their proposed reactors have not yet been constructed or operated elsewhere.

4.3. Russia

Russia has many decades of experience with ship-borne reactors which can be adapted as SMRs for other uses. In July 2020, Rosatom announced plans to build a power plant equipped with an RITM-200 maritime SMR in the village of Ust-Kuyga, in Yakutia, far-east Russia. The land-based small nuclear plant will be able to supply electricity to isolated power systems or remote areas and consumers. At Ust-Kuyga, part of the power generated will be used to supply a gold mine. Plant construction will begin in 2024 and the SMR is expected to be operational in 2028. This will be the first land-based deployment of this type of reactor [77]. FNPPs are already in use in Russia: the Akademik Lomonosov was connected to the grid in 2019, generating electricity for the remote Chaun-Bilibino network in Pevek, in Russia's far east. The FNPP is equipped with two KLT-40C reactor systems, each with a capacity of 35 MW, similar to those used on icebreakers.

In August 2022, construction work began (in China) on the first of four further floating SMRs. Atomflot will take control as the owner and operator of the first when it is complete, and it will be deployed at Cape Nagloynyn in the Russian Arctic where, by 2027, it will supply 105 MWe to a new port and the forthcoming Baimskaya copper and gold mine [78].

4.4. Sri Lanka

In March 2023, the WNA reported that Sri Lanka's cabinet had approved the signing of international conventions related to generating electricity using nuclear power, citing a report in Sri Lanka's Daily Mirror newspaper. The chairman of the Sri Lanka Atomic Energy Board said that the country was planning off-shore or on-shore SMRs of up to 100 MWe per unit. The next step would be MoUs, and it was reported that the government sought to implement the project in collaboration with the Russian government: "the required technology will be provided by them, and they had also agreed to take back the nuclear waste."

In May 2023, the Sri Lanka Atomic Energy Board reported to a government committee that, if all activities go as planned, the first nuclear power plant can be built in Sri Lanka by 2032, with Russian technical support [79]. It appears that FNPPs are being considered as a first option. However, an IAEA mission to Sri Lanka in 2023 pointed out that there is an important pre-requirement for the country to carry out much preparatory work and establish a legislative framework for the introduction of a nuclear power programme [80].

5. Middle East

5.1. Jordan

Jordan is pursuing two parallel tracks for implementing nuclear power: large reactors and SMRs. Large reactor deployment is expected to begin after 2035 and is currently on hold, with the focus being on SMRs in the short term. A target deployment date of 2030-2035 is hoped for.

In March 2017, Jordan and Saudi Arabia signed agreements on co-operation in uranium exploration and for carrying out a feasibility study into the construction of two SMRs in Jordan. In November 2017, Rolls-Royce signed an MoU with state-owned JAEC to conduct a technical feasibility study for the construction of SMRs. At the same time, JAEC signed an MoU with X-energy to assess their Xe-100 HTG pebble bed SMR and, in January 2019, a joint feasibility study on the deployment of NuScale Power's SMR technology. Other designs are also being assessed.

In August 2023, the IAEA reviewed the approach Jordan is taking to assess the use of an SMR to power a reverse osmosis desalination plant and pump drinking water from the Red Sea coast to Amman. A series of reports were reviewed, which will provide the basis for a feasibility study [81].

5.2. Saudi Arabia

In January 2020, King Abdullah City for Atomic and Renewable Energy (KA-CARE) signed a revised pre-project engineering contract with the Republic of Korea's Ministry of Science and ICT (MSIT) to establish a joint entity for the commercialisation and construction of the Korean-designed SMART SMR, with the leading involvement of KHNP. The project will refine the reactor design, license its use for deployment in Saudi Arabia and develop business models and infrastructure, as well as promote the export of the technology to other countries [82]. It is not yet clear if or how the June 2022 announcement in the Republic of Korea to develop an 'i-SMR' will affect these arrangements. Saudi Arabia plans to be an SMR technology provider as well as an end-user. In addition, in December 2017, Saudi Arabia signed a co-operation agreement with China on a joint feasibility study to develop a high-temperature gas-cooled SMR.

In March 2022, the formation of the Saudi Nuclear Energy Holding Company (SNEHC) was announced, which is thought to combine the functions of a conventional nuclear electric utility, its financing arm, and possible export functions [83]. While Saudi Arabia originally had plans for up to 16 large power plants, and in June 2022 launched a request for proposals for the first two of these to the Republic of Korea, France, China and Russia, it is possible that it might also move towards an earlier deployment of SMRs. Their potential use for desalination is a key national interest.

6. North America

6.1. Canada

Canada's SMR Action Plan [84] is the current national plan for the development, demonstration and deployment of SMRs for multiple applications at home and abroad. It builds on the 2018 SMR Roadmap and is the product of more than 100 partners from across the country — the federal government, provinces and territories, Indigenous Peoples and communities, power utilities, industry, innovators, laboratories, academia, and civil society. The Plan aims to make Canada a world leader and desired partner in the SMR area.

In 2021, Canada released an SMR Feasibility Study and have been pursuing the local construction of SMRs, particularly focusing on small-to-medium sized reactors, micro modular reactors and next generation nuclear reactors, while laying down detailed plans for dominating the global SMR market.

The Plan hopes to have the first units in operation by the late 2020s. In March 2022, the governments of Ontario, Saskatchewan, New Brunswick and Alberta provinces released a joint strategic plan setting out a path for developing and deploying SMRs. Three separate streams are envisaged under the plan [85]:

- Stream 1: A grid-scale 300 MWe SMR project to be constructed at the Darlington nuclear site in Ontario by 2028, followed by units in Saskatchewan, with the first unit projected to be in service in 2034. OPG has announced that GE-Hitachi as the preferred technology developer for the Darlington SMR project, and early site preparation works have begun. In early 2022, OPG let a contract to begin site preparation at the Darlington site. The Darlington New Nuclear Project is the only site in Canada with an accepted environmental assessment and site preparation licence [86]. In October 2022, OPG submitted a construction licence application for the SMR and in January 2023 the four companies involved (OPG, GE Hitachi, SNC-Lavalin and Aecon) entered into a formal six-year agreement for the project to construct the 300 MWe BWRX-300 SMR. In July 2023 the Ontario government announced it is working with OPG to begin planning and licensing for three additional BWRX-300s at the Darlington plant site. The plans for Saskatchewan are based on the 2022 decision by SaskPower to select GE-Hitachi's BWRX-300 SMR for potential deployment in the mid-2030s, subject to a decision to build that is expected in 2029. In August 2023, the Canadian government approved CAD 74 million of federal funding to support work to advance the project for SMR development in Saskatchewan [87].

- Stream 2: Two fourth-generation advanced SMRs to be developed in New Brunswick: ARC Clean Energy is targeting 2029 for its ARC-100 advanced sodium-cooled fast neutron SMR to be fully operational at the Point Lepreau nuclear site by 2029. Moltex Energy is aiming to have both a used fuel recovery system and Stable Salt Reactor in operation by the early 2030s, also at Point Lepreau. In July 2023, New Brunswick Power, in partnership with ARC, submitted an environmental impact assessment registration document and an application for a site preparation licence for and SMR at the existing Point Lepreau nuclear site. In October 2023 the Government of Canada announced nearly CAD 20 million ($15 million) in federal funding to support the provinces of Nova Scotia and New Brunswick to help enable a phase-out of coal-fired electricity generation by 2030. The funding includes CAD 7 million to support pre-development work for the Point Lepreau SMR project [88].
- Stream 3: A new class of micro-SMRs designed primarily to replace the use of diesel in remote communities and mines. Global First Power, a joint venture between OPG and Ultra Safe Nuclear Corporation, is proposing to build a 5 MW micro-SMR at the federally owned Chalk River Laboratories in Ontario, aiming for an in-service date of 2026.

In early 2022, Westinghouse Electric Canada signed agreements with the Saskatchewan Research Council (SRC) and Penn State University in the USA to promote its eVinci micro-reactor. Westinghouse and SRC will jointly develop a project to locate an eVinci micro-reactor in Saskatchewan for the development and testing of industrial, research, and energy use applications [89].

In November 2022, the Belledune Port Authority (BPA, New Brunswick) announced plans to use SMR technology as part of future expansion at the port, using an ARC-100, which could be in operation by 2030–2035. It would provide energy for hydrogen production and other industries based at the port, such as metal fabrication and advanced manufacturing [90].

Prodigy Clean Energy (Canada) have linked with NuScale Power (USA) to develop a new conceptual design for a transportable, marine-based SMR that can be used to generate power at grid-scale at any coastal location, worldwide. The Prodigy SMR Marine Power Station is scalable and can house up to 12 NuScale modules to generate 924 MW.

In September 2023, the province of Alberta announced it is investing CAD 7 million in a multi-year study to explore how SMRs could be deployed for oil sands operations. It had already joined the provinces of New Brunswick, Ontario and Saskatchewan as a signatory to an MoU to collaborate on SMR development in 2021, and more recently signed MoUs with several SMR developers, including ARC Clean Technology, X-Energy and the Korea Atomic Energy Research Institute [91].

6.2. Mexico

In 2016 Mexico was considering the potential of SMRs [92]. The ‘Electricity Sector Outlook 2015–2029’ produced by the Ministry of Energy considered the use of SMRs in small scale isolated grids as an alternative to gas-fired combined-cycle plants. One study assessed cogeneration using a Pebble Bed Modular Reactor (PBMR) to produce process heat for an oil refinery; another looked at using IRIS reactors for desalination. Other off-grid applications were being considered, including regional electricity supplies in areas into which it is expensive to transport fuel. A conclusion at the time was that to avoid first-of-a-kind costs, it would be necessary to have a large number of initial orders and a joint programme for North, Central and South America might be valuable. More recently, Rolls Royce have included Mexico among their list of potential SMR markets.

6.3. United States

The USA is at the forefront of SMR development and aims to be a major provider of SMR technology. In addition, it has a number of active projects to deploy SMRs in the USA to cover a wide range of power requirements from grid electricity to mining to data centres. The leading potential providers at present are:

- NuScale Power: VOYGR module (the first SMR design to receive approval from the Nuclear Regulatory Commission)
- TerraPower: Natrium SMR (developed jointly with GE-Hitachi)
- X-energy: Xe-100 SMR
- Westinghouse: eVinci SMR

These commercial developers have also received significant government funding from the USDOE.

Progress is being made on initial deployment within the USA of the SMRs developed by these three companies, as well as initiatives from other technology developers:

- In May 2023, NuScale Power signed an MoU with Nucor Corporation to explore the deployment of VOYGR SMRs at Nucor's scrap-based Electric Arc Furnace (EAF) steel mills [93]. In addition, Standard Power plans to develop SMR facilities in Ohio and Pennsylvania using 24 NuScale VOYGR modules to power data centres [94]. Until late 2023, NuScale was developing a project at the Idaho National Laboratory with Utah Associated Municipal Power Systems (UAMPS) as part of the Carbin Free Power Project. However, plans to construct a plant with 6 NuScale Power VOYGR modules have now been terminated [95].
- In November 2021, TerraPower announced the selection of a site at Kemmerer, Wyoming, as the preferred location for its Natrium reactor demonstration project [96]. Site investigations have taken place and a request for a construction permit was planned to be submitted in early 2024 [97]. The Wyoming Energy Authority is also evaluating BWXT's Advanced Nuclear Reactor (BANR), to assess how process heat and power from the high-temperature gas-cooled reactor can be coupled to Wyoming industries, especially extractive (mining) industries [97].
- X-energy plans to submit a reactor construction permit application to the NRC, with the first reactor of a four-unit Xe-100 plant planned for construction at a site in Washington State to be operational by 2028 [98]. In July 2023, Energy Northwest announced plans to deploy up to 12 Xe-100s in central Washington State, bringing the first module online by 2030, at a location close to their Colombia power plant site [99]. In addition, the materials science company, Dow, is collaborating with X-energy to deploy the Xe-100 to provide process heat and power at one of their manufacturing sites in Texas. Construction work is planned to begin in 2026 and the reactor is expected to be operational in around 2030 [100, 101].
- In May 2022, Pennsylvania State University and Westinghouse signed a MoU for an R&D partnership exploring and applying nuclear engineering and science innovations to societal needs. They will also consider siting Westinghouse’s eVinci micro-reactor at University Park.
- The State of Nebraska is funding a siting study for SMRs, which is being carried out by Nebraska Public Power District (NPPD), a nuclear power plant operator. The aim is to identify 15 possible sites, which will then be reduced to a short-list of four.
- US and Canadian regulators are co-operating on licensing GE-Hitachi’s BWRX-300 technology and the Tennessee Valley Authority has started planning and preliminary licensing for potential deployment of the reactor at Clinch River near Oak Ridge, Tennessee and is collaborating to coordinate design, licensing, construction and operation efforts with OPG.
- In May 2023, Kairos Power submitted an application to the NRC for permission to build its Hermes 2 plant next to the Hermes molten salt test reactor it plans to build at Oak Ridge, Tennessee. The two-unit, 35 MWth demonstration plant would produce and sell electricity [102].

The potential for deploying SMRs in more remote areas of the USA is being studied in the Emerging Energy Market Analysis (EMA) project, formed by Idaho National Laboratory in partnership with the University of Alaska, Boise State University, Massachusetts Institute of Technology, University of Michigan, and the University of Wyoming [103]. The project is assessing case studies in Alaska and Wyoming, looking at potential deployment at a re-purposed coal-fired plant, or for use at a federal (or other large) facility, or to power mining activities.

7. South America

7.1. Argentina

Argentina is developing indigenous technology for an SMR. The Central ARgentina de Elementos Modulares (CAREM) 32 MWe prototype is the first domestically designed and developed nuclear power unit, with at least 70% of the components and related services for CAREM-25 sourced from Argentine companies [104]. The commercial model ultimately envisaged by the National Atomic Energy Commission (CNEA) as the basis of a muti-reactor plant would have a higher power of between 100 and 120 MWe.

The 25MW(e) CAREM utilises natural circulation for cooling and includes passive safety features such as an automatic residual heat removal system. It is intended for small electric grids and could support seawater desalination. Argentina intends the CAREM25 prototype to be the first step in the development of a competitive SMR.

7.2. Brazil

Brazil has no development work of its own on SMRs but has been seeking collaboration and investment. In 2019, it approached the USA to explore investment possibilities. Through the Brazilian Association for the Development of Nuclear Activities (ABDAN), the IAEA is supporting Brazil in analysing SMR technologies and market readiness, regulatory issues, and requirements for SMR siting. In February 2022 the Russian President Vladimir Putin visited Brazil and stated that Rosatom, which exports fuel for Brazilian nuclear power plants, was also interested in participating in the construction of new power units in Brazil, including SMRs for use both on land and as floating plants.

8. Africa

The advantage of SMRs for African countries is that they can be placed where required to supply electricity in areas without good grid infrastructure or capacity.

According to a 2018 “Atoms for Africa” study [105], “Ghana, Kenya, Namibia, Nigeria, South Africa, Sudan, Tanzania, Uganda and Zambia are the sub-Saharan African countries that have shown the most interest in new nuclear programs. The one thing almost all these countries have in common is some sort of signed agreement with an international nuclear power developer that covers various aspects of deploying nuclear power: from providing the actual technology to training local nuclear experts and setting up regulatory bodies. Russia’s Rosatom is the most popular among these developers and has signed agreements with Ghana, Kenya, Nigeria, Tanzania, Uganda and Zambia. Agreements with Chinese entities such as China General Nuclear (CGN) and [CNNC] are also common with Kenya, Sudan, Uganda, and Namibia. For now, Kenya is the only sub-Saharan country with a signed agreement for developing nuclear power with [KEPCO].”

The authors of this study assessed capacity versus motivation for implementing an SMR-based nuclear power programme in the countries most likely to take the possibility forwards and produced the diagram shown in Figure 3.

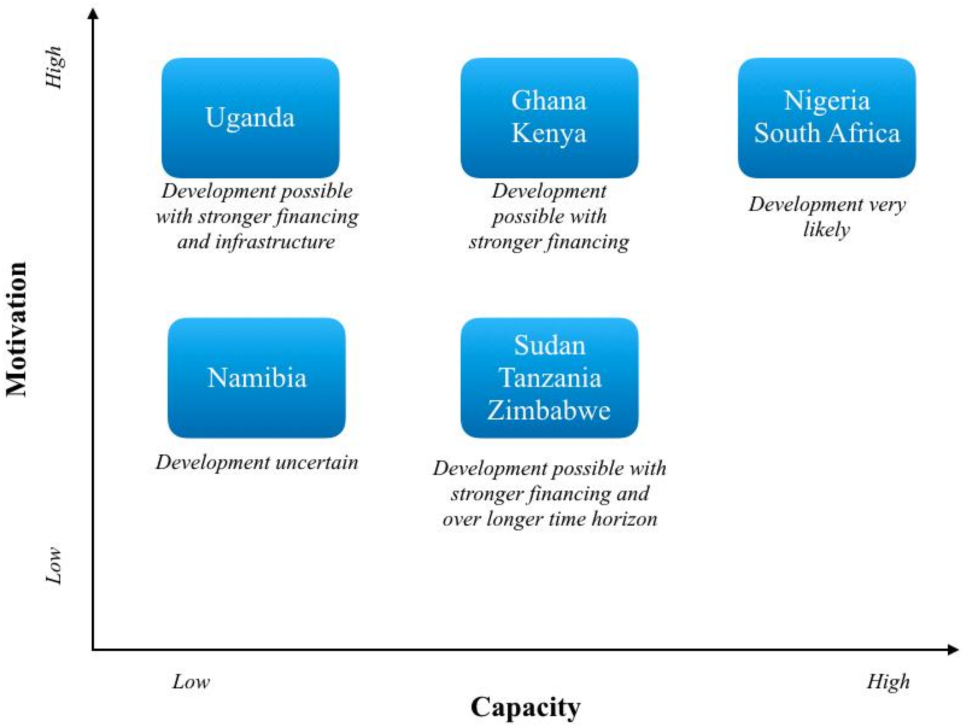

Figure 3: Capacity versus motivation for implementing an SMR-based nuclear power programme, taken from [105].

The authors concluded that there is great interest and demand for nuclear across the African continent and competition among the major vendors (Russia, China, and the Republic of Korea) may accelerate deployment, with "dozens" of co-operation agreements and MoUs having been signed already. The active interest of Rosatom is illustrated by their website, which has a page dedicated to the possibility of deploying its existing and developing floating and marine SMRs (KLT-40 and RITM series) specifically for Africa [106].

The Africa Nuclear Business Platform (NBP) has recently begun publishing an annual report 'Africa SMR Report: Accelerating the Adoption of SMR Technology in Africa'. Editions were published in 2021 and 2022.

The 2022 edition, which carried out an opinion survey among 221 nuclear industry, regulatory and government representatives across Africa, observes that "an emerging development is the acceptance by the majority of African countries to the idea of considering the adoption of SMRs. Some African countries have switched their reticence and refusal to assess SMR to a more positive position. [...] However, a common consensus among most African countries is their dissatisfaction with the current level of engagement of global SMR developers."

The survey indicated that the leading companies and SMR designs that have been most engaged with by African countries are (in decreasing order of interest): SMART (Republic of Korea), NuScale (USA), ACP100 (China), Rolls Royce (UK) and X-Energy (USA). The preference for different SMR technologies was found to be LWR (73%), HTGR (10%), Micro-modular (9%), fast neutron spectrum (3%), floating/marine (3%) and molten salt (2%). Potential end-use applications were 59% for electricity generation and 26% for industrial uses, with 11% for desalination and 4% for district heating. A large majority of responders (64%) were keen to have a regional SMR manufacturing facility in their country and 86% would be willing to adopt international or regional standardised regulations and licensing for SMRs.

Asked which African countries that are currently without nuclear power are actually likely to have a nuclear power programme, only Ghana (39%), Nigeria (26%) and Kenya (16%) were given significant credibility, with Uganda (6%) and Zambia (5%) as possibilities. Few respondents considered that other countries had significant likelihood of starting a programme.

With respect to international collaboration with potential suppliers, a majority of respondents preferred the Republic of Korea (30%), followed by preferences for Russia (23%), China (21%), USA (15%), Canada (6%) and France (5%), although a majority favoured the USA taking leadership for shaping the African nuclear landscape. The tabulation of national data shows a growing number of countries with bilateral agreements in the nuclear sector with countries outside Africa. The dominance of Russia is apparent:

- with Russia: Algeria, Egypt, Ethiopia, Ghana, Kenya, Nigeria, Rwanda, Sudan, Tanzania, Tunisia, Uganda, Zambia
- with China: Kenya, South Africa, Sudan, Uganda
- with Republic of Korea: Kenya
- with France: Morocco, South Africa, Tunisia
- with USA: Ghana, Morocco

It is noteworthy that the importance of the Republic of Korea's involvement has increased significantly over the last year. In addition, and significant with respect to this project, increased collaboration with providers of international solutions is seen as very important by most respondents.

In terms of the perceived most critical factors for SMR deployment, waste management has risen from sixth (2021) to second place (with safety in first place).

8.1. Ghana

In March 2022, the USA and Ghana announced a partnership to support Ghana's adoption of SMR technology under the US Department of State's FIRST programme. The agreement includes support for stakeholder engagement, advanced technical collaboration, and project evaluation and planning. Japan, which has partnered the USA on the FIRST programme, will also build on its existing partnership with Ghana to advance Ghana's civil nuclear power aspirations [107]. The Nuclear Regulatory Authority also has a co-operation agreement with the US Nuclear Regulatory Commission.

In October 2022, as part of their joint Winning an Edge Through Co-operation in Advanced Nuclear (WECAN) initiative, the USA and Japan announced a partnership with Ghana to support Ghana's aim to be among the first countries in Africa to advance SMR deployment and to establish itself as an advanced nuclear technology hub. In the initial step, the Japanese government is supporting an SMR feasibility study by IHI Corporation, JGC Corporation, Regnum Technology Group and NuScale Power. The study will consider the potential deployment of a NuScale VOYGR SMR.

8.2. South Africa

In South Africa, a nuclear site for the construction of a prototype SMR nuclear reactor has been identified at the Pelindaba site of the South African Nuclear Energy Corporation (NECSA), near Pretoria [108]. Another site, Kragbron, in the Free State Province has been offered as a site for setting up facilities for the fabrication of multiple reactor components and assemblies, for deployment nationally and internationally.

South Africa was a leading developer of the original PBMR design in the 1990s and 2000s, but government funding for the project terminated in 2010. In 2023 a private company, Stratek Global, announced that it hoped to build a pilot plant for the production of a 35 MWe version of the PBMR in the next 5 years, aimed at industrial and other applications, such as process heat or desalination [109].

9. Summary of International Analysis

Based on the scoping review of the current global SMR end-user landscape, many SMR vendors are identified. These are presented in Table 2. In addition to the SMR vendors, various SMR designs are specifically referenced. These are presented in Table 3.

The national surveys in Sections 1 to 8 above are driven by the availability of data. This analysis of the open literature provides credibility for the claim that the SMR designs in Table 3 are more mature with respect to the perceived readiness for commercialisation and hence are valuable SMR designs on which to focus our analysis.

Table 2: List of vendors identified through a scoping review of the current global end-user landscape.

Vendors		
• Electricité de France (EDF)	• Rolls-Royce SMR (Rolls-Royce)	• ARC Clean Technology (ARC)
• NuScale Power (NuScale)	• BWX Technologies (BWXT)	• ThorCon Power (ThorCon)
• Moltex Energy	• Terrestrial Energy	• Korea Atomic Energy Research Institute (KAERI)
• China National Nuclear Corporation (CNNC)	• Rosatom State Nuclear Energy Corporation (Rosatom)	• Korea Electric Power Company (KEPCO)
• X Energy (X-Energy)	• TerraPower	• Nuclear Power Corporation of India (NPCIL)
	• Last Energy	
• Comisión Nacional de Energía Atómica (CNEA)	• Dual Fluid Energy (Dual Fluid)	• Seaborg Technologies (Seaborg)
• An Ontario Power Generation / Ultra Safe Nuclear Corporation joint venture (Global First Power)	• A General Electric / Hitachi joint venture (GE-Hitachi Nuclear Energy)	• Westinghouse Electric Corporation (Westinghouse)

Table 3: SMR vendors and SMR designs of interest, where 'Nuclear Status' refers to whether the nation has a nuclear power programme, and where Chinese and Russian vendors/technologies appear in *blue italic text* as they are not taken forward.

Region	Nation & Nuclear Status		Vendors (and Technologies) of Interest
European Union	Belgium	Nuclear	• EDF and Partners (NUWARD)
	Bulgaria	Nuclear	• NuScale (VOYGR SMR Module / Plant)
	Czechia	Nuclear	• NuScale (VOYGR SMR Module / Plant) • GE Hitachi (Boiling Water Reactor, BWRX-300) • Rolls-Royce (UK SMR) • EDF and Partners (NUWARD) • KEPCO & KAERI (System-integrated Modular Advanced ReacTor, SMART)

Region	Nation & Nuclear Status		Vendors (and Technologies) of Interest
	Denmark	Non-nuclear	• Seaborg (Compact Molten Salt Reactor, CMSR)
	Estonia	Non-nuclear	• Moltex Energy (Stable Salt Reactor –Wasteburner, SSR-W300) • Terrestrial Energy (Integral Molten Salt Reactor, IMSR400) • GE-Hitachi (Boiling Water Reactor, BWRX-300) • NuScale (VOYGR SMR Module / Plant)
	Finland	Nuclear	• AP300 (Westinghouse)
	France	Nuclear	• EDF (NUWARD)
	Hungary	Nuclear	• No specifics identified.
	Italy	Nuclear	• EDF (NUWARD)
	Netherlands	Nuclear	• Rolls-Royce (UK SMR)
	Poland	Non-nuclear	• Last Energy (PWR-20) • GE-Hitachi (Boiling Water Reactor, BWRX-300) • NuScale (VOYGR SMR Module / Plant)
	Romania	Nuclear	• NuScale (VOYGR SMR Module / Plant)
	Slovakia	Nuclear	• AP300 (Westinghouse)
	Slovenia	Nuclear	• No specifics identified.
	Sweden	Nuclear	• Moltex Energy (Stable Salt Reactor –Wasteburner, SSR-W300) • Terrestrial Energy (Integral Molten Salt Reactor, IMSR400) • GE-Hitachi (Boiling Water Reactor, BWRX-300) • NuScale (VOYGR SMR Module / Plant)
	Norway	Non-nuclear	• Rolls-Royce (UK SMR) • Seaborg (Compact Molten Salt Reactor, CMSR)
Rest of Europe	Turkey	Non-nuclear	• Rolls-Royce (UK SMR)
	Ukraine	Nuclear	• Rolls-Royce (UK SMR) • AP300 (Westinghouse)
	United Kingdom	Nuclear	• Rolls-Royce (UK SMR)
Asia-Pacific	Australia	Non-nuclear	• NuScale (VOYGR SMR Module / Plant) • GE-Hitachi (Boiling Water Reactor, BWRX-300) • Terrestrial Energy (Integral Molten Salt Reactor, IMSR400)
	China	*Nuclear*	• *CNNC*
	Indonesia	Non-nuclear	• NuScale (VOYGR SMR Module / Plant) • Seaborg (Compact Molten Salt Reactor, CMSR) • ThorCon (ThorCon Module / Plant) • *Rosatom (Floating Nuclear Power Plants)*
	Japan	Nuclear	• NuScale (VOYGR SMR Module / Plant) • TerraPower (Natrium Reactor, Traveling Wave Reactor)

Region	Nation & Nuclear Status		Vendors (and Technologies) of Interest
			• TerraPower & GE Hitachi (Natrium SMR) • GE Hitachi (Boiling Water Reactor, BWRX-300)
	Myanmar	Non-nuclear	• *Rosatom*
	Philippines	Non-nuclear	• KEPCO & KAERI (System-integrated Modular Advanced ReacTor, SMART) • NuScale (VOYGR SMR Module / Plant) • Rosatom
	Republic of Korea	Nuclear	• KEPCO & KAERI (System-integrated Modular Advanced ReacTor, SMART) • NuScale (VOYGR SMR Module / Plant) • TerraPower (Traveling Wave Reactor) • TerraPower & GE Hitachi (Natrium SMR) • Seaborg (Compact Molten Salt Reactor, CMSR) • Global First Power (Micro Modular Reactor, MMR) • KEPCO (BANDI-60S)
	Singapore	Non-nuclear	• No specifics identified.
	Thailand	Non-nuclear	• No specifics identified.
Central Asia	India	Nuclear	• NPCIL (Heavy Water Reactor, PHWR-220)[1] • GE Hitachi (Boiling Water Reactor, BWRX-300)
	Sri Lanka	Non-nuclear	• No specifics identified.
	Kazakhstan	Non-nuclear	• NuScale (VOYGR SMR Module / Plant) • EDF and Partners (NUWARD) • KEPCO & KAERI (System-integrated Modular Advanced ReacTor, SMART) • *CNNC* • *Rosatom*
	Russia	*Nuclear*	• *Rosatom*
Middle East	Jordan	Non-nuclear	• NuScale (VOYGR SMR Module / Plant) • X-Energy (Xe-100)
	Saudi Arabia	Non-nuclear	• KEPCO & KAERI (System-integrated Modular Advanced ReacTor, SMART)
North America	Canada	Nuclear	• GE Hitachi (Boiling Water Reactor, BWRX-300) • ARC Nuclear Canada (ARC-100) • Global First Power (Micro Modular Reactor, MMR) • Westinghouse (eVinci Micro Reactor)

[1] As a scaled-down version of a Generation II reactor design, this reactor does not align with the IAEA SMR definition of "*advanced reactors that produce electricity of up to 300 MW(e) per module*" and is therefore not taken forward.

Region	Nation & Nuclear Status		Vendors (and Technologies) of Interest
			• Moltex Energy (Stable Salt Reactor-Wasteburner, SSR-W300)
	Mexico	Nuclear	• Westinghouse-led Consortium (International Reactor Innovative and Secure, IRIS) • Rolls-Royce SMR Technology (UK SMR)
	United States	Nuclear	• NuScale (VOYGR SMR Module / Plant) • TerraPower & GE Hitachi (Natrium SMR) • X-Energy (Xe-100) • Westinghouse (eVinci Micro Reactor) • BWXT (BWXT Advanced Nuclear Reactor, BANR)
South America	Argentina	Nuclear	• CNEA (Central Argentina de Elementos Modulares, CAREM)
	Brazil	Nuclear	• No specifics identified.
Africa	General	Mixed	• KEPCO & KAERI (System-integrated Modular Advanced ReacTor, SMART) • NuScale (VOYGR SMR Module / Plant) • Rolls-Royce SMR Technology (UK SMR) • X-Energy (Xe-100) • Dual Fluid (DF300) • *CNNC* • *Rosatom*

Appendix 3: Disposability of SNF

In exploring the characteristics of SMR SNF, operational wastes and decommissioning wastes, an important consideration is the availability of options for disposal of these wastes.

Geological disposal programmes require the specification of Waste Acceptance Criteria (WAC) for the facility in which disposal of wastes is expected to take place. The responsibility for the development and management of WAC varies by nation and regulatory regime. This is outlined in Requirement 20 of IAEA Specific Safety Requirment-5 (SSR-5): “Waste packages and unpackaged waste accepted for emplacement in a disposal facility shall conform to criteria that are fully consistent with, and are derived from, the safety case for the disposal facility in operation and after closure” [110].

In the UK, for example, the “ability of a waste package to satisfy the defined requirement for disposal” [111] in such a facility (in accordance with the WAC, or in accordance with waste packaging advice until the WAC has been fully defined) is defined as ‘disposability’.

Nuclear Waste Services (NWS) is the Waste Management Organisation (WMO) responsible for geological disposal in England and Wales. NWS and the Nuclear Decommissioning Authority (NDA) use a Disposability Assessment Process [112], which examines the waste package properties listed in Table 4 (as well as other characteristics such as records management) to assess whether the proposed waste packages are suitable for disposal. The safety assessments cover the transport, operations and post-closure phases.

Table 4: UK NDA & NWS waste package properties that are assessed for disposability (taken from [112]) and their relevance for this study.

Disposability Topic	Consideration within the context of this study
Nature and quantities of waste evaluation and preparation of waste package data summary sheets	Highly relevant.
Wasteform Properties	Highly relevant.
Criticality Safety	Less relevant, as this is difficult to consider without becoming waste package specific.
Fire Accident Performance	Less relevant, as this is difficult to consider without becoming waste package specific.
Impact Accident Performance	Not applicable for this study as this cannot be considered without defining the package within which the waste is placed for disposal.
Container Design	
Container Integrity	
Concept Compatibility	Not applicable for this study as this cannot be considered without the geological disposal concept within which the waste is placed for disposal.

The European Union (EU) Horizon 2020 Theramin (thermal treatment for radioactive waste minimisation and hazard reduction) project covers the disposability of thermally treated radioactive waste. This was done through the consideration of WAC against disposability topics and is summarised in a ‘Waste Acceptance Criteria and requirements in terms of characterisation’ report [113] which uses the topics outlined in Table 5.

Table 5: EU Theramin disposability topics (taken from [113]) and their consideration in the context of this study.

Disposability Topic	Consideration within the context of this study
Physical dimensions, weight	Highly relevant and a sub-set of ‘Nature and quantities of waste…’ in Table 4.
Integrity	Not applicable for this study as this cannot be considered without defining the package within which the waste is placed for disposal.
Activity content	Less relevant, as this is difficult to consider without becoming waste package specific.
Radionuclide inventory	Relevant, as the activity content and radionuclide inventory per package influences container loading and, therefore, the number of packages. This is therefore related to the ‘Nature and quantities of waste…’ in Table 4 but is not covered in detail to avoid becoming waste package specific.
Dose rate	Less relevant, as this is difficult to consider without becoming waste package specific.
Surface contamination	Not relevant for this study and specific to the waste packaging process.
Nuclear criticality	Less relevant, as this is difficult to consider without becoming waste package specific.
Containment	Not applicable for this study as this cannot be considered without defining the package within which the waste is placed for disposal.
Thermal output	Highly relevant and a sub-set of ‘Wasteform properties’ in Table 4.
Radiological gas generation	Relevant and a sub-set of ‘Wasteform properties’ in Table 4.
Non-radiological gas generation	
Chemical content	
Chemical durability	
Volume of voids	Not applicable for this study as this cannot be considered without the defining package within which the waste is placed for disposal.
Stackability	Not applicable for this study as this cannot be considered without defining the package within which the waste is placed for disposal.
Impact performance	
Fire performance	Less relevant, as this is difficult to consider without becoming waste package specific.
Identification	Not relevant for this study and specific to the waste packaging process.
Quality control	
Quality assurance	
Data requirements	

Drawing from [112] and [113], Table 6 presents a reference set of disposability topics considered to be a suitable baseline for a high-level evaluation of waste arisings, along with potential data from a given SMR technology which could be used as a basis for evaluation against those topics.

Table 6: Topics for evaluating waste stream disposability, drawn from [112] and [113], noting that disposability applies to waste packages specifically but is considered here more generally. For our down-selected SMR designs, data that are generally available are highlighted green; data that are not available but can be estimated through assumptions and/or calculation are highlighted blue and data that are not available and would rely on very qualitative and high-level reasoning to make general claims are highlighted yellow.

Disposability Topic	Potential SMR data which could be used for evaluation
Quantity of Waste	• **Waste volume**. It should be noted that a design with a relatively high volume of waste per MWe power output produced may nevertheless have wider benefits, e.g., an SME design with a smaller Reactor Pressure Vessel (RPV) and a low power output could make direct disposal easier and therefore reduce worker dose rate; an SMR are designed for radioactive waste transmutation could potentially reduce the global waste inventory of a nation when considered holistically.
Nature of Waste	• **Waste material**. Consideration of exotic or unconventional waste streams (specifically MSR and SFR coolants) will likely be most important. Much more research into disposability will be required in these cases because little work has been carried out on the existing limited inventories of activated salts and sodium from molten salt- and sodium-cooled research reactors. • **Waste geometry and dimensions**. Significant work has been carried out to develop bespoke waste packages for specific wasteforms, e.g., conventional large LWR fuel rods. • **Heat output**. For SNF, this depends on the neutron spectrum, the fuel burnup and the elemental composition of the materials used in the fuel assembly. For other waste streams shielding must also be considered. • **Stability**. This is a key issue for exotic and unconventional waste streams, as comparatively little effort has been conducted to develop a stable wasteform suitable for disposal in an existing waste package. • **Gas generation potential**. The potential for gas generation of both the waste stream and any materials which require introduction for the purpose of processing and/or stabilisation should be considered. • **Radionuclide inventory**. SMR designs that have different neutron spectra, materials and burnups will generate different radionuclide inventories. A further key differentiator is whether the SMR is a 'waste burner' or not.

Disposability Topic	Potential SMR data which could be used for evaluation
Criticality Safety	• **Fuel type**. Exotic and unconventional fuels may require significantly more work than fuels used routinely in large reactors. • **Fuel enrichment**. • **SNF fissile material content**.
Fire Performance	• **Combustion or reaction potential**. The combustibility and/or reactivity of both the waste stream and any materials which require introduction for the purpose of processing and/or stabilisation should be considered.
Handling Safety	• **Activity content** and **Dose Rate**. This level of detail could only be covered through assumptions around acceptable activity per waste package and therefore waste packages per SMR and is therefore linked closely with 'Waste volume'.

Given the availability of data for evaluating SMR wastes against the disposability topics outlined in Table 6, and with a view towards analysis around the subject of DGRs, and MNRs more specifically, the key impacts of SMR waste streams on a DGR (and therefore a MNR) are simplified to the five waste stream properties captured in Table 7.

Table 7: UK NDA & NWS disposability topics (taken from [112]) and their consideration in the context of this study.

Disposability Topic	Consideration within the context of this study
Volume	The volume of waste generated by an SMR, per unit of **electrical power**, over its operational lifetime has a direct impact on the size of a MNR, which is directly related to the cost of a MNR and other strategic elements, such as siting.
Heat Output	The heat output generated by SMR fuel (a function of **fuel type**, **fuel enrichment** and **fuel burnup**), per unit **volume** of waste (and therefore per unit of **electrical power**), has a direct impact on the size of a MNR as waste packages with a higher or longer-lasting thermal power will require greater spacing between waste packages.
Fissile Material	The amount of fissile material in an SMR waste stream (a function of **fuel type**, **fuel enrichment** and **fuel burnup**), per unit **volume** of waste (and therefore per unit of **electrical power**), has a direct impact on the size of a MNR. SMR waste streams with a greater amount of fissile material could require separation among a greater number of waste packages, to ensure criticality safety.
Physical Characteristics	The **geometry**, **dimensions** and **physical form** of an SMR waste stream may directly impact the waste package in which it can be disposed of and/or the suitability of a DGR disposal concept / Engineered Barrier System (EBS).
Chemical Characteristics	The **chemical make-up** of an SMR waste stream may directly impact the waste package in which it can be disposed of and/or the suitability of a DGR disposal concept and EBS.

Appendix 4: Down-selected SMR Design Waste Data & Information

1. Design Parameters and Assumptions

Table 8: Down-selected SMR designs and associated data / information for key design parameters.

SMR Vendor	NuScale	X-Energy	TerraPower and GE-Hitachi Nuclear Energy	Terrestrial Energy	Westinghouse
SMR Design	**VOYGR Module**	**Xe-100**	**Natrium SMR**	**IMSR400**	**eVinci**
Reactor Type	PWR	HTGR	SFR	MSR	HPR
Power (MWth)	250	200	840	440	7 to 12
Power (MWe)	77	82.5	345	195	2 to 3.5
Fuel Cycle	LEU once-through	HALEU once-through	HALEU once-through	LEU once-through	HALEU once-through
Fuel	Standard 17x17 fuel rod assembly using UO_2 pellets	UCO TRISO particle fuel pebbles	hexagonal array of metallic U fuel bundles, no sodium bond	UF_4 in molten salt coolant	Particle fuel, e.g., TRISO
Enrichment (%)	4.95 (max)	15.5	5 to 20 *(Demo will use 19)*	< 5	5 to 19.75
Burnup (MWd/kg)	45 (min)	165	150-200 *(DEMO will reach 150)*	26 – 29	*Data unavailable*
Core	37 fuel assemblies	220,000 pebbles (each with 18,000 particles) in the core at any one time	*Data unavailable*	Continual circulation of molten salt fuel-coolant mixture	Monolithic block with fuel, moderator, and heat pipe channels
Fuel Re-loading Pattern	Nominal 18-month three batch shuffling	Online refuelling; 170-179 pebbles in/out per day, each in-core for >1,320 days	Fuel in reactor for 1.5 years	Core replaced after 84-month operation	Canister return after ~8-year operation
Reactor Vessel (Dimensions / Mass)	Height: 17.7 m Radius: 1.35 m Mass: Unknown	Height: 16.5 m Radius: 2.44 m Mass: 274 t	*Data unavailable*	Height: 7 m Radius: 1.75 m Mass: 170 t	*Data unavailable*
Design Life (Years)	60	60	*Data unavailable*	56	40
Coolant	Light water	Helium	Sodium	Fluoride salt	Sodium-filled heat pipes
Moderator	Light water	Graphite	None	Graphite	Metal hydride
Reference(s)	[124, 114]	[124, 146, 115]	[116, 139]	[124, 117]	[124, 118, 119]

Table 9: Key sources of global SMR design information available in the open literature.

Resource	Description	Reference
IAEA SMR Book 2016	The IAEA SMR books provide a summary of the various SMR designs under development. Each book includes a 2-to-3-page data sheet for each of tens of SMR designs, covering core design data and additional information on safety features, etc., for each SMR design. Notably, there is a Waste Management and Disposal Plan for each, but these are typically very brief. The books are supplemental summaries for the IAEA Advanced Reactors Information System (ARIS) [120], where they are underpinned by additional data and information.	[121]
IAEA SMR Book 2018		[122]
IAEA SMR Book 2020		[123]
IAEA SMR Book 2022		[124]
NEA SMR Dashboard	The NEA SMR dashboard briefly summarises key information associated with deployment (and, hence, potential for commercialisation) of various SMR designs. The progress of the twenty or so SMR designs is briefly summarised in terms of Licensing, Siting, Financing, Supply Chain, Engagement and Fuel, but no dedicated underpinning is included.	[125]
NEA SMR Dashboard Volume II		[126]

2. Disposal of Operational and Decommissioning Wastes

Our focus here is on wastes associated with specific parts of different reactor technologies that may arise through routine operations and end of lifetime decommissioning activities. The process of fabricating and supplying fuel, or the comparative risk of contamination during decommissioning of different reactor technologies are out of scope. We come back to this distinction in Section 5 of this Appendix when exploring quantitative metrics for ILW and LLW that may arise through operations and decommissioning.

2.1. VOYGR PWR

Activated metals from the reactor core supporting structure comprise the main types of material in this group. Also included would be non-fuel core components such as control rods and instrument assemblies. The nature of these materials is the same as those from conventional PWRs, although component dimensions are smaller. For disposal, similar packaging designs, DGR design and safety concepts would be appropriate and little development work would be required to include these wastes in a disposal programme that already includes conventional PWR wastes.

2.2. Xe-100 HTGR

The Xe-100 HTGR used as a reference case in [146] includes a large volume of graphite blocks arranged both radially and axially around the core region that contains the TRISO pebbles. The level of activation will depend on the number of times that the blocks are replaced in the lifetime of the reactor and the level of impurities in the graphite, and it is not clear that geological disposal would be the most appropriate solution in all cases. There is no widely accepted and implemented solution for the management of graphite wastes. This is a topic of ongoing research.

2.3. Natrium SFR

The reactor core components include neutron reflector assemblies (predominantly composed of steel), whose level of activation depends on how long they remain in the reactor, i.e., how frequently they might be replaced, which is partly an operational decision. It is suggested in [146] that this might only need to be once during the lifetime of the Natrium SFR. As with the PWR core components, management of SFR activated metals is unlikely to require major new R&D or modification of DGR concepts that already have to handle small volumes of activated metals in their ILW inventory. Following draining of the primary system, the sodium coolant can be solidified as a chemically stable form and disposed of as LLW as has been done for prior sodium cooled reactors. However, any residual sodium would have to be removed from dismantled assembly components before they could be packaged for disposal in a DGR. Various methods of “alkali metal residuals removal” [127] are available, but these techniques would likely require investment to upscale for commercial use. Dismantling would generate activated steel from the fuel cladding and other metallic wastes, which would require geological disposal. It seems reasonable to assume that these types of material could be dealt with together with the other activated metal core components. Techniques are available for packaging metallic fuel cladding generated by the reprocessing of SNF from conventional reactors, typically using compaction.

2.4. IMSR400 MSR

Given the molten salt in this SMR acts as both a fuel and a coolant, this is covered by our consideration of the disposal of IMSR400 SNF. However, it is notable that, should the separation of molten salt from the fuel material be possible by some future processing technique, the operational and decommissioning waste management may be less difficult than for the SNF materials. Experience from the Oak Ridge National Laboratory [147] has shown that salt used to flush the primary loop would be contaminated with fuel-coolant salt, potentially also requiring disposal in a DGR. As a graphite moderator is used, the same considerations as for the Xe-100 apply.

2.5. eVinci HPR

It can be argued that, due to the associated operational strategy, where fuelling is intended to take place before the reactor is delivered to a site, with the reactor being removed when refuelling is required [144], the eVinci technology generates no ‘operational wastes’, instead generating only SNF and decommissioning waste streams. The eVinci is able to do this because its heat pipes enable passive core heat extraction and inherent power regulation, allowing autonomous operation over a period of ~8 years [143].

Plans to replace the eVinci canister by swapping the entire reactor canister with a new micro reactor unit when the end of its operating lifetime has been reached, are novel. Transporting an entire nuclear reactor unit post-operation back to the factory where they can be refuelled and their components can be refurbished [144] has not been done before and raises safety and safeguards concerns and would require regulatory interactions. However, assuming this can be done, separation of SNF particles and decommissioning of the module for processing and disposal would take place at a dedicated, central facility.

The graphite core, with channels for heat pipes and TRISO fuel pellets [144], represents a problematic waste stream, where similar points and arguments as those outlined for the Xe-100 apply.

Following the removal of the SNF, the majority of the activated metal components can be expected to be treated in a similar manner to decommissioning waste from a conventional LWR. However, each of the hundreds of passive in-core heat pipes will contain a small amount of sodium liquid to move heat from the core. As the sodium is designed to be fully encapsulated in a sealed pipe, with no need for replenishment or circulation, concerns in this area are primarily from a safe dismantling and separation perspective as the geological disposal of such materials is feasible with sufficient processing [144].

The eVinci is part of a general trend: metal hydrides are being considered for use as a moderator in microreactors more generally [128]. This material has not been used in commercial reactors and work is underway to investigate its stability and how it interacts with other materials. Therefore, additional research is likely to be required to understand any disposal-relevant properties following irradiation [129].

3. Disposal of SNF – Waste Packaging

3.1. VOYGR PWR

This is the most straightforward SNF to consider, and relevant data can be found in [146]. VOYGR PWR fuel element and assembly configuration, thermal output, and enrichment have close parallels with the characteristics of conventional PWR fuels. The size of VOYGR assemblies is smaller: 2 m length and 0.11 m^3 volume compared to 4 - 5 m length and 0.19 m^3 volume for PWR assemblies.

These parallels indicate that the packaging options and EBS designs developed in existing national disposal concepts would be equally applicable to VOYGR SNF, although the length of disposal containers could be smaller, potentially necessitating a new canister design. However, at close to half the length, stacking two VOYGR module assemblies in one canister may be feasible, although additional dedicated research, feasibility studies and safety verification would still be required, e.g., to ensure that criticality disposal criteria are met.

On the other hand, as already planned for some existing shorter PWR SNF assemblies, smaller containers could readily be accommodated in existing DGR concepts with little impact on space or volume compared to disposing of conventional PWR fuel. Nevertheless, the different container dimensions, fission product inventories, thermal characteristics and contents of fissionable material (different burnups) would have to be accounted for in repository design. Overall, it is expected that there would be only limited requirement for DGR concept and design adaptations or safety case development beyond what is already required for PWR fuel disposal. Possible conditioning and packaging options for VOYGR fuel are likely to be equally applicable in existing or planned facilities for packaging conventional PWR fuel (encapsulation). Should deep borehole disposal become a realistic alternative to a mined repository, the shorter packages may be more easily emplaced.

3.2. Xe-100 HTGR

The TRISO-X particle fuel used in this reactor system presents novel requirements on the design of a system for direct disposal, although such fuels have been in use for some time. The fuel contains a large proportion of carbon, both as pyrocarbon in the layered structure of the fuel particles (~855 micron diameter) and as the graphite matrix in the pebbles (60 mm diameter) that contain thousands of particles and comprise the fuel elements. Direct disposal of pebbles has been evaluated by a number of researchers and, in a recent review [130], it was noted that direct disposal seems to be the most reasonable option.

Experimental work on the stability of TRISO particle fuel in synthetic groundwaters indicates that due to its high stability in reducing conditions, disposal in reducing deep geological environments may constitute a viable solution for its long-term management [131].

Estimates have also been made under oxidising conditions of the containment longevity of particles – the time before the outer pyrolytic carbon and silicon carbide layers fails and fission products could be released – indicating times in the order of hundreds of thousands of years [132].

However, direct disposal of pebbles involves incorporating large volumes of graphite waste, which separately might be classified as ILW, with the much higher activity fuel, in the same packages. As noted by Bader et al. [133], the potentially adverse behaviour of bulk carbon material in a DGR needs to be assessed, including the potential for graphite fires, graphite moderated criticality, and/or organic-promoted or enhanced corrosion inside a TRISO-containing canister. Nevertheless, Dungan et al. [134] observed that "there is very little incentive for retrieving the uranium kernels from the graphite pebbles". The authors go on to say that "reprocessing TRISO fuel would be a challenging and costly process and furthermore would generate a considerable separate inventory of irradiated graphite requiring appropriate disposal [...] Additionally, it is thought the TRISO particles and graphite pebble fuel form will provide further barriers to radionuclide release from the fuel post disposal. There have been several studies on the behaviour of fuel kernels under disposal conditions which suggest that the good durability of TRISO particles under repository conditions may make them a suitable wasteform for long term disposal."

A packaging solution for TRISO pebbles was proposed by Dungan et al. using a 'conventional' PWR SNF package, as illustrated in Figure 4. The pebbles are not to scale in this illustration, and the canister is modelled to contain about 3 tonnes of pebbles (about 14,300) assuming random packing. The authors note that criticality calculations have not been performed to assess this approach. The paper does not discuss whether such containers would require any matrix fill to provide mechanical stability to the canister and heat transfer under disposal conditions.

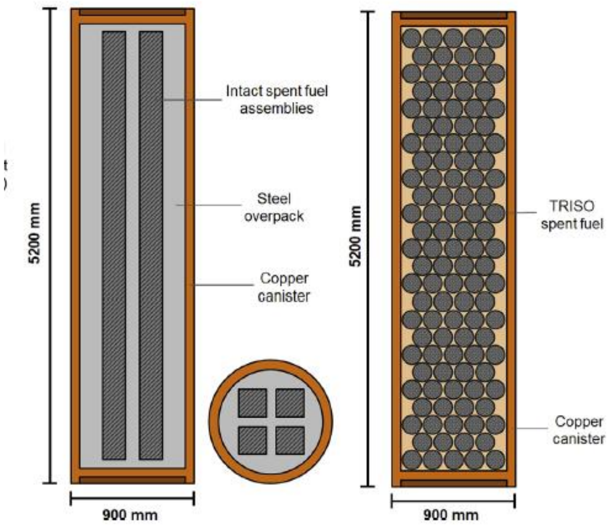

Figure 4: A potential packaging solution for TRISO disposal, taken from [134].

The heat output of such a container is much lower than an equivalent canister of PWR SNF. In [146], it is estimated that Xe-100 SNF will have about 65% of the heat output of its equivalent in PWR fuel for the same energy generation capacity, and will also have a factor of 12.3 greater volume, so the thermal dimensioning requirements for including PWR-sized canisters such as suggested by Dungan et al. in a DGR will allow much closer spacing than for canisters of LWR SNF or HLW. Clearly there is scope (and a requirement) for more work on TRISO SNF package design, including other materials and dimensions. For example, Dungan et al. note that disposal of HTGR fuel in CASTOR casks has also been suggested in the past. However, the inertness and stability of the fuel and its low thermal loading suggest that the R&D needs for packaging and EBS design could be based on existing work for LWR SNF or HLW packaging.

X-energy, the company developing the Xe-100 SMR, proposes to develop the above approach for interim storage and then possibly direct disposal of TRISO fuel [135]. The working design is for a 3 m long by 0.76 m diameter canister (see Figure 5) that would hold about 6,000 pebbles, with around 10 canisters being generated for each year of Xe-100 operation. Canisters would be held in an air-cooled interim storage facility on the reactor site. We note that this dimension of canister could be suitable for deep borehole disposal, as well as conventional DGR disposal.

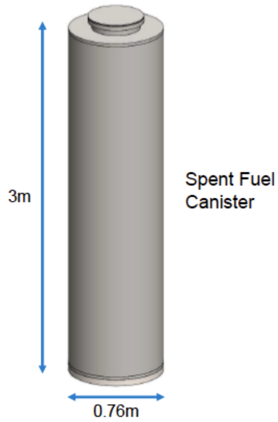

Figure 5: X-energy canister for direct disposal of TRISO fuel, taken from [135].

Should there be a clear requirement to separate the fuel particles from the pebbles (e.g., to reduce the volume of fuel for disposal or to enable reprocessing) part of the considerable development work would include the consideration of an appropriate matrix for particle conditioning for disposal. Sintered glasses have been suggested as a possible matrix for immobilisation of SNF particles for eventual deep geological disposal [136]. Guittonneau et al. [137] tested a number of techniques for the physical separation of the particles from the graphite in a study that illustrates how much development work would be needed if this approach were to be adopted by SMR user countries. The residual problem remains of how to manage the separated graphite. This is a topical issue and, although various solutions for storage and disposal have been proposed and tested (see [138]), it is certainly an area where there is no standard practice, and much development will be required.

3.3. Natrium SFR

Several different types of fuel are considered for this reactor, depending on objective (e.g., recycling SNF and burning transuranics; breeder; commercial). According to [146], the commercial design will use U-Zr metallic fuel, but without a sodium bond within the fuel pins (used in other Natrium configurations to transfer heat to the fuel cladding). If the Natrium SFR were deployed using sodium-bonded fuel, direct disposal would not be an acceptable solution without removal of the sodium. TerraPower communication material [139] states that Natrium fuel will involve pins being “arranged in hexagonal assemblies”, similar to those used in Russian-designed PWRs (VVERs) in operation in Finland, which will be compatible with KBS-3 disposal canisters. Further details of fuel assembly specifications are not readily available and are redacted from publicly available versions of TerraPower documentation provided to the NRC, presumably for commercial reasons.

Some relevant information can be gained from GE-Hitachi documentation on their PRISM reactor. PRISM fuel elements are 4.724 m in length, but the fuel content occupies only about a quarter of this, as significant space is required for a gas plenum and other components. As observed in [146], the Natrium SFR only uses 28% of the mass of uranium of a conventional PWR to generate the same amount of energy, owing to the higher burnup and initial enrichment. But the longer plenum (to accommodate increased quantities of fission gas) means that the total volume of SNF elements is relatively higher, at 42% of that of a conventional PWR.

Assuming direct disposal of such fuel elements, rather than any form of recycling, it is likely that an optimisation analysis would be needed to compare packaging of unmodified assemblies in conventional PWR SNF containers with a solution involving separating the SNF from other assembly components and packaging activated material separately for disposal. At first appearance, the latter seems to offer few advantages when designing and managing a disposal system. However, if the Natrium SFR were deployed using sodium-bonded fuel, direct disposal would not be an acceptable solution without removal of the sodium.

Although Natrium uses metallic rather than oxide fuel, it appears feasible to base packaging for direct disposal on existing SNF concepts, designs and materials. The relatively low SNF to package volume ratio combined with the slightly lower thermal output of Natrium fuel (in kW/m^3, compared with a conventional PWR) suggest that, to achieve thermal requirements on EBS designs, conventional packages could be spaced more closely in a DGR and occupy less rock volume than those for PWR waste for an equivalent energy generation value. Potential criticality issues would need to be addressed.

Nevertheless, this is an area where further R&D would certainly be required, with consequent scheduling and cost implications.

3.4. IMSR400 MSR

Unique among the other reactors covered here, the IMSR400 design involves a fuel-coolant molten salt mixture, potentially tying the SNF, operational and decommissioning waste streams together. One of the potential benefits of MSR technologies unique among Generation IV reactors is the possibility of 'online' reprocessing, where the SNF may be reprocessed using pyrochemical techniques [140] during operations, at the SMR site(s).

Through a partnership with Australian Nuclear Science and Technology Organisation (ANSTO), Terrestrial Energy is investigating the stabilisation of the molten salt fuel-coolant as a synthetic rock (Synroc) [141]. However, as it is not clear whether the IMSR400 is being designed to incorporate online reprocessing of SNF, it is also unclear whether the waste in scope for stabilisation as Synroc will be the unprocessed molten salt SNF-irradiated-coolant mixture (noting that a variant of Synroc was developed for the disposal of [unprocessed SNF] from light water and Candu reactors [142]), or a more concentrated SNF material acquired as a result of online reprocessing.

Therefore, at this time, there are generally such broad uncertainties about the nature of the fuel cycles involved and the wastes that might be generated that the only conclusion we can draw in this document is that major RD&D effort would be required on the part of any organisation having to manage this class of SMR wastes in a DGR programme.

3.5. eVinci HPR

The readily available information on the eVinci design is limited, and the dimensions of components such as the solid steel monolith around which channels for fuel pellets and heat pipes that remove heat from the core will be built, are not known [143]. However, it can be assumed that the encapsulated fuel particles, which are coated with layers of silicon carbide that can handle temperatures higher than those that the reactor and High Assay Low Enriched Uranium (HALEU) particles could produce [144], are able to be treated in a similar manner to the Xe-100 TRISO-X fuel particles. Therefore, similar points and arguments as those outlined for the Xe-100 apply.

4. Disposal of SNF – Fissile Material / Criticality Safety

Criticality Safety is an essential, closely-regulated aspect of radioactive waste disposal implementation. It spans the transport of SNF prior to disposal; the operational process of disposing of SNF; and the post-closure period. Criticality safety is achieved through the control of various parameters depending on the radioactive material concerned, important among which is the amount of fissile content present, which can vary greatly for SNF depending on the type of fuel and the reactor design.

- **Transport.** Various SNFs are transported around the world routinely. Technical measures can be used to ensure criticality safety by precluding criticality events.
- **Operation.** Similar technical measures as for transportation can be applied during the operation of a disposal facility and the emplacement of SNF in its final disposal location. However, whereas SNF assemblies with a particularly high proportion of fissile material can be split across transport casks, disposal facility concepts generally involve the encapsulation of multiple fuel assemblies (or fuel particles) in one waste package. Hence, high levels of fissile material could result in a need for a greater number of waste packages for a given DGR disposal concept, resulting in a larger excavated volume and either greater throughput or a longer period of operation.

- **Post-closure.** No active controls can be maintained during the post-closure period, where designing a DGR to ensure criticality safety requires specific information on:
  - the specific waste for disposal, including the burnup and enrichment of the SNF in each waste package and the SNF waste package loading geometry;
  - the specific disposal concept and design, including the dimensions and materials of the EBS and the proximity of one waste package to another; and
  - the specific host rock, including the hydrochemical environment, the expected degradation behaviour of the near-field materials and the migration or retention behaviour of the fissile material.

Transport, operation and post-closure criticality safety measures and mitigations will vary based on the specific design of a waste packages and/or DGR. In a generic scenario, where an understanding of the host rock environment is not known, criticality safety concerns can generally be addressed through:

1. processing SNF to split high levels of fissile material across many packages, reducing the amount of fissile material per waste package; and/or
2. diluting SNF waste packages with non-fissile material, reducing the amount of fissile material per waste package; and/or
3. optimising disposal container loading, where containers with a high level of fissile material are loaded close to containers with a low level of fissile material, in a configuration where the likelihood of fissile material relocation is low. This may require a greater spacing between waste packages.

Without specific boundary conditions, it is considered appropriate for this generic study to conclude that SNF which is likely to have a higher level of fissile content will likely result in a larger excavated DGR volume, as a result of applying one or more of these three mitigative measures. The following sections present a broad consideration of the level of fissile content for each of the down-selected SMR designs.

4.1. VOYGR PWR

It is likely that spent VOYGR PWR SNF has a similar fissile content to a Reference PWR, as the same fuel assemblies are used, but with a slightly lower typical burnup. In [147] it is posited that SNF from an older NuScale design with a burnup value of 33 MWd/kg would have a higher, but relatively close concentration of fissile material to that of a Reference PWR.

4.2. Xe-100 HTGR

Spent Xe-100 fuel may be somewhat problematic from a criticality safety perspective, given its high enrichment, but this may not be particularly significant given the equivalently high burnup. In [146] it is stated that the Xe-100 HTGR (and the Natrium SFR) “have lower normalised activity due to higher thermal efficiency”. This report goes on to state that “the high burnup and softer neutron spectrum of the Xe-100 fuel results in more of the plutonium being consumed in situ than in the PWRs [...] with the difference reduced at 100,000 years due to plutonium decay in the SNF of the PWRs.”

4.3. Natrium SFR

Spent Natrium SFR fuel presents the greatest potential criticality safety concerns. The fissile content is expected to be high as a result of a high fuel enrichment and use of the fast neutron spectrum, despite the very high burnup. This is because “in a fast reactor like Natrium, the fissile content is not depleted as quickly due to breeding of fertile 238U into fissile 239Pu. One result is higher fissile content, including more [plutonium 239] in the SNF” [146]. This conclusion is also reached in [147], where SNF from a different small modular SFR – the Toshiba 4S, was posited to have a very high level of fissile content. A critical response to the latter by Natrium SMR vendor TerraPower states that the Natrium SFR “will reduce the volume of waste per megawatt hour of energy produced by two-thirds because of the efficiency with which it uses the fuel" [145] but does not touch on the specific issue of fissile content and criticality safety.

4.4. IMSR400 MSR

Spent IMSR400 MSR fuel is likely to have a proportion of fissile content higher than, but relatively close to, the VOYGR PWR as a result of its similar enrichment, but lower burnup. This is echoed in [147], where the fissile density of spent IMSR400 fuel (using an enrichment of 3% as opposed to that of < 5% in Appendix 4: Section 1) is calculated as being close to that of an older NuScale design (which has a lower burnup than the VOYGR Module).

4.5. eVinci HPR

As no burnup data is available for the eVinci and the relevant literature states only a large range of enrichment from 5 to 19.75%, little can be said in terms of fissile content for eVinci SNF. For the very broad purposes of discussion here, there is a potential that spent the eVinci fuel may have a similar concentration of fissile material to the spent Xe-100 fuel. This is due to the similar fuel types (where Xe-100's TRISO fuel of 15.5% enrichment could feasibly be used in an eVinci directly) and common use of the thermal neutron spectrum.

5. Waste Metric References and Calculations

Although much work has been carried out on SMR technology development and commercialisation, there is limited information in the open literature on back-end challenges and, specifically, waste metric estimates and associated data and information.

Understandably, given the lack of SMR deployment, exploring back-end impacts quantitatively is challenging and not necessarily possible given the proprietary or commercially confidential nature of existing data and the lack of its availability in the open literature.

Despite this, various papers and reports attempt to quantify waste metrics for various SMR designs using modelling data, historical experiments, research reactors and commercially operating nuclear power plants.

In order to identify some realistic waste metric data for our down-selected SMR designs, we look to the open literature where it is available and calculate and/or infer where it is not. It cannot be assumed that these metrics will be entirely accurate, but they provide sensible values which supplement a purely qualitative approach.

We use the following two literature sources in some way to specify waste metrics for all five of our SMR designs:

- A study collaboratively executed by Argonne National Laboratory and Idaho National Laboratory, funded by the USDOE, entitled '*Nuclear Waste Attributes of SMRs Scheduled for Near-Term Deployment*' [146]
- A study published in the Proceedings of the National Academy of Sciences led by Lindsay Krall et al., entitled '*Nuclear waste from Small Modular Reactors*' [147]

We consider these sources 'key' as they are the most comprehensive peer-reviewed studies relevant to our study, with a significant crossover in terms of SMR designs. The USDOE study [146] calculates the SNF assembly mass and volume using the equations shown in Figure 6. We utilise the same equation for other SMRs, where possible.

$$M_{DF} = \frac{365}{B \times \eta}$$

$$V_{SNF} = f_{mass}^{volume} \times M_{DF}$$

where

M_{DF} = SNF fuel mass (t/GWe-year),

V_{SNF} = SNF assembly/pebble volume[i] (m^3/GWe-year),

B = average discharge burnup (GWd/t-initial HM),

η = thermal efficiency (%), and

f_{mass}^{volume} = ratio of assembly or pebble volume-to-initial HM mass (m^3/t-initial HM.

Figure 6: Equations used to calculate SNF mass and volume calculations in [146].

Acquisition of ILW and LLW volume generation rate data is complex. Different assumptions around sources of such waste streams can lead to highly varied values. For example, in these studies, reactor components contaminated by fission products from failed fuel assemblies or by activated corrosion products appear to be assigned to the short-lived waste stream (and hence surface disposal), whereas activated materials appear to be assigned to the long-lived waste stream (and hence geological disposal). These assignments may not reflect reality. For example, in the disposability assessment carried out as part of the Generic Design Assessment for the Westinghouse AP1000 [148], the primary circuit filters and the primary and secondary resins were all regarded as ILW requiring geological disposal. The activity in all of these wastes streams results from the fission products and activated corrosion products that are assigned to the short-lived stream in Reference [147]. This is further complicated by the approach to operations assumed by reactor vendors and authors of sources we use from the open literature. The waste volumes will depend on how the reactor deployment unit (i.e. a power station, for conventional reactor deployment) is operated. For example, given the same fuel failure rate, replacing filters as the activity approaches the upper threshold for LLW could result in higher waste volumes but lower costs, by avoiding the need for deep geological disposal. This is reiterated in [146] which states that, rather than being related to reactor physics, LLW from decommissioning "*is highly dependent on decommissioning technologies used*" and there is therefore a "*large uncertainty in the calculated values*" given the opportunity for technology development form a waste minimisation perspective.

This is generally reflected in discussions around the ILW and LLW volume generation rates for the reactors considered here. It is assumed that all SNF and ILW will be disposed of in a DGR (the primary focus of this study where disposal is concerned), but no LLW will be. Hence, LLW volume is considered where available, but not included as a waste metric data. ILW values considered here, however, are often unlikely to be fully representative of the reactor deployment unit in its totality, as a holistic system.

5.1. Reference PWR

For a conventional 3,500 MWth and 1,175 MWe PWR, the USDOE study [146] calculates:

- a SNF volume generation rate of 9.58 m^3 per GWe-year;
- a SNF decay heat output of 40.6 / 9.76 kW per GWe-year, at the point 10 / 100 years after discharge from the reactor, where no assumed storage conditions between discharge and 10 / 100 years are made available;
- a 'Greater Than Class C' (GTCC) waste volume generation rate of 0.13 m^3 per GWe-year. Whilst this is roughly equivalent to Intermediate Level Waste (ILW), sources of GTCC waste

considered in this study include decommissioning only, with no mention of other sources of ILW e.g. filters and resins that would arise during operations and the post-operational clean out process. This value is used in our summary tables, but is unlikely to be fully representative of ILW generation; and

- a decommissioning Low-level Waste (referred to as 'LLW' in our summary tables) volume generation rate of 645.3 m^3 per GWe-year.

For a conventional 3,400 MWth and 1,000 MWe PWR, the Krall et al. study [147] calculates:

- a SNF volume generation rate of 21 tonnes per station-year which, given the 1 GWe power output, equates to 21 tonnes per GWe-year. Applying the equation in Figure 6 to the data from this study (assuming the same assembly volume-to-initial HM mass ratio of 0.441 from [146], as no other value is provided) results in a SNF generation rate of 9.26 m^3 per GWe-year.
- a SNF decay heat output of 3.85 kW per GW per year of irradiation, at the point 100 years after discharge from the reactor. No 10-year value is provided nor are any assumed storage conditions between discharge and 100 years. The study normalises by thermal rather than electrical powers so, assuming a thermal efficiency of 29%, the quoted decay heat output equates to 13.28 kW per GWe-year.
- a long-lived Low- to Intermediate-Level Waste volume generation rate 0.031 m^3 per GWth-year which, given the thermal efficiency of 29%, equates to 0.107 m^3 per GWe-year. As with the USDOE study [146], whilst this is roughly equivalent to ILW, this study only considers the near-core reactor components generated through decommissioning, with no mention of other sources of ILW. Therefore, this value is also used in our summary tables, but is unlikely to be a fully representative ILW generation rate; and
- a short-lived Low- to Intermediate-Level Waste (referred to as 'LLW' in our summary tables) volume generation rate of 3.3 m^3 per GWth-year which, given the thermal efficiency of 29%, equates to 11.4 m^3 per GWe-year. The study includes the pressure vessel, containment vessel, activated concrete in the biological shield and primary systems to calculate this value.

The values discussed here are summarised in Table 10, where those in bold have been selected for use in our analysis. These values have been chosen because the sources that we explore here report values that are close to one another, so values from either would be acceptable. However, the LLW generation rate is an exception. The value reported in the USDOE study [146] aligns with the expectation that nuclear power generates more LLW than SNF. Using the USDOE study [146] values has added benefit in that all our data is selected from a single source, with common underlying assumptions.

Table 10: Waste metric data for a Reference PWR, where those used in quantitative analysis are shown in bold.

Waste Metric (Unit)	Value in, or calculated from, the USDOE study [146]	Value in, or calculated from, the Krall et al. study [147]	Value in, or calculated from other sources [with source(s)]
SNF Volume (m^3 / GWe-year)	**9.58**	9.26	N/A
SNF decay heat at 10 years (kW / GWe-year)	**40.6**	N/A	N/A
SNF decay heat at 100 years (kW / GWe-year)	**9.76**	13.28	N/A
ILW Volume (m^3 / GWe-year)	**0.13**	0.11	N/A
LLW Volume (m^3 / GWe-year)	**645**	11.4	N/A

5.2. VOYGR PWR

The USDOE study [146] uses a NuScale PWR as one its focal SMR designs – the NuScale VOYGR. The design data are almost identical to those that we have found in recent open literature publications. Using these equations for our design data (where we use the same assembly volume-to-initial HM mass ratio of 0.441 as used in [146], as this is unavailable in the open literature) results in a SNF generation rate of 11.5 m^3 per GWe-year. However, this is likely conservative, as our burnup of 45 MWd/kg-HM is a minimum value [124], where the value used in [146] is average of 49.5 MWd/kg-HM. Hence, the SNF generation of 10.4 m^3 per GWe-year in [146] is likely more accurate.

Krall et al. [147] include a NuScale PWR in their study, but this is an older 'iPWR' design, as raised by NuScale in their response to that study's publication [149]. The iPWR has a power output of 160MWth, which is lower than the 250 MWth / 77 MWe power output of the more recent VOYGR Power Module used in our study and the USDOE study [146]. The Krall et al. study calculates a SNF generation of 5.1 m^3 per GWth-year. An electrical power of 50 MWe is quoted in [147] but the underpinning reference is not included. A 160 MWth / 50 MWe power output equates to a thermal efficiency of 31.25%. Applying this to the value of 5.1 m^3 per GWth-year gives a SNF generation rate of 16.32 m^3 per GWe-year.

SMR Nuclear Technology reports a value of 60 MWe for same 160 MWth design in an initial scoping assessment submitted to an Australian governmental inquiry in 2019 [150]. This would equate to a thermal efficiency of 37.5%, which would lead to a SNF generation of 13.6 m^3 per GWe-year when scaling the 5.1 m^3 per GWth-year value from [147] to account for thermal efficiency. In their Australian governmental inquiry submission [150], SMR Nuclear Technology estimates a SNF generation rate of 1,500 kg per year per module, which would equate to 25 tonnes per GWe-year (using the reported 60 MWe electrical power output). Applying the equation in Figure 6 to the data from this submission (assuming the same assembly volume-to-initial HM mass ratio of 0.443 from [146], as no other value is provided), this results in a SNF generation rate of 10.9 m^3 per GWe-year, less than 5% higher than the figure in [146].

The decay heat values in the USDOE study [146] are computed using the ORIGEN code, resulting in a SNF heat output of 42.2 / 10.3 kW per GWe-year at 10 / 100 years after discharge from the reactor. Krall et al. [147] also use ORIGEN simulations but with the NuScale iPWR design data, resulting in 3 kW per GWth-year at 100 years following reactor discharge, which equates to 11.4 kW per GWe-year when accounting for thermal efficiency.

The USDOE study [146] calculates a decommissioning LLW volume of 573 m^3 per GWe-year and a GTCC volume of 0.72 m^3 per GWe-year, using the same NuScale design parameters we identified independently. As only small parts of this waste volume are assumed to generated during operations, with the majority being produced through decommissioning (potentially rendering this non fully representative of ILW generation, as already discussed above), the calculations involve scaling a single volume over the operational lifetime of the reactor to get a value in m^3 per GWe-year.

For the older 160MWth NuScale design on which they focus, Krall. et al. [147] calculate a long-lived low- and intermediate-level waste (roughly equivalent to the GTCC waste explored in [146]) volume generation rate between 0.055 – 0.10 m^3 per MWe, equivalent to 0.92 – 1.67 m^3 per GWe-year, when scaled over the 60-year lifetime of the reactor. The range is due to the in/exclusion of the RPV volume, where even the upper limit is unlikely to be fully representative of ILW generation, as already discussed above. With the same lifetime scaling, Krall et al. calculate a short-lived low- and intermediate-level waste (roughly equivalent to the decommissioning LLW explored in [146]) volume generation rate of 1.2 m^3 per MWe, equivalent to 20.0 m^3 per GWe-year, when scaled over the 60-year lifetime of the reactor.

SMR Nuclear Technology estimate that 120 m^3 of LLW [150] (roughly equivalent to the decommissioning LLW explored in [146]) would be produced by a plant constructed of twelve 160 MWth / 60 MWe NuScale modules each year. This equates to ~167 m^3 per GWe-year for the 720 MWe plant. For ILW (roughly equivalent to the GTCC waste explored in [146]), SMR Nuclear Technology estimate ~1.5 m^3 a year [150] which, assuming this is for the same twelve-module plant, equates to ~2 m^3 per GWe-year.

The values discussed here are summarised in Table 11, where those in bold have been selected for use in our analysis. These values have been chosen because the reactor data we found in the open literature is identical to that presented in the USDOE study [146], whereas the Krall et al. study [147] uses slightly design data for an older version of the reactor. As with the arguments for the Reference PWR data, the LLW generation rate reported in the USDOE study [146] aligns with the expectation that nuclear power generates more LLW than SNF. The SNF generation rate presented in the USDOE study [146] is slightly lower than the value estimated using other sources. However, the difference is small (10.4 m^3 per GWe-year in contrast to 10.9 - 13.6 m^3 per GWe-year) and using the USDOE study [146] value means that all our data is selected from a single source, with common underlying assumptions.

Table 11: Waste metric data for the VOYGR PWR, where those used in quantitative analysis are shown in bold.

Waste Metric (Unit)	Value in, or calculated from, the USDOE study [146]	Value in, or calculated from, the Krall et al. study [147]	Value in, or calculated from other sources [with source(s)]
SNF Volume (m^3 / GWe-year)	**10.4**	16.3	10.9 [150] 11.5 [124] 13.6 [147, 150]
SNF decay heat at 10 years (kW / GWe-year)	**42.2**	N/A	N/A
SNF decay heat at 100 years (kW / GWe-year)	**10.3**	11.4	N/A
ILW Volume (m^3 / GWe-year)	**0.72**	1.67	N/A
LLW Volume (m^3 / GWe-year)	**573**	20.0	2.0 [150]

5.3. Xe-100 HTGR

The USDOE study [146] uses the X-Energy HTGR as one its focal SMR designs. Using the equations shown in Figure 6, the study calculates a SNF volume generation rate of 118 m^3 per GWe-year. This is significantly higher than for the NuScale VOYGR due primarily to the very high pebble volume-to-initial HM mass ratio of the TRISO fuel. The X-Energy Xe-100 design data are very similar to those that we have found in the open literature, differing only very slightly in electrical power output and burnup. The use of our data in the equations shown in Figure 6 (assuming the same assembly volume-to-initial HM mass ratio of 21.8 from [146], as this is unavailable in the open literature) results in a SNF generation rate of 117 m^3 per GWe-year.

The SNF heat output for the Xe-100 is calculated in [146] as 32.2 / 6.36 kW per GWe-year at 10 / 100 years after discharge from the reactor.

As Krall et al. do not look at a HTGR in their study [147], and hence no values are available, this can be compared with other sources:

- In a report primarily focused on PWR type SMR waste management [151], VTT notes that "*SNF generated by [HTGR type SMRs] will produce more waste for the same output of energy when compared to fuel and reactor types in conventional large NPPs. However, the waste produces less heat per volume*". This is based on an analysis of the Fort St. Vrain reactor in the US, which was found to generate "*significantly more volume per unit energy generation*" but a SNF with "*lower heat load per unit volume than LWR UO_2 fuel*". [152] This conclusion is observed when comparing the analysis between Sections 5.1 and 5.3 of this Appendix.
- A USDOE presentation at a NEA conference focused on SMR waste management [153] states that "*HTGRs will likely generate 25x more SNF than light water reactors (LWR) per ton of fuel*" (assumed to imply per ton of uranium). Such a high multiplier is not observed in our analysis or our key USDOE study [146]. However, this trend matches that stated by VTT and, therefore, both of these sources support the use of the SNF-related values from [146].

Rather than a point value, a range of ILW generation rates is presented in the USDOE study [146]. This is due to the uncertainty around the purity of graphite blocks in the reactor core, where the activation of nitrogen impurities can generate C-14. This is a similar concern raised by VTT but from the perspective of fuels, noting that "*nitride fuel is expected to generate more radioactive and mobile C-14 than conventional fuels where nitrogen typically only exists as an impurity*" [154]. The USDOE study [146] calculates that high-purity graphite would be classed as ILW once it had remained in the reactor for ~17 years, but low-purity graphite would be classed as ILW after only 3 years of irradiation. The upper estimate of 24.5 m^3 per GWe-year can therefore be considered a conservative value, and one which would also minimise the generation of LLW in lieu of LLW data, or information with which to make estimates around LLW.

The values discussed here are summarised in Table 12, where those in bold have been selected for use in our analysis. These values have been chosen because very little quantitative data is available in the open literature for this reactor, but the other sources explored here generally justify the values reported in the USDOE study [146].

Table 12: Waste metric data for the Xe-100 HTGR, where those used in quantitative analysis are shown in bold.

Waste Metric (Unit)	Value in, or calculated from, the USDOE study [146]	Value in, or calculated from, the Krall et al. study [147]	Value in, or calculated from other sources [with source(s)]
SNF Volume (m^3 / GWe-year)	**118**	N/A	117 [124]
SNF decay heat at 10 years (kW / GWe-year)	**32.2**	N/A	N/A
SNF decay heat at 100 years (kW / GWe-year)	**6.36**	N/A	N/A
ILW Volume (m^3 / GWe-year)	**24.5**	N/A	N/A
LLW Volume (m^3 / GWe-year)	N/A	N/A	N/A

5.4. Natrium SMR SFR

The USDOE study [146] uses the Natrium SMR as one of its focal SMR designs. Using the equations shown in Figure 6, the study calculates the SNF assembly volume to be 5.56 m^3 per GWe-year. The Natrium SMR design data are almost identical to those that we have found in the open literature publications, differing only very slightly in burnup to the point that the use of our data in the equations shown in Figure 6 results in a SNF generation rate of 5.48 m^3 per GWe-year. The study calculates this SNF generation rate as ~58% of a conventional PWR, at 9.58 m^3 per GWe-year which aligns with TerraPower's claims that Natrium SNF "*occupies 2/3 less volume than today's reactors, per gigawatt-hour of power generated*" [155].

Krall et al. [147] include a SFR in their study, but they analyse the Toshiba 4S rather than the Natrium SMR. The key differences in the available design parameters (Natrium SMR vs Toshiba 4S) include: thermal power (840 vs 30 MWth), electrical power (345 vs 10 MWe, where the latter is taken from [124] as not made available in [147]) and burnup (150 vs 34 MWd/kg). The calculations in [147] result in a Toshiba 4S SNF generation rate of 2 m^3 per GWth-year, which equates to 6 m^3 per GWe-year when accounting for the thermal efficiency of 33.3%, less than 10% more than the value for the Natrium SMR in [146].

The SNF heat output for the Natrium SMR is calculated in the USDOE study [146] as 24.5 / 4.65 kW per GWe-year at 10 / 100 years after discharge from the reactor. Krall et al. [147] do not calculate a heat output for the Toshiba 4S due to the limitations of the Origami module (a user interface to the ORIGEN code) used to support their modelling. However, their extrapolation of data with substituted boundary conditions led to an estimated heat output of 5.8 kW per GW-year at 100 years following reactor discharge, which (assuming this GW-year is associated with a thermal power output i.e. GWth-year, as with most of the values in [147]) equates to 17.5 m^3 per GWe-year when accounting for the thermal efficiency.

As with the Xe-100, a range of ILW generations rates is presented in the USDOE study [146]. In this case, the range is due to uncertainty on the residence time of reflector assemblies in the core, where neutron activation could cause them to be classed as ILW, rather than LLW, upon decommissioning. As no dimensional data is available in the open literature for the Natrium SMR core, the study uses the PRISM/Mod-B reactor [156] as a suitable comparison, on the basis of a similar burnup value and electrical power output. For this reactor, an ILW value of 0 m^3 per GWe-year is expected to be achievable if the components in question are replaced within 30 years of operation, but this could be 0.55 m^3 per GWe-year if the components are not replaced over the reactor's operational lifetime. The Natrium SMR design life is not available in the open literature, but [146] assumes a lifetime of 60 years for all reactors for normalisation purposes. Therefore, it can be assumed that, if these assemblies are replaced halfway through an assumed reactor lifetime of 60 years, 0 m^3 per GWe-year of ILW would be generated, but 0.55 m^3 per GWe-year of ILW would be generated if they are not replaced.

The ILW value calculated for the Toshiba 4Sby Kral et al. [147] is calculated using a similar assumption that neutron activation will cause the reflector and shielding assemblies to be classed as ILW. As with the USDOE study [146], dimensional analysis is used, resulting in an ILW value of 24.7 m^3 per GWth-year. This is equivalent to 74.1 m^3 per GWe-year, when accounting for thermal efficiency.

Whilst a 2022 National Academies consensus study report [157] states that treatment methods for sodium-bonded SNF (as stated in [153], the Natrium SMR will not use a sodium-bonded fuel) are "*not yet technically mature at the industrial scale*", [157] notes that "*coolant sodium can be solidified as a chemically stable form and disposed of as* [LLW] *as has been done for prior sodium cooled reactors*". This is echoed by a 2007 IAEA report which presents "two proven technologies […] for the treatment of bulk sodium" [158]. Hence, the Natrium SMR coolant is assumed to be included as LLW, not ILW. For the PRISM/Mod-B reactor, the USDOE study [146] calculates a sodium coolant volume of ~360 m^3. Assuming it is not replaced throughout the reactor lifetime (assumed to be 60 years) and the volume would not increase through treatment prior to disposability as LLW, this equates to ~19.3 m^3 per GWe-year when accounting for its 311 MWe power output [156]. If we were to assume the assemblies noted in the ILW discussion above were replaced halfway through the operational lifetime, this source of ILW could be avoided, but an additional 1.10 (i.e. double 0.55) m^3 per GWe-year of LLW would be added to LLW generation rate. Combining these two sources would then equate to 20.4 m^3 per GWe-year. Kral et al. [147] calculate a short-lived low- and intermediate-level waste (roughly equivalent to the decommissioning LLW explored in [146]) volume of 7.3 m^3 per GWth-year for the Toshiba 4S, which is equivalent to 21.9 m^3 per GWe-year, when accounting for thermal efficiency.

The values discussed here are summarised in Table 13, where those in bold have been selected for use in our analysis. The SNF-related values have been chosen because the USDOE study [146] is the only source for this reactor that covers all of the relevant metrics. The SNF generation rate is supported by values estimated using other sources, despite the use of different reactor design data. At almost four times greater, the SNF decay heat value in the Krall et al. [147] study would be more conservative. However, using the USDOE study [146] values has added benefit in that all our SNF-related data is selected from a single source, with common underlying assumptions, including the same reactor design that we are focusing on, rather than a substitute. The ILW and LLW values have been chosen to be conservative. The selected ILW value aligns with the expectation that nuclear power generates more LLW than SNF. Using the Krall et al. study [147] the ILW and LLW values has added benefit in that all our non-SNF-related data is selected from a single source, with common underlying assumptions.

Table 13: Waste metric data for the Natrium SMR SFR, where those used in quantitative analysis are shown in bold.

Waste Metric (Unit)	Value in, or calculated from, the USDOE study [146]	Value in, or calculated from, the Krall et al. study [147]	Value in, or calculated from other sources [with source(s)]
SNF Volume (m^3 / GWe-year)	**5.56**	6.0	5.48 [139]
SNF decay heat at 10 years (kW / GWe-year)	**24.5**	N/A	N/A
SNF decay heat at 100 years (kW / GWe-year)	**4.65**	17.5	N/A
ILW Volume (m^3 / GWe-year)	0.55	**74.1**	N/A
LLW Volume (m^3 / GWe-year)	20.4	**21.9**	N/A

5.5. IMSR400 MSR

The USDOE study [146] does not look at a MSR but, in any case, the equations shown in Figure 6 are not directly transferable as the IMSR400 uses a fuel-coolant mix.

Krall et al. [147] use the Terrestrial Energy MSR as one their focal SMR designs. Simple dimensional analysis is used to estimate a total SNF generation volume of 31 m^3 and a rate of 11 m^3 per GWth-year for the total 7-year life of each reactor core, which is then replaced entirely. No electrical power output is provided alongside the thermal power output of 400 MWth in the study and we find a power output of 440 MWth / 195 MWe in the open literature. Scaling the rate from [147] to this electrical power output (a thermal efficiency of 400/195 = 48.75%) equates to 22.56 m^3 per GWe-year. However, this may be optimistic, so it would be better to take the total volume of 31 m^3 calculated by Kral et al. and scale that to the thermal efficiency (440/195 = 44.3%) and 7-year operational lifetime from the open literature, which equates to 22.71 m^3 per GWe-year, a slightly larger value.

Krall et al. [147] do not calculate a heat output for the IMSR400 due the limitations of the Origami module they used to support their modelling. However, extrapolation of data with substituted boundary conditions led them to an estimated heat output of 2.74 kW per GW-year at 100 years after discharge, which (assuming this GW-year is associated with a thermal power output i.e. GWth-year, as with most of the values in [147]) equates to 6.18 kW per GWe-year when accounting for the thermal efficiency of 44.3%.As no values are available in [146], the Krall et al. values should be compared with other sources:

- A 2020 study by Xu. et al. [159] (referenced by VTT in [160]) estimates a fuel salt volume generation of 0.34 m^3 using simple dimensional analysis. With the quoted power output of 30 MWth and thermal efficiency of 40%, i.e., an electrical power output of 0.012 GWe, this equates to ~4.05 m^3 per GWe-year over the 7-year life of a Moltex SSR-U MSR core. This is significantly lower than the value presented in [147], predominantly due to the use of a fuel-coolant mixture for the IMSR400 and a separation of salt fuel and salt coolant in the primary and secondary loops for the SSR-U design, likely resulting in a greater volume of non-SNF salt waste for the latter.

- A Terrestrial Energy presentation [161] at the same NEA conference referenced in Section 5.3 of this Appendix includes a graph showing the expected decay heat of MSR SNF after processing into a Synthetic Rock (Synroc) wasteform (see Figure 7). This graph presents a decay heat of ~8 x 10^{-5} kW per kg at 10 years and ~4 x 10^{-5} kW per kg at 100 years for IMSR400 SNF Synroc. The density of the molten salt fuel in the Molten Salt Reactor Experiment (MSRE), on which the IMSR400 philosophy is based, was observed to be 2.3 g per cm^3 [162], i.e., 2,300 kg per m^3. Using this density, the Figure 7 data points, and the SNF generation rate of 22.71 m^3 per GWe-year resulting from [147] and [124], this would equate to a heat output of 4.18 / 2.09 kW per GWe-year at 10 / 100 years after discharge.

The key contributor to the ILW volume will be the graphite moderator. Krall et al. [147] carry out the same simple dimensional analysis used for SNF to calculate a graphite ILW volume of 37 m^3 and 11 m^3 per GWth-year. Using the same approach described above for the SNF volume generation rate, this equates to 29.33 m^3 per GWe-year when assuming a thermal efficiency of 48.75%, and 27.11 m^3 per GWe-year for the less optimistic thermal efficiency of 44.3%.However, whilst this dimensional analysis can be roughly followed for the molten fuel-coolant, it could be considered overly conservative for ILW, as it assumes the entire core is solid graphite. Combining the visual representation of the IMSR400 core in [147] with that in [117], and to account for the transport of molten fuel-coolant through the core, if we assume that only half of this 37 m^3 is made up of graphite moderator material then we have a total ILW volume of 18.5 m^3. Then, accounting for the 7-year operational lifetime and the electrical power output of 0.195 GWe, we could calculate an ILW volume generation rate of 13.55 m^3 per GWe-year.

The values discussed here are summarised in Table 14, where those in bold have been selected for use in our analysis. These values have been chosen because the SNF and ILW volume generation rates we estimate using other sources are very similar to that calculated by Krall et al. [147]. For the SNF decay heat, we opt to select values estimated using other sources, as they use the same reactor design that we are focusing on, rather than a substitute.

Table 14: Waste metric data for the IMSR400 MSR, where those used in quantitative analysis are shown in bold.

Waste Metric (Unit)	Value in, or calculated from, the USDOE study [146]	Value in, or calculated from, the Krall et al. study [147]	Value in, or calculated from other sources [with source(s)]
SNF Volume (m^3 / GWe-year)	N/A	22.6	**22.7** [147, 124]
SNF decay heat at 10 years (kW / GWe-year)	N/A	N/A	**4.18** [161, 162, 147, 124]
SNF decay heat at 100 years (kW / GWe-year)	N/A	6.18	**2.09** [161, 162, 147, 124]
ILW Volume (m^3 / GWe-year)	N/A	29.3	**27.1** [147, 124] 13.55 [117, 147, 124]
LLW Volume (m^3 / GWe-year)	N/A	N/A	N/A

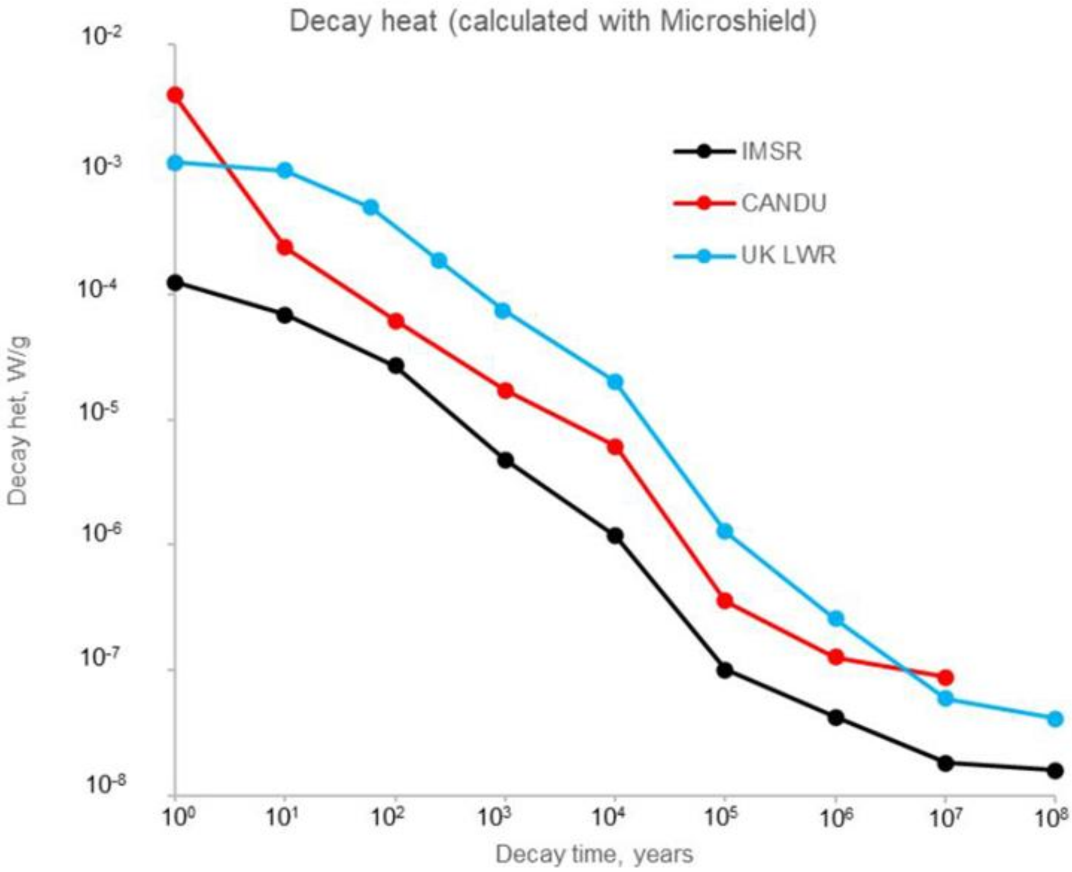

Figure 7: A calculation of decay heat from SNF processed as Synroc over time, taken from [161].

5.6. eVinci HPR

Neither the USDOE study [146] nor that of Krall et al. [147] look at an HPR, hence no values are available. In order to use the equations shown in Figure 6, we require eVinci values for burnup and pebble volume-to-initial HM mass ratio, neither of which is available in the open literature. However, both eVinci and Xe-100 use TRISO fuels. If we apply the Xe-100 burnup and pebble volume to eVinci (noting that a different fuel makeup would lead to different ratios and hence different burnup values), and use the upper range of the thermal and electrical power output from the open literature (7 - 12 MWth and 2 - 3.5 MWe, respectively), the equations shown in Figure 6 give a SNF generation rate of 165.43 m^3 per GWe-year. This significant increase in volume over the Xe-100 may be a result of the lower thermal efficiency of the eVinci which, in turn, is likely due to its 'micro' size when compared to the Xe-100.

Looking to other sources, in a 2019 presentation to Idaho National Laboratory [163] Westinghouse notes that the "*eVinci core only needs < 600 kg HALEU TRISO*" fuel particles to operate. The use of 0.600 tonnes of TRISO fuel to generate the upper end of the electrical power range, i.e. 0.0035 GWe, over the 8-year operational lifetime reported in the open literature, equates to 21.43 tonnes per GWe-year. Applying the equation in Figure 6 to this value (assuming the Xe-100 TRISO pebble volume-to-initial HM mass ratio of 21.8 m^3/tHM in [146]) equates to ~467 m^3 per GWe-year.

The decay heat values in the key reference studies were calculated using the ORIGEN code to which we did not have access as part of this study. Furthermore, no burnup data for the eVinci is available in the open literature. Hence, no decay heat values are available. However, in [146] the calculated SNF decay heat output values are roughly proportional to the values for SNF activity. A study which focuses on a theoretical 'eVinci-like' reactor [164] calculates an activity range of 1 to 1.4 x 10^6 Ci per GWe-year 100 years after removal from the reactor. This range covers the 1.06 x 10^6 Ci per GWe-year 100 years after removal value presented for the Xe-100 in [146], which utilises the same type of TRISO fuel. Therefore, it is reasonable to assume the same SNF decay heat values that were used for the Xe-100.

In lieu of data from the open literature, we can use various assumptions to perform simple dimensional analysis to calculate a rough value for ILW volume. The schematic image of the eVinci core in Figure 8 and the model used to drive the SERPENT code for the eVinci-like reactor in Figure 9 differ greatly in that the former assumes a central space for a graphite block whereas the latter assumes a central void.

A simple image measurement of Figure 9 provides a void to core linear scaling factor of ~0.143. This leads to a void radius of ~0.111 m when the quoted core radius of 0.7785 m is used (i.e., 0.7785 multiplied by 0.143 is 0.111), which can be used to calculate a volume of 0.058 m^3 when the quoted core height of 1.5 m is used (simplifying the hexagonal shape to a circle and, therefore, simplifying the void to a cylinder of radius 0.111 m and height 1.5 m). Through image comparison, we assume that the void in the model from Figure 9 has the same dimensions as the graphite block in the schematic in Figure 8, i.e., a volume of 0.058 m^3. As in Section 5.3 of this Appendix, we can assume that any graphite in the core (besides the TRISO SNF, i.e., the monolithic graphite moderator) could be classed as ILW. Using the upper limit of the 2 to 3.5 MWe power output (i.e., 0.0035 GWe) and the 8-year eVinci operational lifetime, this equates to an ILW generation rate of ~2.08 m^3 per GWe-year.

Total LLW volume or LLW volume generation rate estimation is particularly complex for the eVinci, given the use of sodium coolant within pipes and the stated operational concept of operations, where sealed modules would be returned to a factory for refurbishment at the end of their operational life.

Figure 8: Schematic image of the eVinci core, taken from [119].

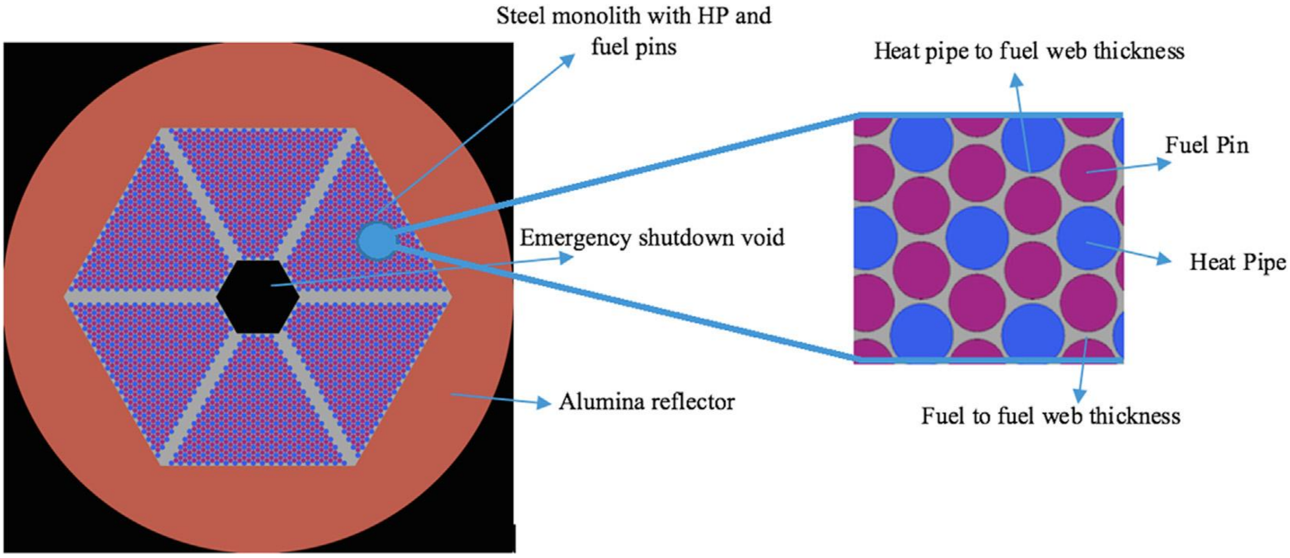

Figure 9: Core geometry of the model used to drive the SERPENT code in [164].

The values discussed here are summarised in Table 15, where those in bold have been selected for use in our analysis. These values have been chosen because very little quantitative data is available in the open literature for this reactor.

Table 15: Waste metric data for the eVinci HPR, where those used in quantitative analysis are shown in bold.

Waste Metric (Unit)	Value in, or calculated from, the USDOE study [146]	Value in, or calculated from, the Krall et al. study [147]	Value in, or calculated from other sources [with source(s)]
SNF Volume (m^3 / GWe-year)	N/A	N/A	**165** [146, 124] 467 [146, 124, 163]
SNF decay heat at 10 years (kW / GWe-year)	N/A	N/A	**32.2** [146, 164]
SNF decay heat at 100 years (kW / GWe-year)	N/A	N/A	**6.36** [146, 164]
ILW Volume (m^3 / GWe-year)	N/A	N/A	**2.08** [124, 119, 164]
LLW Volume (m^3 / GWe-year)	N/A	N/A	N/A

Appendix 5: National Radioactive Waste Management Programme Scenarios

Rather than assessing the specific impact of one or more SMR technology on any one national RWM programme, our study aims at a high-level assessment of the impact of introducing SMR technologies to generic national energy generation portfolios. We establish generic categories of countries to represent a broad range of potential countries interested in deploying SMRs.

For this purpose, we define five representative categories, where the key differentiators are the size and diversity of the national radioactive waste inventory, the approach taken to radioactive waste disposal and the availability of fuel cycle facilities and expertise:

- A Category 1 country has a large nuclear power programme, highly diverse radioactive waste inventory and an established strategy and/or programme for geological disposal that is considered to be relatively advanced, e.g., in terms of siting, disposal concept. They have a potential interest in developing new nuclear power and a national SMR vendor. They also have considerable fuel cycle facilities with world-leading fuel cycle expertise[2]. Countries that could be considered Category 1 include Canada, France, UK and USA.
- A Category 2 country has a medium nuclear power programme, relatively uniform radioactive waste inventory and an established strategy and/or programme for geological disposal that is considered to be relatively advanced, e.g., in terms of siting, disposal concept. They have a potential interest in developing new nuclear power and have various fuel cycle facilities with appropriate accompanying expertise. Countries that could be considered Category 2 include Belgium, Finland, Japan and Sweden.
- A Category 3 country has a small nuclear power programme, relatively uniform radioactive waste inventory and an established strategy and/or programme for geological disposal but is yet to advance significantly towards implementation. They have a potential interest in developing new nuclear power but have limited fuel cycle facilities and expertise, primarily focused on storage of SNF on-site following removal from nuclear power reactors. Countries that could be considered Category 3 include Croatia and Slovenia combined (due to their single shared nuclear power plant), Czechia, Mexico, Netherlands and South Africa.
- A Category 4 country has research reactor(s) or other R&D facilities, but no nuclear power programme. They have a strong interest in developing a large and ambitious nuclear power programme. Countries that could be considered Category 4 include Poland and Saudi Arabia.
- A Category 5 country has no nuclear power programme, but a potential interest in developing a limited nuclear power programme by building on the expertise acquired through existing research reactors(s) or other nuclear R&D facilities. Countries that could be considered Category 5 include Australia, Denmark, Estonia, Jordan and Norway.

These country categories are summarised in Table 16, noting that direct mapping between categories and example countries is not possible, as each country's approach to nuclear power and RWM is unique. This study, however, uses only broad / generic categories to analyse scenarios and make general conclusions.

[2] This does not explicitly include current SNF reprocessing facilities/expertise as only France holds this capability. However, it does assume a strong position from which to establish a reprocessing capability.

Table 16: Categories of country defined to be representative of a range of different countries.

	Category of Country				
	1	2	3	4	5
Nuclear power programme	Large	Medium	Small	None, with ambitious plans	None, with limited plans
Existing radioactive waste inventory	Highly diverse	Relatively uniform	Relatively uniform	Minimal	Minimal
National disposal strategy and/or programme	Highly mature	Highly mature	Relatively immature	None	None
Nuclear fuel cycle facilities & expertise	Considerable facilities & world-leading expertise	Various facilities with sufficient expertise	Limited (primarily on-site SNF storage)	Research reactor(s) / R&D facilities only	Research reactor(s) / R&D facilities only
National SMR vendor(s)	Yes	No	No	No	No
Example countries	Canada, France, UK, USA	Belgium, Finland, Japan, Sweden	Croatia and Slovenia combined (with a single shared nuclear power plant), Mexico, South Africa	Poland, Saudi Arabia	Australia, Denmark, Estonia, Jordan, Norway

Quantitative scenario-building and analysis requires realistic figures for nuclear capacity, and installed or required additional nuclear capacity, i.e., using specific values instead of ‘large’ and/or ‘ambitious’. Table 17 shows the current operational nuclear capacity for the various countries listed as examples in Table 16. The data range for some of these categories is wide; in particular, the USA and Japan skew the data for the average capacity of their categories.

Table 17: Development of illustrative nuclear capacity for categories of country defined in Table 16, where all values are based on WNA data [165].

Category	Country	Number of Operational Commercial Nuclear Power Reactors	Operational Nuclear Capacity (GWe)	Category Average Capacity (GWe)
1	Canada	19	13.624	~44
	France	56	61.370	
	UK	9	5.883	
	USA	93	95.835	
2	Belgium	5	3.928	~12
	Finland	5	4.394	
	Japan	33	31.679	
	Sweden	6	6.937	
3	Croatia and Slovenia combined, with a single shared nuclear power plant	1	0.688	~1.5
	Mexico	2	1.552	
	South Africa	2	1.854	
4	Poland	0	0	0
	Saudi Arabia	0	0	
5	Australia	0	0	0
	Denmark	0	0	
	Estonia	0	0	
	Jordan	0	0	
	Norway	0	0	

Figure 10 presents 'low case' and 'high case' estimates for the global deployment and operation of SMRs by the year 2035. The high case scenario, with a global SMR power output of ~21 GWe, indicates ~3.5 GWe and ~2.5 GWe of operational SMR capacity in North America and in Europe respectively. On the basis of an assumption of ~0.5 GWe in Mexico with the remaining 3 GWe evenly split between the USA and Canada alone, this would equate to ~1.5 GWe for Category 1 countries and ~0.5 GWe for Category 3 countries. In Europe, France dominates, so ~1 GWe could be expected, with 0.5 GWe for the UK, 300 MWe for the three Category 3 countries and 100 MWe for Slovenia and Croatia combined (with a single shared nuclear power plant) too.

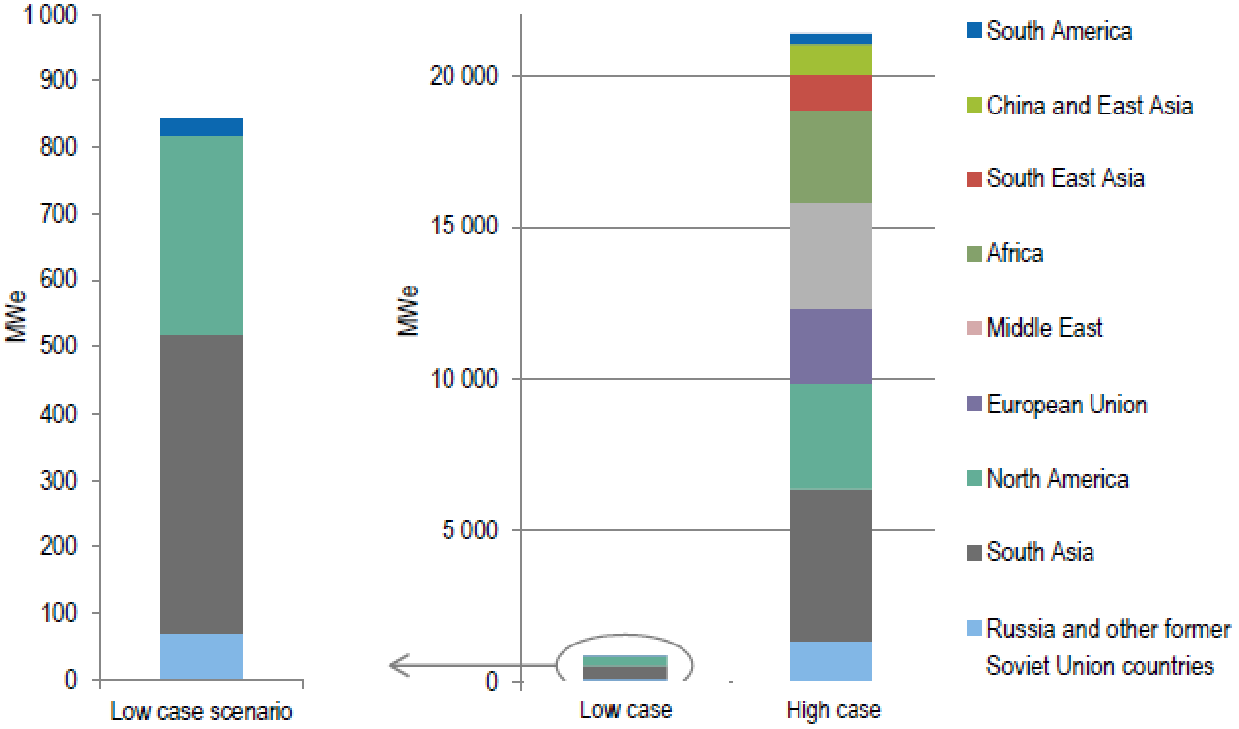

Figure 10: NEA-estimated SMR capacity in 2035 by region, Diagram copied from NEA [2], noting that the grey bar chart segment and pink legend are both Middle East but the colours do not match.

Our study does not focus on a specific time period and, therefore, a more optimistic assumption of SMR roll-out to even the high case in Figure 10 can be considered. Furthermore, the country categories account for more than only the existing and required capacity, e.g., Japan is a potential example of a Category 2 country but has a far greater nuclear power output than the UK and Canada in Category 1. Therefore, when considering the content of Table 16, Table 17 and Figure 10 in combination, the values presented in Table 18 can be considered reasonable for a generic and simplified approach that enables a step change between the different categories of country (notably, the values for European nations in Table 17 have been scaled up by roughly double the value that could be expected from Figure 10).

Table 18: Definition of country category nuclear capacity values for use in representative analysis.

Category of Country	1	2	3	4	5
Installed Nuclear Capacity (GWe)	44	12	1.5	0	0
Additional Capacity Required (GWe)	2	1	0.5	2.5	0.2

Finally, in order to simplify the discussion in the main report, five hypothetical countries (OneLand, TwoLand, ThreeLand, FourLand and FiveLand) are defined to represent the categories. Table 19 summarises this for use in the main report.

Table 19: Hypothetical countries used to represent generic categories based on radioactive waste considerations of example countries, around which our scenarios for the consideration of SMR deployment are built.

	Hypothetical Country				
	OneLand	**TwoLand**	**ThreeLand**	**FourLand**	**FiveLand**
Nuclear power programme	Large	Medium	Small	None, with ambitious plans	None, with limited plans
Existing radioactive waste inventory	Highly diverse	Relatively uniform	Relatively uniform	Minimal	Minimal
National disposal strategy and/or programme	Yes	Yes	Yes	No	No
Nuclear fuel cycle facilities & expertise	Considerable facilities & world-leading expertise	Various facilities with sufficient expertise	Limited (primarily on-site SNF storage)	Research reactor(s) / R&D facilities only	Research reactor(s) / R&D facilities only
National SMR vendor(s)	Yes	No	No	No	No
Installed Nuclear Capacity (GWe)	44	12	1.5	0	0
Additional Nuclear Capacity Required (GWe)	2	1	0.5	2.5	0.2

Appendix 6: Multinational Repository Scenarios

1. MNR Models

Two overall frameworks for MNR development exist, both of which have some level of precedent:

- An MNR may be implemented through partnership between various nations, e.g., a shared DGR, potentially with including upstream facilities distributed between partner nations. Extensive work has been carried out on this by the Arius and ERDO Associations. [166, 167]
- An MNR may be implemented as a commercial endeavour, where one DGR is made available to multiple nations through contracting, where the specific boundary conditions regarding the commercial solution could extend upstream, or not. A major study in Australia examined this option over 20 years ago and the South Australian state government took the analyses further in 2016 [168].

Within these frameworks, we consider four different MNR models to support our study:

A. An MNR through partnership of a few small countries currently without nuclear power or previous RWM experience (‘new nuclear nations’) agree to share a DGR. For example, given their interest in the use of SMRs as a means to deploy their first nuclear power capacity it could be envisioned that Norway, Denmark and Estonia decide to align strategy and collaborate. Aspects such as a geographical proximity and shared membership in the European Economic Area are not necessarily essential but would be likely to improve the ease of such collaboration. This is referred to as ‘**New-nuclear Partner MNR Model**’ in Table 20.

B. An MNR through partnership of a mix of nuclear and non-nuclear nations with some shared or aligned interest agree to share a DGR. The ERDO Association is committed to exploring such an option and, whilst the ERDO Association does involve any commitment to specifically sharing an MNR, it is reasonable to expect that the ERDO member nations would be interested in such a solution. This is referred to as ‘**ERDO Partner MNR Model**’ in Table 20.

C. A specific SMR vendor identifies an opportunity arising from the lack of available SNF disposal options and the high barrier to entry with regards initiating a DGR programme. This vendor then decides to fill this gap in the market by developing a DGR (in collaboration with a host country, likely the country in which the vendor is based) to offer a ‘cradle to grave’ solution for its clients. This would involve the vendor offering to take back all the SNF from any of its clients and disposing of it in this DGR. This is referred to as ‘**Commercial Vendor Take-back MNR Model**’ in Table 20.

D. A specific country identifies an opportunity arising from the lack of available SNF disposal options, and the high barrier to entry with regards initiating a DGR programme. This country then decides to fill this gap in the market by developing a DGR and offering it to client countries as a commercial SNF MNR. This is referred to as ‘**Commercial Disposal Service MNR Model**’ in Table 20.

2. MNR Scenarios

In order to explore different, somewhat realistic, SMR deployment options, we have defined different scenarios for each of these MNR models which could be considered:

A. For a **New-nuclear Partner MNR Model**, we define two scenarios:

   1. The partner countries agree on an approach for MNR implementation prior to selecting the specific technologies which they wish to deploy to initiate their nuclear power programmes. As a result, they opt to align their choice of nuclear reactor design, opting for the same conventional PWR design from the same vendor. No SMRs are deployed to attain the required nuclear capacity, merely Reference PWRs.
   2. The partner countries agree on an approach for MNR implementation prior to selecting the specific technologies which they wish to deploy to initiate their nuclear power programmes.

As a result, they opt to align their choice of nuclear reactor design, both opting to deploy the same SMR design – the VOYGR PWR, to attain the required nuclear capacity.

B. For an **ERDO Partner MNR Model**, we define two scenarios:

3. The ERDO member nation MNR partners agree on an approach for MNR implementation prior to selecting the specific technologies which they wish to deploy to initiate their nuclear power programmes. As a result, they opt to align their choice of nuclear reactor design, all opting to deploy the same SMR design, assumed to be the VOYGR PWR, to attain their required nuclear capacity.
4. The ERDO member nation MNR partners initiate SMR deployment prior to coming to an agreement on an approach for MNR implementation. As a result of varying national drivers, various different SMR designs are selected to attain the required nuclear capacity. The Category 2 countries deploy the Xe-100 HTGR; the Category 3 countries deploy the Natrium SFR; the Category 4 countries deploy the IMSR400; and the Category 5 countries deploy the eVinci HPR.

C. For a **Commercial Vendor Take-back MNR Model**, we define five scenarios:

5. As a result of the take-back offer by the VOYGR PWR vendor, the vendor host country and all of the ERDO member nations opt to deploy its SMR design, where the waste will be sent back to the vendor.
6. As a result of the take-back offer by the Xe-100 HTGR vendor, the vendor host country and all of the ERDO member nations opt to deploy its SMR design, where the waste will be sent back to the vendor.
7. As a result of the take-back offer by the Natrium SFR vendor, the vendor host country and all of the ERDO member nations opt to deploy its SMR design, where the waste will be sent back to the vendor.
8. As a result of the take-back offer by the IMSR400 MSR vendor, the vendor host country and all of the ERDO member nations opt to deploy its SMR design, where the waste will be sent back to the vendor.
9. As a result of the take-back offer by the eVinci HPR vendor, the vendor host country and all of the ERDO member nations opt to deploy its SMR design, where the waste will be sent back to the vendor.

D. For a **Commercial Disposal Service MNR Model**, we define two scenarios:

10. A host country initiates a commercial MNR programme and offers it to the ERDO member countries as potential clients prior to any of them selecting an SMR design to deploy. The MNR host has a fleet of Reference PWRs. All clients adopt this design, and no SMRs are deployed to attain the required nuclear capacity.
11. The ERDO member nation MNR partners initiate SMR deployment prior to the availability of a commercial MNR. As a result of varying national drivers, various different SMR designs are selected to attain the required nuclear capacity, where: the Category 1 host country deploys the VOYGR PWR; the Category 2 countries deploy the Xe-100 HTGR; the Category 3 countries deploy the Natrium SFR; the Category 4 countries deploy the IMSR400; and the Category 5 countries deploy the eVinci HPR.

Table 20: MNR scenarios defined across four MNR models, with example countries used for illustration based on profiles defined in Table 19, where Croatia and Slovenia are combined due to their single shared nuclear power plant.

MNR Model		Example Countries (Representative Hypothetical Country)	SMR Deployment Scenarios	
A	New-nuclear Partner MNR Model	• Denmark (FiveLand) • Norway (FiveLand) • Estonia (FiveLand)	1	• All deploy Reference PWRs.
			2	• All deploy VOYGR Modules.
B	ERDO Partner MNR Model	• Netherlands (TwoLand) • Slovenia and Croatia combined (ThreeLand) • Denmark (FiveLand) • Norway (FiveLand) • Italy (ThreeLand) • Poland (FourLand)	3	• All deploy VOYGR Modules.
			4	• TwoLand deploys Xe-100s. • ThreeLand deploys Natrium SMRs. • FourLand deploys IMSR400s • FiveLand deploys eVincis.
C	Commercial Vendor Take-back MNR Model	• **Host:** SMR-dependent (OneLand, given SMR Vendor) • Netherlands (TwoLand) • Slovenia and Croatia combined (ThreeLand) • Denmark (FiveLand) • Norway (FiveLand) • Italy (ThreeLand) • Poland (FourLand)	5	• All deploy VOYGR Modules.
			6	• All deploy Xe-100s.
			7	• All deploy Natrium SMRs.
			8	• All deploy IMSR400s.
			9	• All deploy eVincis.
D	Commercial Disposal Service MNR Model	• **Host:** Dependent on interest (assume OneLand) • Netherlands (TwoLand) • Slovenia and Croatia combined (ThreeLand) • Denmark (FiveLand) • Norway (FiveLand) • Italy (ThreeLand) • Poland (FourLand)	10	• All deploy Reference PWRs.
			11	• OneLand deploys VOYGR Module. • TwoLand deploys Xe-100s. • ThreeLand deploys Natrium SMRs. • FourLand deploys IMSR400s. • FiveLand deploys eVincis

3. MNR Scenario Metrics

With the waste metrics identified in Appendix 4: Section 2 and the MNR scenarios defined in Appendix 5: Section 2, we are able to outline a quantitative context for potential global SMR deployment. Combining the down-selected SMR design data in Appendix 4: Section 1 with the Country Category nuclear capacity data defined in Table 18 and MNR scenarios presented in Table 20 leads to a set of quantitative MNR scenarios, summarised in Table 21.

Within these scenarios, the SNF waste metrics data from Table 10, Table 11, Table 12, Table 13, Table 14 and The values discussed here are summarised in Table 15, where those in bold have been selected for use in our analysis. These values have been chosen because very little quantitative data is available in the open literature for this reactor.

Table 15 are used to calculate the SNF volume and decay heat contributed by each reactor type. These calculations are presented in Table 22, Table 23 and Table 24, with a summary of the total values for each scenario in Table 25.

The calculations underpinning these tables assume a reactor lifetime of 60 years for all reactors for normalisation purposes. However, this is an approximation as the IMSR400 lifetime is only 56 years, with a complete core replacement every ~7 years; the eVinci lifetime is only 40 years, with a factory refurbishment every ~8 years; and the lifetime of the Natrium reactor is unknown. This has a relatively minor impact as all of the waste metric data is given in GWe-year. Hence, the potential impact of replacing reactor cores, other parts, or entire units is excluded from these calculations.

Table 21: Number of each reactor design in each of the scenarios in Table 20 (this is rounded up, so becomes less accurate for low nuclear capacity scenarios), with the total power contribution of that reactor design using Table 18 data (assuming that, although this is not the case for the example countries in Table 20, all current installed nuclear capacity is provided by conventional, large PWRs, represented by a Reference PWR).

MNR Model	MNR Scenario	Total (Installed + Required) Nuclear Generation Capacity (and Estimated Number of Reactors) by Reactor Type						
		Reference PWR	VOYGR PWR	Xe-100 HTGR	Natrium SFR	IMSR400 MSR	eVinci HPR	Total
A	1	0.6 GWe (1 Reactors)	-	-	-	-	-	0.6 GWe (1)
	2	-	0.6 GWe (8 Reactors)	-	-	-	-	0.6 GWe (8)
B	3	15 GWe (13 Reactors)	4.9 GWe (64 Reactors)	-	-	-	-	19.9 GWe (77)
	4	15 GWe (13 Reactors)	-	1 GWe (13 Reactors)	1 GWe (3 Reactors)	2.5 GWe (13 Reactors)	0.4 GWe (115 Reactors)	19.9 GWe (157)
C	5	59 GWe (51 Reactors)	6.9 GWe (90 Reactors)	-	-	-	-	65.9 GWe (141)
	6	59 GWe (51 Reactors)	-	6.9 GWe (84 Reactors)	-	-	-	65.9 GWe (135)
	7	59 GWe (51 Reactors)	-	-	6.9 GWe (20 Reactors)	-	-	65.9 GWe (71)
	8	59 GWe (51 Reactors)	-	-	-	6.9 GWe (36 Reactors)	-	65.9 GWe (87)
	9	59 GWe (51 Reactors)	-	-	-	-	6.9 GWe (1972 Reactors)	65.9 GWe (2023)
D	10	65.9 GWe (57 Reactors)	-	-	-	-	-	65.9 GWe (57)
	11	59 GWe (51 Reactors)	2 GWe (26 Reactors)	1 GWe (13 Reactors)	1 GWe (3 Reactors)	2.5 GWe (13 Reactors)	0.4 GWe (115 Reactors)	65.9 GWe (221)

Table 22: SNF volume generated from each reactor, by reactor type within each MNR Scenario, assuming a reactor lifetime of 60 years for all reactors for normalisation purposes.

MNR Model	MNR Scenario	SNF Volume by Reactor Type (m^3)						
		Reference PWR	VOYGR PWR	Xe-100 HTGR	Natrium SFR	IMSR400 MSR	eVinci HPR	Total
A	1	345	-	-	-	-	-	345
	2	-	374	-	-	-	-	374
B	3	8,622	3,058	-	-	-	-	11,680
	4	8,622	-	7,080	334	3,407	3,970	23,412
C	5	33,913	4,306	-	-	-	-	38,219
	6	33,913	-	48,852	-	-	-	82,765
	7	33,913	-	-	2,302	-	-	36,215
	8	33,913	-	-	-	9,402	-	43,315
	9	33,913	-	-	-	-	68,488	102,401
D	10	37,879	-	-	-	-	-	37,879
	11	33,913	1,248	7,080	334	3,407	3,970	49,952

Table 23: Decay Heat of the SNF generated at a point 10 years after discharge from the reactor, by reactor type within each MNR Scenario, assuming a reactor lifetime of 60 years for all reactors for normalisation purposes.

MNR Model	MNR Scenario	Decay Heat @ 10 Years by Reactor Type (kW)						
		Reference PWR	VOYGR PWR	Xe-100 HTGR	Natrium SFR	IMSR400 MSR	eVinci HPR	Total
A	1	1,462	-	-	-	-	-	1,462
	2	-	1,519	-	-	-	-	1,519
B	3	36,540	12,407	-	-	-	-	48,947
	4	36,540	-	1,932	1,470	627	773	41,031
C	5	143,724	17,471	-	-	-	-	161,195
	6	143,724	-	13,331	-	-	-	157,055
	7	143,724	-	-	10,143	-	-	153,867
	8	143,724	-	-	-	1,731	-	144,598
	9	143,724	-	-	-	-	13,331	157,055
D	10	160,532	-	-	-	-	-	160,532
	11	143,724	5,064	1,932	1,470	627	773	153,279

Table 24: Decay Heat of the SNF generated at a point 100 years after discharge from the reactor, by reactor type within each MNR Scenario, assuming a reactor lifetime of 60 years for all reactors for normalisation purposes.

MNR Model	MNR Scenario	Decay Heat @ 100 Years by Reactor Type (kW)						
		Reference PWR	VOYGR PWR	Xe-100 HTGR	Natrium SFR	IMSR400 MSR	eVinci HPR	Total
A	1	351	-	-	-	-	-	351
	2	-	371	-	-	-	-	371
B	3	8,784	3,028	-	-	-	-	11,812
	4	8,784	-	382	279	314	153	10,232
C	5	34,550	4,264	-	-	-	-	38,815
	6	34,550	-	2,633	-	-	-	37,183
	7	34,550	-	-	1,925	-	-	36,476
	8	34,550	-	-	-	865	-	36,302
	9	34,550	-	-	-	-	2,633	37,183
D	10	38,591	-	-	-	-	-	38,591
	11	34,550	1,236	382	279	314	153	37,234

Table 25: Total SNF volume generated and SNF Decay Heat at 10 and 100 years after discharge from the reactor for each MNR scenario, assuming a reactor lifetime of 60 years for all reactors for normalisation purposes.

MNR Model	MNR Scenario	Total SNF Volume (m^3)	Total SNF Decay Heat @ 10 Years (kW)	Total SNF Decay Heat @ 100 Years (kW)
A	1	345	1,462	351
	2	374	1,519	371
B	3	11,680	48,947	11,812
	4	23,412	41,342	9,911
C	5	38,219	161,195	38,815
	6	82,765	157,055	37,183
	7	36,215	153,867	36,476
	8	43,315	145,455	35,416
	9	102,401	157,055	37,183
D	10	37,879	160,532	38,591
	11	49,952	153,590	36,913

References

1 Nuclear Energy Agency (NEA). *Meeting Climate Change Targets: The Role of Nuclear Energy*, Nuclear Technology Development and Economics, NEA No. 7628, 2022.

2 Nuclear Energy Agency (NEA). *Small Modular Reactors: Nuclear Energy Market Potential for Near-term Deployment*, Nuclear Development, NEA No. 7213, 2016.

3 Nuclear Energy Agency. (n.d.). Nuclear Energy Data 2021, https://www.oecd-nea.org/jcms/pl_69894/nuclear-energy-data-2021.

4 Tractebel Engie. (2022). *Supporting the first EU designed Small Modular Reactor technology*, https://tractebel-engie.com/en/news/2022/supporting-the-first-eu-designed-small-modular-reactor-technology.

5 World Nuclear News. (n.d.). *Belgium government allocates funding for SMR research*, https://www.world-nuclear-news.org/Articles/Belgium-government-allocates-funding-for-SMR-resea.

6 NucNet, Nuclear News Daily, 21st November 2023.

7 Nuclear Energy Agency. (n.d.). Nuclear Energy Data 2021, https://www.oecd-nea.org/jcms/pl_69894/nuclear-energy-data-2021.

8 NucNet, Nuclear News Daily, 5th November 2022 edition.

9 NucNet, Nuclear News Daily, 28th October 2022 edition.

10 World Nuclear Association. (n.d.). *Small Nuclear Power Reactors*, https://www.world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/small-nuclear-power-reactors.aspx.

11 NucNet, Nuclear News Daily, 26th August 2022 edition.

12 Deep Isolation. (n.d.). *Study: Estonia Geology Holds Promise for Nuclear Waste Disposal*, https://www.deepisolation.com/press/study-estonia-geology-holds-promise-for-nuclear-waste-disposal/.

13 NucNet, Nuclear News Daily, 2nd March 2023.

14 NucNet, Nuclear News Daily, 14th April 2023.

15 NucNet, Nuclear News Daily, 7th June 2023.

16 NucNet, Nuclear News Daily, 28th June 2023.

17 NucNet, Nuclear News Daily, 10th July 2023.

18 NucNet, Nuclear News Daily, 10th March 2023.

19 Government of Poland. (n.d.). *Energy Policy of Poland until 2040* (EPP2040), https://www.gov.pl/web/climate/energy-policy-of-poland-until-2040-epp2040.

20 NucNet, Nuclear News Daily, 14th September 2022 edition.

21 NucNet, Nuclear News Daily, 17th January 2023 edition.

22 NucNet, Nuclear News Daily, 4th April 2023 edition.

23 NucNet, Nuclear News Daily, 14th July 2023 edition.

24 NucNet, Nuclear News Daily, 7th December 2023 edition.

25 https://energie.gov.ro/wp-content/uploads/2016/11/Romanian-Energy-Strategy-2016-2030-executive-summary3-1.pdf

26 Nuclear Energy Agency. (n.d.). Nuclear Energy Data 2021, https://www.oecd-nea.org/jcms/pl_69894/nuclear-energy-data-2021.

27 NucNet, Nuclear News Daily, 21st June 2022 edition.

28 World Nuclear News. (n.d.). *Biden pledges USD14 million for Romanian SMR project*, https://www.world-nuclear-news.org/Articles/Biden-pledges-USD14-million-for-Romanian-SMR-proje.

29 NucNet, Nuclear News Daily, 8th September 2022 edition.

30 NucNet, Nuclear News Daily, 23rd May 2023 edition.

31 World Nuclear News. (n.d.). *Changes to Swedish law proposed to enable nuclear*, https://www.world-nuclear-news.org/Articles/Changes-to-Swedish-law-proposed-to-enable-nuclear.

32 NucNet, Nuclear News Daily, 8th March 2023 edition.

33 NucNet, Nuclear News Daily, 6th November 2023 edition.

34 U.S. Department of Commerce. (n.d.). *Turkey: Green Energy and Clean Technologies*, https://www.trade.gov/market-intelligence/turkey-green-energy-and-clean-technologies.

35 Nuclear Energy Agency (NEA). *Small Modular Reactors: Challenges and Opportunities*, Report Number 7560, March 2021.

36 UK Government (2020). *Powering our Net Zero Future*, December 2020, CP337, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/945899/201216_BEIS_EWP_Command_Paper_Accessible.pdf.

37 UK Government (2023). *Advanced Nuclear Technologies, Policy Paper*, 15th August 2023. https://www.gov.uk/government/publications/advanced-nuclear-technologies/advanced-nuclear-technologies.

38 NucNet, Nuclear News Daily, 12th May 2023 edition.

39 NucNet, Nuclear News Daily, 18th July 2023 edition.

40 UK Government (2023). Six companies through to next stage of nuclear technology competition, Press Release, 2nd October 2023, https://www.gov.uk/government/news/six-companies-through-to-next-stage-of-nuclear-technology-competition

41 NucNet, Nuclear News Daily, 11th October 2023 edition.

42 SMR Nuclear Technology (2021). *The Case for SMRs in Australia*, http://www.smrnuclear.com.au/wp-content/uploads/2021/07/The-case-for-SMRs-in-Australia_Aug2021.pdf

43 Heard, B (2022). *Small Modular Reactors in the Australian Context*, Minerals Council of Australia, 2nd Edition, December 2022.

44 Australian Energy Council (2022). *Small nuclear reactors come with big price tag*, 31st March 2022, https://www.energycouncil.com.au/analysis/small-nuclear-reactors-come-with-big-price-tag-report/.

45 Defence Connect (2022). *A Milestones Approach to Introduction of Small Nuclear Reactors in Australia*, 13th April 2022, https://www.defenceconnect.com.au/key-enablers/9855-a-milestone-approach-to-introduction-of-small-nuclear-reactors-in-australia.

46 World Nuclear News (2021). *China Starts Construction of Demonstration SMR*, 13th July 2021, https://world-nuclear-news.org/Articles/China-starts-construction-of-demonstration-SMR.

47 ERIA (2021). *Global Situation of Small Modular Reactor Development and Deployment*, ERIA Research Project Report FY2021 No. 7, https://www.eria.org/uploads/media/Research-Project-Report/2021-07-Small-Modular-Reactor-/Global-Situation-Small-Modular-Reactor-Development-Deployment.pdf

48 World Nuclear News (2018). *Progress with Indonesian SMR Project*, 16th March 2018, https://www.world-nuclear-news.org/Articles/Progress-with-Indonesian-SMR-project

49 World Nuclear News (2023). *USA, Indonesia announce partnership on SMRs*, 20th March 2023, https://world-nuclear-news.org/Articles/USA,-Indonesia-announce-partnership-on-SMRs

50 Rosatom (2020). *The Indonesian Nuclear Society webinar focussing on Russian SMR technologies*, 27th August 2020, https://rosatom-asia.com/press-centre/news/the-indonesian-nuclear-society-webinar-focusing-on-russian-smr-technologies-took-place-on-august-27/

51 World Nuclear News (2023). *Seaborg power barge considered for use in Indonesia*, 12th September 2023, https://www.world-nuclear-news.org/Articles/Seaborg-power-barge-considered-for-use-in-Indonesi.

52 World Nuclear News (2023). *ThorCon beings pre-licensing consultation in Indonesia*, 5th April 2023, https://world-nuclear-news.org/Articles/ThorCon-begins-pre-licensing-consultation-in-Indon.

53 World Nuclear News (2023). *SMRs considered for Indonesian fertiliser plant*, 19th May 2023, https://www.world-nuclear-news.org/Articles/SMRs-considered-for-Indonesian-fertiliser-plant

54 Nuclear Engineering International (2021). *Does Japan offer rich pickings for SMRs? 12th* August 2021. https://www.neimagazine.com/features/featuredoes-japan-offer-rich-pickings-for-smrs-8991006/

55 World Nuclear News (2023). *Myanmar and Russia sign nuclear infrastructure MoU*, 11th October 2023, https://www.world-nuclear-news.org/Articles/Myanmar-and-Russia-sign-nuclear-infrastructure-MoU.

56 ERIA (2022). *Small Modular Reactor (SMR) Deployment: Advantages and Opportunities for ASEAN*. https://www.eria.org/uploads/media/Research-Project-Report/RPR-2022-10/Small-Modular-Reactor-(SMR)-Deployment-Advantages-and-Opportunities-for-ASEAN.pdf.

57 NUCNET (2022). *Philippines - Asian Nation to Collaborate with Russia on SMR Feasibility Study*, 1st May 2022, https://www.nucnet.org/news/asian-nation-to-collaborate-with-russia-on-smr-feasibility-study-1-5-2022.

58 US Gov (2022). *Fact Sheet: Vice President Harris Launches New Initiatives to Strengthen U.S. – Philippines Alliance*, November 20th 2022, https://www.whitehouse.gov/briefing-room/statements-releases/2022/11/20/fact-sheet-vice-president-harris-launches-new-initiatives-to-strengthen-u-s-philippines-alliance/.

59 World Nuclear News (2023). *NuScale in talks with the Philippines on SMR deployment*, 2nd May 2023. https://www.world-nuclear-news.org/Articles/NuScale-in-talks-with-the-Philippines-on-SMR-deplo.

60 World Nuclear News (2023). *Korea Considers Deployment of NuScale SMR for Hydrogen production*, 15th May 2023, https://www.world-nuclear-news.org/Articles/Doosan-starts-forging-components-for-NuScale-SMR.

61 World Nuclear News (2023). *Korea Considers Deployment of NuScale SMR for Hydrogen production*, 10th May 2023, https://www.world-nuclear-news.org/Articles/Korea-considers-deployment-of-NuScale-SMR-for-hydr.

62 World Nuclear News (2023). *US-Korean partners to build SMR powered hydrogen production facility*, 21st April 2023, https://www.world-nuclear-news.org/Articles/US-Korean-partners-to-build-SMR-powered-hydrogen-p.

63 World Nuclear News (2023). *Expansion of US-Korean cooperation on SMRs*, 26th April 2023, https://www.world-nuclear-news.org/Articles/Expansion-of-US-Korean-cooperation-on-SMRs.

64 World Nuclear News (2023). *ABS approves Korean SMR Power Barge Design*, 4th October 2023, https://www.world-nuclear-news.org/Articles/ABS-approves-Korean-SMR-power-barge-design.

65 Energy Intelligence (2021). *South Korea: Kaeri's ARA SMR Push Raises Eyebrows*, 3rd December 2021, https://www.energyintel.com/0000017d-76b3-d7ae-a37d-7ebfa1db0000.

66 World Nuclear News (2023). *South Korean Partnership to Develop SMR-Powered Ships*,10th February 2023, https://www.world-nuclear-news.org/Articles/South-Korean-partnership-to-develop-SMR-powered-sh.

67 World Nuclear News (2023). *South Korea forms SMR Alliance*, 5th July 2023, https://www.world-nuclear-news.org/Articles/South-Korea-forms-SMR-Alliance.

68 Energy Market Authority (2022). *Charting the Energy Transition to 2050*, Energy 2050 Committee Report, March 2022.

69 Neutron Bytes (2022). *VP Harris in Talks with Philippines, Thailand on Nuclear Energy*, 27th November 2022, https://neutronbytes.com/2022/11/27/vp-harris-in-talks-with-philippines-thailand-on-nuclear-energy/

70 American Nuclear Society (2022). *U.S. to assist Thailand, Philippines with Nuclear Energy Plans*, 29th November 2022, https://www.ans.org/news/article-4525/us-to-assist-thailand-philippines-with-nuclear-energy-plans/.

71 World Nuclear News (2022). *India sets out climate commitments, ponders SMRs*, 9th August 2022, https://www.world-nuclear-news.org/Articles/India-sets-out-climate-commitments,-ponders-SMRs.

72 The Hindu (2022). *India should use SMRs to meet energy demands*, 7th August 2022, https://www.thehindu.com/news/national/india-should-use-small-modular-reactors-to-meet-energy-demands-niti-aayog-member-v-k-saraswat/article65740530.ece.

73 World Nuclear News (2022). *India sees SMRs in its clean energy future*, 28th November 2022, https://www.world-nuclear-news.org/Articles/India-sees-SMRs-in-its-clean-energy-future.

74 World Nuclear Association (2024). Small Modular Reactors (updated February 2024). https://www.world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/small-nuclear-power-reactors.aspx.

75 World Nuclear News (2023). *India eyes SMRs but focuses on large reactors*, 3rd August 2023, https://www.world-nuclear-news.org/Articles/India-eyes-SMRs-but-focuses-on-large-reactors.

76 World Nuclear News (2022). *Kazakh, Korean Companies to Cooperate in Nuclear Power Projects*, 29th June 2023, https://www.world-nuclear-news.org/Articles/Kazakh,-Korean-companies-to-cooperate-in-nuclear-p.

77 World Nuclear News (2021). *Arctic SMR plans make progress*, 9th August 2021, https://world-nuclear-news.org/Articles/Arctic-SMR-plans-make-progress.

78 World Nuclear News (2022). *Construction starts on Russia's next floating nuclear power plant,* 31st August 2022, https://world-nuclear-news.org/Articles/Construction-starts-on-Russia-s-next-floating-nucl.

79 Parliament of Sri Lanka (2023). *Sri Lanka's first nuclear power plant could be built by 2032*, 16th May 2023, https://www.parliament.lk/en/news-en/view/3232.

80 Nuclear Engineering International (2023). *Behind a Nuclear Decision*, 24th August 2023, https://www.neimagazine.com/features/featurebehind-a-nuclear-decision-11095080/

81 World Nuclear News (2023). *IAEA Assesses Jordanian Plans for EMR Deployment*, 6th October 2023, https://world-nuclear-news.org/Articles/IAEA-assesses-Jordanian-plans-for SMR-deployment.

82 World Nuclear News (2020). *Korea, Saudi Arabia progress with SMART collaboration*, 7th January 2020, https://world-nuclear-news.org/Articles/Korea-Saudi-Arabia-progress-with-SMART-collaborati.

83 Neutron Bytes (2022). *Saudi Arabia launches a nuclear energy company*, 12th March 2022, https://neutronbytes.com/2022/03/12/saudi-arabia-launches-a-nuclear-energy-company/

84 Govenrment of Canada, *Canada's SMR Action Plan*, https://smractionplan.ca/content/statement-principles.

85 World Nuclear News (2022). *Canadian provinces release strategic plan for SMRs, 30th March 2022*, https://www.world-nuclear-news.org/Articles/Canadian-provinces-release-strategic-plan-for-SMRs.

86 World Nuclear News (2022). *Early site work to begin for Canadian SMR*, 11th March 2022, https://www.world-nuclear-news.org/Articles/Early-site-work-to-begin-for-Canadian-SMR.

87 World Nuclear News (2023). *Federal funds announced for Saskatchewan SMR project*, 21st August 2023, https://world-nuclear-news.org/Articles/Federal-funds-announced-for-Saskatchewan-SMR-proje.

88 World Nuclear News (2023). *Canadian provinces announce collaborative coal phase-out,* 17th October 2023, https://www.world-nuclear-news.org/Articles/Canadian-provinces-announce-collaborative-coal-pha.

89 Nuclear Engineering International (2022). *Westinghouse promotes its SMR in Canada and USA*, 25th May 2022, https://www.neimagazine.com/news/newswestinghouse-promotes-its-smr-in-canada-and-usa-9722957.

90 World Nuclear News (2022). *ARC SMR proposed for green energy hub at Canadian port*, 29th November 2022, https://www.world-nuclear-news.org/Articles/ARC-SMR-proposed-for-green-energy-hub-at-Canadian

91 World Nuclear News (2023). *Alberta funds SMR deployment study*, 21st September 2023, https://world-nuclear-news.org/Articles/Alberta-funds-SMR-deployment-study.

92 ININ (2016). *Issues to consider for the implementation of SMR technology in Mexico*, National Institute for Nuclear Research, Mexico, October 2016, https://nucleus.iaea.org/sites/INPRO/df13/Presentations/020_Implementing%20New%20Reactor%20Technologies%20in%20Mexico.pdf.

93 World Nuclear News (2023). *Steel maker considers use of NuScale SMRs at its mills*, 16th May 2023, https://www.world-nuclear-news.org/Articles/Steel-maker-considers-use-of-NuScale-SMRs-at-its-m.

94 World Nuclear News (2023). *US computing infrastructure provider announces SMR plans*, 9th October 2023, https://www.world-nuclear-news.org/Articles/US-computing-infrastructure-provider-announces-SMR.

95 NuScale (2023). Utah associated municipal power systems (UAMPS) and NuScale Power agree to terminate the Carbon Free Power Project (CFPP), 11th August 2023, https://www.nuscalepower.com/en/news/press-releases/2023/uamps-and-nuscale-power-agree-to-terminate-the-carbon-free-power-project

96 World Nuclear News (2022). *Wyoming, INL sign MoU on advanced nuclear development and deployment*, 9th May 2022, https://world-nuclear-news.org/Articles/Wyoming,-INL-sign-MoU-on-advanced-nuclear-developm.

97 TerraPower (2022). *TerraPower provides Natrium Demonstration update to local community*, 13th October 2022, https://www.terrapower.com/terrapower-provides-natrium-demonstration-update-to-local-community/.

98 World Nuclear News (2022). *DOE marks milestone as Xe-100 basic design completed*, 23rd August 2022, https://world-nuclear-news.org/Articles/DOE-marks-milestone-as-Xe-100-basic-design-complet.

99 World Nuclear News (2023). *Multiple Xe-100 SMRs planned for Washington State*, 19th July 2023, https://www.world-nuclear-news.org/Articles/Multiple-Xe-100-SMRs-planned-for-Washington-State.

100 World Nuclear News (2023). *Dow to decarbonise with advanced nuclear*, 10th August 2022, https://world-nuclear-news.org/Articles/Dow-to-decarbonise-with-advanced-nuclear.

101 World Nuclear News (2023). *Dow's Seadrift site selected for X-energy*, SMR project, 11th May 2023, https://www.world-nuclear-news.org/Articles/Dow-s-Seadrift-site-selected-for-X-energy-SMR-proj.

102 World Nuclear News (2023). *Kairos seeks construction licence for two-unit Hermes plant*, 25th July 2023, https://world-nuclear-news.org/Articles/Kairos-seeks-construction-licence-for-two-unit-Her.

103 World Nuclear News (2023). *US initiative aims to help find best decarbonisation fit,* 6th October 2022, https://world-nuclear-news.org/Articles/US-initiative-aims-to-help-find-best-decarbonisati.

104 World Nuclear News (2021). *Construction of Argentina's CAREM025 unit to restart*, 8th November 2021, https://www.world-nuclear-news.org/Articles/Construction-of-Argentinas-small-CAREM-25-unit-to.

105 A. Sah, J. Lovering, O. Masely, and A. Saxena, *Atoms for Africa: Is There a Future for Civil Nuclear Energy in Sub-Saharan Africa?*, Washington DC Center for Global Development Policy Paper 124,

April 2018, https://www.cgdev.org/publication/atoms-africa-there-future-civil-nuclear-energy-sub-saharan-africa.

106 Rusatom Overseas. (n.d.). *Russian Nuclear Group protesting Small Modular Reactors for Africa*, http://www.rusatom-overseas.com/media/mass-media-about-us/russian-nuclear-group-protesting-small-modular-reactors-for-africa.html.

107 World Nuclear News. (n.d.). *US programme supports Ghana nuclear progress*, https://www.world-nuclear-news.org/Articles/US-programme-supports-Ghana-nuclear-progress.

108 ESI-Africa. (n.d.). *Small Modular Reactors: Designing Nuclear Energy for African Landscapes*, https://www.esi-africa.com/industry-sectors/generation/small-modular-reactors-designing-nuclear-energy-for-african-landscapes/.

109 World Nuclear News (2023). HTMR-100 team aim for pebble bed SMR in South Africa, 23rd June 2023, https://www.world-nuclear-news.org/Articles/HTMR-100-team-aim-for-PBMR-SMR-in-South-Africa.

110 IAEA (2011). *Disposal of Radioactive Waste*, Specific Safety Requirements No. SSR-5, https://www-pub.iaea.org/mtcd/publications/pdf/pub1449_web.pdf.

111 Radioactive Waste Management Ltd., *RWM Glossary*, RWPR34-G02 Rev 3, August 2018.

112 Nuclear Decommissioning Authority, *Geological Disposal: An overview of the RWM Disposability Assessment Process*, WPSGD No. WPS/650/03, April 2014

113 VTT Technical Research Centre of Finland Ltd., *Waste Acceptance Criteria and requirements in terms of Characterisation*, EU Horizon 2020 Deliverable D4.1, May 2018.

114 International Atomic Energy Agency (IAEA). *NuScale Status Report*, Advanced Reactors Information System, 28th May 2020, https://aris.iaea.org/PDF/NuScale-NPM200_2020.pdf.

115 X Energy (2023). Spent Fuel Management White Paper, 10th January 2023, Submittal of X Energy, LLC (X-energy) Xe-100 White Paper Slide Deck, "Spent Fuel Management White Paper" (nrc.gov).

116 TerraPower. *Natrium website homepage*, https://natriumpower.com/.

117 International Atomic Energy Agency (IAEA). *IMSR400 Status Report*, Advanced Reactors Information System, 28th July 2016, https://aris.iaea.org/PDF/IMSR400.pdf.

118 Y. Arafat, and J. Van Wyk (Westinghouse Electric Company LLC.). *Our Next Disruptive Technology*, eVinci Micro Reactor, 2019, MA19.indd (westinghousenuclear.com).

119 Westinghouse. *eVinci Microreactor*, Energy Systems, Westinghouse Nuclear > Energy Systems > eVinci™ Microreactor.

120 IAEA, *Advanced Reactors Information System*, https://aris.iaea.org.

121 International Atomic Energy Agency (IAEA). *Advances in Small Modular Reactor Technology Developments*, 2016 Edition, August 2016.

122 International Atomic Energy Agency (IAEA). *Advances in Small Modular Reactor Technology Developments*, 2018 Edition, September 2018.

123 International Atomic Energy Agency (IAEA). *Advances in Small Modular Reactor Technology Developments*, 2020 Edition, September 2020.

124 International Atomic Energy Agency (IAEA). *Advances in Small Modular Reactor Technology Developments*, 2022 Edition, September 2022.

125 Organisation for Economic Cooperation and Development (OECD) Nuclear Energy Agency (NEA), *The NEA Small Modular Reactor Dashboard*, NEA No. 7650, Revised Version, April 2023.

126 Organisation for Economic Cooperation and Development (OECD) Nuclear Energy Agency (NEA), *The NEA Small Modular Reactor Dashboard: Volume II*, NEA No. 7657, July 2023.

127 International Atomic Energy Agency (IAEA). *Decommissioning of Fast Reactors after Sodium Draining*, IAEA-TECDOC-1633, November 2009.

128 US Office of Nuclear Energy (2020). *National Lab Designs System to Produce Solid Metal Hydride Moderator*, November 10th 2020, https://www.energy.gov/ne/articles/national-lab-designs-system-produce-solid-metal-hydride-moderator#:~:text=Metal%20hydrides%20are%20being%20considered%20for,and%20other%20national%20security%20related%20systems.&text=Metal%20hydrides%20are%20being,national%20security%20related%20systems.&text=are%20being%20considered%20for,and%20other%20national%20security

129 Oak Ridge National Laboratory (2020). *Fast Fabrication: ORNL develops, produces metal hydride for moderator in 3D-printed reactor*, September 15th 2020, https://www.ornl.gov/news/fast-fabrication-ornl-develops-produces-metal-hydride-moderator-3d-printed-reactor#:~:text=As%20a%20moderator%20in%20a,reaction%20that%20produces%20nuclear%20energy.

130 Kiegiel, K., Herdzik-Koniecko, I., Fuks, L. and Zakrzewska-Kołtuniewicz, G. (2022) *Management of RadioactiveWaste from HTGR Reactors including Spent TRISO Fuel State of the Art*. Energies 2022, 15, 1099, en15031099.

131 Abdelouahed Ait Chaou, Abdesselam Abdelouas, Gökhan Karakurt, Bernd Grambow (2014). *Aqueous alteration of VHTR fuels particles under simulated geological conditions*. *Journal of Nuclear Materials*, 2014, 448 (1-3), pp.206-216.

132 Peterson, J-L. and Dunzik-Gougar, M. L. (2011). *Modeling spent TRISO fuel for geological disposal: corrosion and failure under oxidizing conditions in the presence of water*. Progress in Nuclear Energy 53 (2011) 278-284.

133 Bader, S. Henry, P and Buxton, D. (2023). *Storage of Advanced Reactor Fuels and the Standard Contract – 23454*, Proceedings of WM2023 Conference, February 26 – March 2, 2023, Phoenix, Arizona, USA.

134 Dungan, K., Gregg, R., Morris, K., Livens, F. and Butler, G. (2021). *Assessment of the disposability of radioactive waste inventories for a range of nuclear fuel cycles: Inventory and evolution over time*. Energy 221 (2021) 119826.

135 Lyford, S. (2023). *Xe-100 Overview and Spent Fuel Management*. Presented at Waste Management Symposia 2023, Phoenix, USA.

136 Abdesselam Abdelouas, S. Noirault, Bernd Grambow (2006). *Immobilization of inert TRISO-coated fuel in glass for geological disposal*. *Journal of Nuclear Materials*, 2006, 358, pp.1-9.

137 Guittonneau, F., Abdelouas, A., Grambow, B., Dialinas, M. and Cellier, F. (2009). *New Methods for HTR Fuel Waste Management*, 4th International Topical Meeting on High Temperature Reactor Technology, Sep 2008, Washington, United States. in2p3-00362477.

138 L. Fuks, I. Herdzik-Koniecko, K. Kiegiel, and G. Zakrzewska-Koltuniewicz (2020). *Management of Radioactive Waste Containing Graphite: Overview of Methods*. Energies 2020, Vol. 13, Iss. 18, en13184638.

139 TerraPower. *Natrium Advanced Reactor Fuel Cycle Management*, presented at the Nuclear Energy Agency conference on Management of Spent Fuel, Radioactive Waste and Decommissioning in SMRs or Advanced Reactor Technologies, 7th – 10th November 2022.

140 S. Nicole, O. Gastaldi, T Penit, O. Cohin, and P-Y. Campion (2008). *On-line reprocessing of a molten salt reactor: a simulation tool*, atalante2008-paper-P1-20 (iaea.org).

141 World Nuclear News (2023). *IMSR developer partners with ANSTO on waste treatment technology*, IMSR developer partners with ANSTO on waste treatment technology : Waste & Recycling - World Nuclear News (world-nuclear-news.org).

142 World Nuclear Association (2019). *SynRoc Wasteform*, World Nuclear Radioactive Waste Management Appendix 1, Synroc - World Nuclear Association (world-nuclear.org).

143 World Nuclear News. (2018, Feb 20). *More SMR vendor design reviews for CNSC*, More SMR vendor design reviews for CNSC - World Nuclear News (world-nuclear-news.org).

144 Power Engineering (2022, Nov 23rd). *Westinghouse sees a tech disrupter in its eVinci Microreactor*, Westinghouse sees a tech disrupter in its eVinci microreactor (power-eng.com).

145 Energy Wire (2022). *Small reactors create more waste than large ones*, 31st May 2022, https://subscriber.politicopro.com/article/eenews/2022/05/31/small-reactors-create-more-waste-than-large-ones-paper-00035834?source=email

146 T.K. Kim, L. Boing, and W. Halsey (Argonne National Laboratories), and B. Dixon (Idaho National Laboratories), *Nuclear Waste Attributes of SMRs Scheduled for Near-Term Deployment*, ANL/NSE-22/98, Revision 1, 18th November 2022.

147 Lindsay M. Krall, Allison M. Macfarlane and Rodney C. Ewing (2022). *Nuclear waste from small modular reactors*, PNAS 2022 Vol. 119 No. 23 e2111833119.

148 Mehdi Askarieh and Matt White, *Generic Design Assessment: Disposability Assessment for Wastes and Spent Fuel arising from Operation of the Westinghouse Advanced Passive Pressurised Water Reactor (AP1000); Part 1: Main Report*, NDA Assessment Report NXA/10897959, issue 2, 15 Jan 2010, https://westinghousenuclear.com/media/v34ald1a/assessment-report-for-westinghouse-ap1000-part-1.pdf.

149 Nuclear Newswire (2022). *NuScale responds to SMR critique*, 2nd June 2022, https://www.ans.org/news/article-4013/nuscale-responds-to-smr-critique/.

150 SMR Nuclear Technology (2019). *Submission to The House of Representatives Standing Committee on the Environment and Energy Inquiry into the Prerequisites for Nuclear Energy in Australia*, https://www.aph.gov.au/DocumentStore.ashx?id=c7bc01ab-dfac-44ef-b661-a180cdc0b700&subId=669049

151 VTT (2022). *Waste Management of Small Modular Nuclear Reactors in Finland*, Research Report VTT-R-00076-22, 28th February 2022.

152 Handbook of Small Modular Nuclear Reactors - Google Books, 2014

153 S. T. Arm (United States Department of Energy). *Strategies for Processing TRISO Nuclear Fuel*, presented at the Nuclear Energy Agency conference on Management of Spent Fuel, Radioactive Waste and Decommissioning in SMRs or Advanced Reactor Technologies, 7th – 10th November 2022.

154 VTT (2021). *SMR Waste Management in Finland*, KYT 2022 Project Seminar & Workshop, 3rd June 2021.

155 CNBC (2021). *How Bill Gates' TerraPower is building next generation nuclear power*, 8th April 2021, Bill Gates' TerraPower is building next-generation nuclear power (cnbc.com).

156 B. S. Triplett, E. P. Loewen, and B. J. Dooies (2010). *Prism: A Competitive Small Modular Sodium-Cooled Reactor*, https://www.gevernova.com/content/dam/gevernova-nuclear/global/en_us/documents/prism-technical-paper.pdf.

157 National Academies. *Merits and Viability of Different Nuclear Fuel Cycles and Technology Options and the Waste Aspects of Advanced Nuclear Reactors*, Consensus Study Report, ISBN 978-0-309-29511-6, 2023.

158 International Atomic Energy Agency (IAEA). *Radioactive Sodium Waste Treatment and Conditioning: Review of Main Aspects*, IAEA-TECDOC-1534, January 2007.

159 S. G. Xu, S. Chester, K. Choi, and E. Bulemela (2020). *Characteristic Waste Streams from Small Modular Reactors Considered for Deployment in Canada*, CNL Nuclear Review, Vol. 9, No. 1, CNR-2019-00008.

160 S. G. Xu, S. Chester, K. Choi, and E. Bulemela (2020). *Characteristic Waste Streams from Small Modular Reactors Considered for Deployment in Canada*, CNL Nuclear Review, Vol. 9, No. 1, CNR-2019-00008.

161 Terrestrial Energy. *Radioactive Waste Management*, presented at the Nuclear Energy Agency conference on Management of Spent Fuel, Radioactive Waste and Decommissioning in SMRs or Advanced Reactor Technologies, 7th – 10th November 2022.

162 M. Fratoni, D. Shen, G. Ilas, and J. Powers (2020). Molten Salt Reactor Experiment Benchmark Evaluation, DOE-UCB-8542, 16-10240; TRN: US210648, https://www.osti.gov/biblio/1617123.

163 Y. Arafat (Westinghouse). *Westinghouse eVinci™ Micro-Reactor Program*, GAIN-EPRI-NEI-US NIC Micro-Reactor Workshop, Idaho National Laboratory, June 2019.

164 R. Hernandez, M. Todosow, N. R. Brown (2019). *Micro heat pipe nuclear reactor concepts: Analysis of fuel cycle performance and environmental impacts*, Annals of Nuclear Energy, Vol. 126, Pages 419-426, S0306454918306509.

165 World Nuclear Association (WNA), Country Profiles, World Nuclear Information Library, https://world-nuclear.org/information-library/country-profiles.aspx.

166 Arius Association. *Arius website homepage*, https://arius-world.org/

167 ERDO Association. *ERDO website homepage*, https://www.erdo.org/

168 Government of South Australia (2016), *Nuclear Fuel Cycle Royal Commission Report*, ISBN 978-0-9945776-4-1.

MCM Environmental Services Ltd

Science & Technology Facilities Council
Rutherford Appleton Laboratory
Building R104 Office 2 12
Harwell Campus
Didcot OX11 0QX

Email: info@mcmenvironmental.co.uk

www.mcmenvironmental.co.uk