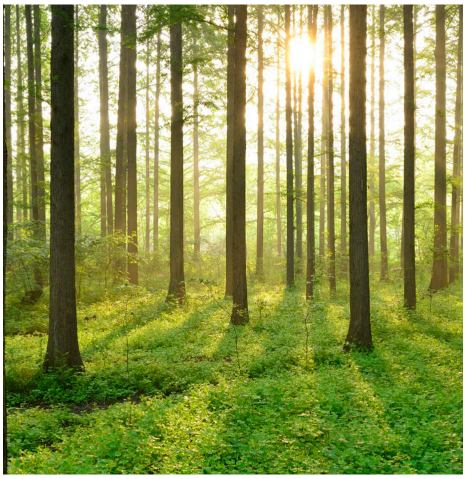
SMALL MODULAR REACTORS

REPORT 2019:625



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Energiforsk

Small Modular Reactors

Market Survey

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Foreword

Small modular reactors (SMRs) are smaller than conventional reactors, manufactured at a plant and brought to a site to be assembled. SMRs have been proposed as a less expensive alternative to conventional nuclear reactors. They are believed to bring many advantages in addition to economical, for example that they will be scalable, factory built leading to fast, cheap and easy assembly at the site, feasibility to build at remote sites and feasibility to combine with district heating.

It's important for the Nordic nuclear industry to get an overview of the development within the SMR area. This report is a market survey that points to some of the most promising SMR concepts and describes the development in some of the rising SMR-markets plus the situation in Sweden and Finland.

The survey was carried out by Konsta Värri and Petra Seppälä at Fortum. It is part of the Energiforsk nuclear portfolio, financed by Vattenfall, Uniper, Fortum, TVO, Skellefteå Kraft and Karlstads Energi.

Sammanfattning

Små modulära reaktorer (SMR) är en viktig del av kärnkraftsindustrins framtid. Tecken på detta är både antalet olika teknologier som förespråkas och mognadsgraden av de teknologier som utvecklats längst, samt intresset i teknologin från olika länder, deras regeringar och elmarknader.

Som stöd för detta uttalande, försöker denna rapport ge läsaren en kortfattad överblick om grundtekniken av SMR och det aktuella marknadsläget. I rapporten granskas även mera noggrant ett antal utvalda SMR teknologier och deras marknadsläge. Potentiella spridningen av denna teknologi är en mångfasetterad fråga, som omfattar teknisk utvecklingen, utmaningar gällande myndighetstillsyn, lokal och global energipolitik och många andra faktorer.

Vissa SMR teknologier kommer att tas i drift redan under 2019 medan nästa våg av mer mogna SMR teknologier väntas lanseras innan 2030. De tekniska detaljerna i dessa teknologier verkar tämligen robusta och utmaningarna är främst relaterade till myndighetsföreskrifter och -tillsyn. Det råder dock en viss osäkerhet gällande hur färdiga teknologierna är med tanke på tillverkning och lanseringsstrategin, vilka är de primära verktygen för att försäkra att anläggningarna når en konkurrenskraftig pris-nivå utgående från deras modularisering.

Det tydliga intresset för marknaderna motiveras av både dekarbonisering och löftet om att SMR teknologin utvidgar kärnkraftens användningsområden ytterligare. Anläggningarna anses både utvidga elproduktionsmöjligheterna med kärnkraft från enbart baskraft och göra kärnkraft genomförbart inom industriella- och fjärrvärmetillämpningar. På grund av att det tillsvidare ännu finns mycket osäkerheter gällande teknologin, kommer de första-i-sitt-slag anläggningarna högst antagligen byggas i de länder där teknologin utvecklats. En större utbredning av teknologin kräver både de första anläggningarna, som ett bevis på teknologins giltighet och kärnkraftsföreskrifter som erkänner de nya tekniska särdragen av SMR-anläggningarna.

Summary

Small Modular Reactors (SMRs) are an important part of the future of the nuclear industry. This can be seen from the number of designs promoted, the maturity of the designs that have advanced the furthest, and the interest in the technology, as expressed by different countries, their governments and markets.

To back this statement, this report attempts to give the reader a brief overview of the basics of SMR technology and the current status of the market as well as a deeper dive into a few shortlisted SMR designs and markets. The potential deployment of this technology is a multifaceted issue involving technological developments, regulatory challenges, local- and global-level energy policy and many other factors.

Some SMR designs are already being brought online in 2019, and the next wave of more mature SMR deployments will be seen before 2030. While the technical details of these designs seem fairly robust, there are challenges primarily from a viewpoint of regulation. There is also still uncertainty regarding how far along the designs are in the context of manufacturing and deployment strategies, which are the primary tools to ensure that these plants reach competitive price levels utilising the modularity of the designs.

The clear interest in the markets is driven both by decarbonisation and the promise of SMRs expanding the use cases of nuclear power further. The plants are seen as both expanding the electricity production capabilities of nuclear away from pure baseload and making nuclear viable in industrial and district heat applications. There is still plenty of uncertainty about the technology, so the first-of-a-kind plants will most likely be seen in the countries where the designs are being developed. Wider deployment of the technology will need not only the first SMRs as proof of the validity of the technology, but also nuclear regulation that acknowledges the new design characteristics of SMRs.

List of content

1 Introduction

As the need for CO_2-free energy production is becoming clearer by the day, especially after the 2018 IPCC -report [1], the role that nuclear holds in our future energy systems has a chance of becoming more prominent. While the EU sees a clear role for nuclear and the technology still holds the record for the fastest decarbonisation rates, the challenges faced by the current new-build plants in the western world have made it clear that the industry needs to renew itself. One potential answer to the cost and schedule overruns suffered by traditional large nuclear power plant (LNPP) projects can be found in SMRs. The smaller scale plants promise to be cheaper and more easily deployable by utilising modularisation, simplification and economies of scale based on the number of units instead of the size of the units.

The term SMR is still slightly in flux and can be originated to either mean Small- and Medium-size Reactors or Small Modular Reactors. Generally the term is used to refer to advanced reactors producing up to 300 MWe per module. The advanced design generally refers to advanced safety systems and to the modularisation of the plant manufacturing and deployment process. This is more or less the definition used by IAEA, OCED NEA, NRC etc. [2] This report expands slightly on that definition by not necessarily limiting the power output of the reactor to 300 MWe if the design otherwise exhibits a clear focus on the other features associated with the plants, especially modularity.

1.1 WHY SHOULD SMRs BE CONSIDERED?

The basic promise of SMRs – reliable, low-cost, zero-carbon energy production – seems like an ideal solution to many of the issues facing energy systems at the moment, but the market is also quite saturated with hordes of designs at varying levels of maturity and a level of hype that can be deemed counterproductive for evaluating the actual state of the technology. As a technology only starting to be deployed, there is still a significant amount of uncertainty on how well SMRs can actually fulfil the promises of the technology. Still, based on the history of the nuclear industry and learnings from other industries, there is a significant potential in the designs.

Compared to traditional large designs, SMR's can be said to differ in 5 key areas:

- Safety approach
- Scalability
- Flexibility
- Deployability
- Economics

Many of these can be said to be a result of the smaller size and the modularity and simplicity of the designs. The safety of SMRs is generally driven by the smaller size, allowing for increasingly passive safety systems, in some cases utilising fully natural circulation for cooling. Most SMR designs claim to sustain fully passive cooling for 24-72h without operator intervention. Some integral designs also eliminate issues like loss-of-coolant-accidents (LOCA) almost fully. Generally speaking, the smaller sizes and passive safety features allow for further simplification of the designs, making them more viable from multiple points of view. Compared to the route LNPPs have been taking with increasing numbers of systems to ensure safety, especially post-Fukushima, the advantages are fairly clear. The increased safety and smaller nuclear inventory could also open up the plants to smaller emergency planning zone sizes to increase the siting possibilities for various applications.

The effect of Fukushima is also partly visible in the focus on autonomy, passivity and dealing with a station blackout. The plants also often feature an additional layer of protection through below-the-grade installation. Building the reactor module itself below the ground level creates an additional barrier in the case of airplane crashes, natural disasters etc. Some plants feature reactor pools for additional cooling capacity.

The scalability generally refers to the ability to reserve slots for additional individual reactor modules in new-build projects, allowing the plant capacity to be further expanded later on, if necessary, while utilising the existing infrastructure.

Flexibility refers to both the application of the plants as well as the role of the plants in the power system. While traditional NPPs have been generally considered almost purely for baseload electricity production, SMRs are often designed with at least some level of load-following capabilities, although these are often at odds with how the plant should be run when considering its economy. SMRs could potentially also see application for heat production, either for process or district heating, desalination etc. The suitability of different SMR technologies for these use cases is better visualised in Figure 1. The smaller plant size further supports their use in cases like the production of baseload district heating, or supplying more limited or remote power grids.

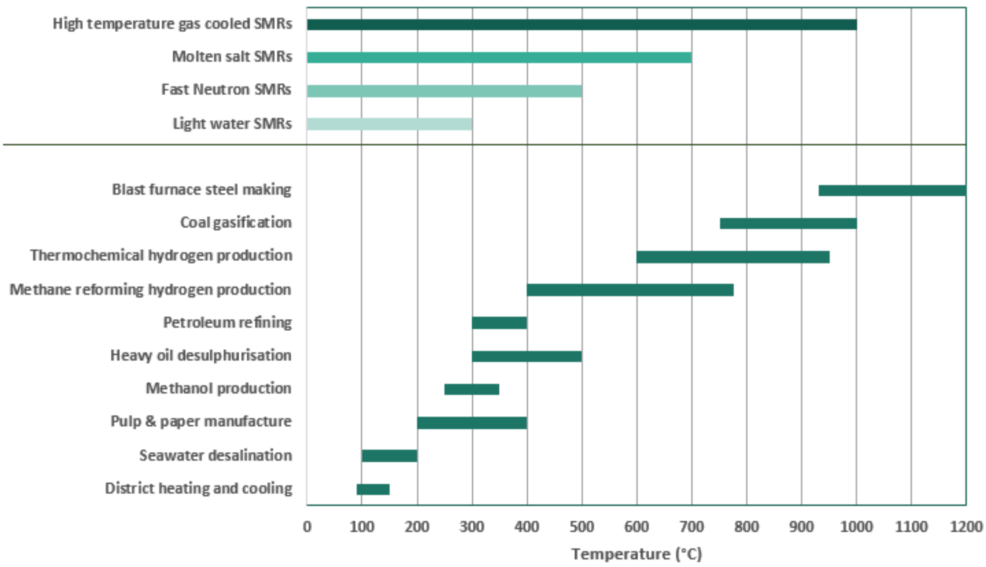


Figure 1. SMR heat production and use cases

Deployability is almost fully based on the modularity of the designs. In contrast to the huge and complex LNPP projects, some SMRs could potentially be almost fully fabricated and inspected at factories. This would significantly simplify the actual construction part of the project, leaving the site works and installation to be done on the site itself. This would also mean that the actual manufacturing of the plant could be done alongside the site works, thereby reducing the timetable. Many vendors believe that building a full plant could be done in 3-5 years.

Most of these differences are also an important part of the perhaps most significant advantage SMRs could potentially gain in comparison to LNPPs: the economy of new-build. One of the primary cost drivers for all nuclear plants is the cost of capital for the investment. The smaller and simpler designs with short deployment schedules should ideally drive down both the absolute capital investment as well as the risk associated with the projects. These could potentially also make the projects more viable as investments, bringing the cost of capital down. Reducing the number of buildings, simplifying the structure and installation of components, like the RPV, and minimising the number of systems needed all help drive down the costs. Beyond allowing for simpler designs, the size of these designs can also increase the amount of off-the-shelf components used for plants. Instead of e.g. huge custom-built turbine systems, SMRs could utilise readily designed turbines with minor modifications.

While many of these aspects seem promising, widespread deployment of the technology still remains to be seen. As the technology is meant to, in a way, save nuclear from itself, there is plenty of hype around the designs. Many of the advantages mentioned here do have plenty of studies and merits behind them, but the full realisation of these will most likely start becoming visible as the first-of-a-kind (FOAK) plants start coming online. Many of the vendors in the field promise a lot with their SMRs, especially when it comes to the costs of investment. The SMR study ordered by the British government, for example, evaluates that SMR FOAK prices include a 54-66% optimism bias – even for the fairly mature designs. [3]

Generally speaking, the competitiveness of these plants relies heavily on the presumed learning rates the designs achieve when they've been deployed enough times. These learning rates are of course presumptions at the moment, but learnings from other industries and previous experience from, e.g., the French nuclear deployment [4] do bring some credibility to these claims. Nevertheless, to reach these learning rates fast, a few designs might need to become fairly dominant in the beginning. If a plant design achieves the promised cost level after, say, 8 deployments, there might not be room for significant competition in the area at the early stages of SMRs for the designs to quickly move from first-of-a-kind (FOAK) to nth-of-a-kind (NOAK).

2 State of SMR Designs

2.1 OVERVIEW AND SUMMARY OF SMR TECHNOLOGY

This section takes a deeper look at the various types of SMRs currently considered and performs a case study on six fairly mature designs. The majority of the SMR designs proposed are light water reactor variants. As these are primarily based on existing commercial reactor technologies, they could be generally referred to as the most mature designs as well. Utilising existing learnings, the designs scale down traditional large NPPs to better allow for modularisation, passive safety solutions etc. Out of the designs considered here in the case studies, NuScale, ACP100, UK SMR and DHR400 all fall under this category [5].

Beyond these, there exists a variety of generation IV designs; of these, the gas-cooled HTR-PM and the molten salt reactor IMSR are considered in the case studies. These are especially interesting from the point of view of further expanding the use cases of nuclear, but they also offer new safety approaches.

All of the plant designs considered here could be considered to enjoy a fairly high level of technological readiness, with the exception of the IMSR perhaps being slightly more uncertain. All of these are still expected to see a first-of-a-kind plant brought online by 2030. Perhaps surprisingly, the Chinese DHR400 and HTR-PM are likely the most mature. This can be explained by both the heavy Chinese emphasis on R&D as well as the DHR400 being a very simple pool-type design and the HTR-PM enjoying from the benefits of having a proper demonstration unit built (the HTR-10 at Tsinghua University).

When it comes to the manufacturing and deployment of these plants, simply having the purely technological maturity is still not necessarily enough, as it does not automatically translate into the same level of readiness in deployment. To fully realise the advantages of SMRs, the manufacturing and deployment processes have to reach the same level of maturity. Most of the designs here have manufacturers behind them with strong backgrounds, but fully optimising the deployment of an NPP will still be a challenge. Most likely, fabricating premade systems and building modules is not necessarily a direct challenge, as the methods are well known in other industries, but fulfilling the regulations of nuclear installations will pose additional considerations. At this point it is also difficult to say if the designs will differ significantly in this area, as most of the deployment plans seem fairly similar in their basic approach.

Manufacturing and deployment will also most likely be the most significant challenges when it comes to bringing the LCOE and CAPEX evaluations down to the level that the plant manufacturers are giving for their designs. The first plants will be more costly and this will require early movers to see other benefits in the plants, such as building towards export opportunities or being a forerunner in the area.

The first builders will also have to worry about licensing. From the regulator perspective, it would seem likely that the first widely deployed SMRs, especially in countries with existing nuclear infrastructure, would be one of the LWR designs.

While these plants do bring some new approaches to e.g. safety, the base technology is similar enough to existing plants so these designs would most likely be the easiest to license.

2.2 CURRENT DEVELOPMENTS OF DIFFERENT SMR TYPES

The commonly referenced number of SMR designs at the moment is about 50, but if you include all of the currently existing SMR concepts and advanced designs, the number grows to over 100.

Figure 2. SMR designs in different areas of the world

The majority of these designs can be commonly classified under a few subcategories:

- Light Water Reactors (LWR) (GEN III+)
  - × Commonly Pressurised Water Reactors (PWR) or integral PWRs (IPWR), Boiling Water Reactor (BWR) designs are rare.
- High-Temperature Gas-Cooled Reactors (HTGR) (GEN IV)
- Molten Salt Reactors (MSR) (GEN IV)
- Fast Reactors (GEN IV)

Light water reactors make up the single biggest share of the designs, as about 30% of the designs proposed are LWRs. The clear majority of these are either traditional PWRs or IPWRs. These reactor types also have a fairly clear advantage when it comes to deployment, as the designs are not that different from the large light water NPPs that are the subject of most of the current licensing regulations. Especially for the traditional PWR SMRs with separate steam generators, most of the advantages of the designs are based on their smaller size and the modularisation of the plant. Integral PWR designs are similar, but drive the size and modularisation further by integrating the primary circuit into the reactor vessel itself. This both reduces the effects and chances of LOCAs and increases the modularity of the plant, as the whole reactor module can be manufactured, transported and installed as a single piece. Similarly to the PWR designs, BWR SMRs are also fairly similar to their larger cousins.

Out of the Generation IV designs the HTGRs are the closest to actual application with the first Chinese HTGR SMR, HTR-PM, expected to come online during 2019. These plants primarily utilise coated particle fuel in either pebble-bed or hexagonal prism graphite block formations cooled by helium. The coated particle fuel – TRISO – is stable to over 1600°C and, in combination with the passive decay heat removal and the negative reactivity coefficient that the rise of temperature in these reactors has, the designs are inherently safe. The output temperatures of the reactors start from 700°C and are eventually expected to rise to 1000°C. This means that the HTGR designs are also fairly viable for a multitude of process heat uses. When used for electricity production, the designs vary on the turbine format with some plants using the helium coolant directly to drive a turbine (e.g. the Japanese GTHTR300) while others use a more traditional steam generator formation similar to PWRs (e.g. HTR-PM).

Molten salt SMRs are in a slightly more disadvantageous position compared to the previous plant types, as the technology has not yet been deployed commercially. Presumably, the first one to market could be the Canadian IMSR, which aims to have its first plant online in the late 2020s and at the moment has completed the first phase of the Canadian pre-licensing vendor design review [6]. Instead of having separate fuel and coolant, the internals of the molten salt reactors core units are fully comprised of the liquid fuel salt that is circulated through the graphite-moderated core and the heat exchangers. These heat exchangers transfer the heat to a secondary salt circuit that is then used for transferring the heat to a tertiary power conversion circuit. The supplied temperature ranges vary somewhere between 600°C to 800°C, making the designs viable for a range of process heat applications alongside electricity production. In addition, some of the main drivers behind the design are the passive safety inherent to the fuel type and the low system pressure, <0.4 MPa for the IMSR compared to the 12.8 MPa of the NuScale for example, as well as the enhanced load-following capabilities compared to traditional NPPs.

Similarly, the fast SMR designs are further from commercial the "licensing and deployment" point of view compared to the LWR designs. While there are a multitude of fast reactor designs, the most common concepts utilise either sodium or lead/lead-bismuth coolant. The fast reactors have some very desirable features, including smaller and more simplified designs, better fuel performance and long refuelling intervals. However, due to the differences in the technology compared to traditional NPPs, the licensing efforts will most likely require significant resources. The fast reactors also require fuel enrichment of around 20%, making fuel supply and proliferation an additional consideration. Traditional thermal reactors usually use fuel enriched to about 5%. The use of sodium as a coolant creates further challenges, as the metal is flammable and volatile in combination with water, while lead/lead-bismuth coolants cause corrosion [7]. Most likely, the first fast SMR deployments will be as test reactors.

In addition to the design types mentioned here, there are also SMRs based on heavy water, heat pipe and some other more exotic technologies.

As new reactor types are developed, the primary role that universities seem to have taken is a more practical one with researchers looking into the obstacles in front of SMR deployment. The subjects of these studies include the cost drivers and construction of SMRs as well as building test facilities for the new technologies utilised by SMRs, including, for example, helical steam generators. Similarly, universities have an important role in developing simulation codes for independent verification of the safety systems planned to be deployed in SMRs.

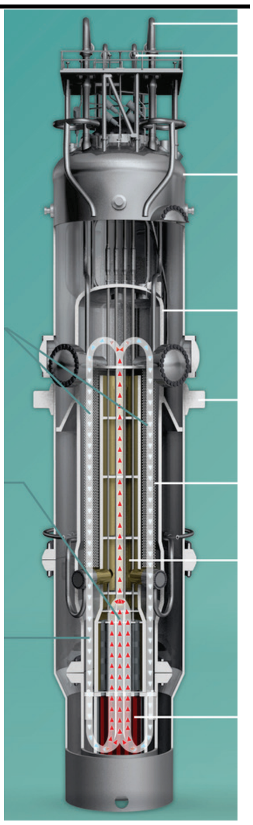
2.3 CASE STUDIES - DESIGNS

The case studies performed here are intended to give a deeper look into a variety of different SMR technologies for different use cases from several regions. The designs chosen are all fairly mature designs inside their own categories with FOAK deployments forecast to happen before 2030.

2.3.1 NuScale

Table 1. Basic data on the NuScale design

Design	Module Power	Coolant/ Moderator	FOAK ETA	Applications	Safety Approach
Integral pressurised water reactor	200 MWth / 60 MWe	Light water	2026	Electricity and/or heat production	Fully passive coolant circulation



NuScale is often seen as the poster-design for SMRs fulfilling many of the goals put onto the new plant types. A NuScale power plant is planned to include from 1 up to 12 fully independent reactor modules in a single reactor pool monitored and controlled from a single control room. The reactor modules utilise natural coolant circulation to eliminate main coolant pumps from the system and each module has its own steam cycle, including turbine and condenser. [8]

The deployment schedule given by NuScale would see a new plant built in 54 months from mobilisation with a 32-month critical path. A large share of the components, including the reactor modules, are prefabricated before being installed on site and the design would allow for the plant to be started with only a single module and expanded later. The financial calculations of the vendor are still based on the full 12-module plant, and there is fairly limited data available on how well the economics of the plant scale down to fewer modules.

Alongside this, it's also worth noting that NuScale is relatively young for a nuclear vendor company but they've partnered with several more experienced companies, including Fluor and Doosan Heavy Industries, and have started to build a client basis. The FOAK build at the Idaho National Laboratory site will still be an important showcase of the company's capabilities.

Figure 3. NuScale reactor design [9]

NuScale aims for a 65$/MWh LCOE for its design, but similarly to other aspects of the plant, there is plenty of uncertainty around the figure. The modularity and the focus on the export of the design are still important when considering the learning rate potentially applicable to the design.

When considering the readiness of the technology, NuScale is potentially quite far ahead of the competition, at least when it comes to western manufacturers. The design is the first one to go through the NRC licensing process and is currently scheduled to complete it in 2021. There are still open questions, one of which from a European point of view is that the plant was designed for the US 60 Hz electricity grid; thus there could be a potential need for a redesign for European markets.

2.3.2 ACP100

Table 2. Basic data on the ACP100 design

Design	Module Power	Coolant/ Moderator	FOAK ETA	Applications	Safety Approach
Integral pressurised water reactor	385 MWth / 125 MWe	Light water	2025	Electricity and/or heat production	Intrinsic and passive safety features

The ACP100 is an integral pressurised light water reactor designed by China National Nuclear Corporation (CNNC). The design is based on the validated technology of the ACP1000 NPP [10] and can be scaled up from 2 to 8 modules per plant. The construction of the FOAK plant is planned to begin at Changjiang, China, by the end of 2019 with an estimated construction time of 65 months. There are also plans for an offshore version.

While the reactor still uses main coolant pumps for forced coolant circulation, it's designed with integral steam generators and passive safety features and will be installed below-grade. [10]

Based on the Chinese nuclear industry’s experience and growth over the last years, the ACP100 is an interesting design especially from the technology readiness, manufacturing and economy points of view. CNNC has experience with multiple in-house designs, solid international contacts and an impressive track record [11]. Even so, most of their experience so far comes from China, and knowledge of their capabilities for building a plant in e.g. Europe is uncertain. [10]

There are no public numbers available on the cost of the ACP100, but based on assumptions utilising previous knowledge of Chinese nuclear projects, the plant should be fairly cost competitive. There is always uncertainty around how much this is based on different manufacturing and workforce costs as well as different licensing practices in China. Nevertheless, considering the Chinese expansion into nuclear, there is reason to believe that the design could easily benefit from a fast learning curve.

As with all yet-to-be-built designs, there is still uncertainty around the ACP100; but considering how CNNC is moving forward with the pilot plant, there is reason to believe that the plant could fulfil its promises.

2.3.3 UK SMR

Table 3. Basic data on the UK SMR design

Design	Module Power	Coolant/ Moderator	FOAK ETA	Applications	Safety Approach
Pressurised water reactor	1276 MWth / 443 MWe	Light water	2030	Electricity and/or heat production	Passive and active

The UK SMR is a pressurised water reactor with a three-loop configuration, developed by a Rolls-Royce-lead consortium. Compared to many other SMRs, the UK SMR is a fairly traditional mid-sized PWR plant, but is still considered an SMR, especially due to its highly modular deployment structure. The UK SMR is primarily intended for electricity production, but it can also be configured to support heat or cogeneration. [12]

The site layout enhances repeatable reactor and power station build. The reactor is highly modularised to enable the plant to be transported by road or sea and to minimise work on site. The design, however, is not scalable and is developed to accommodate one module per nuclear power plant. The reactor relies on both active and passive safety features with substantial internal redundancy, while the whole reactor area is protected by a robust shield.

The developers aim for an LCOE of 75 £/MWh for a FOAK plant, which would drop to 60-70 £/MWh for a NOAK plant.

Rolls-Royce is a well-known designer with a long history in nuclear and the consortium built around the design has wide knowledge of the different aspects of a new-build. The risks of the design are not necessarily caused by the designer, but have more to do with the UK's current political situation. As the government prepares for Brexit, there are a number of open questions regarding their future policies. The UK government confirmed in July 2019 that the consortium had been granted additional funding for the design development. While the uncertainty caused by the Brexit is significant, the British government would certainly appreciate a significant export product that the UK SRM is proposed to become. [12]

2.3.4 DHR400

Table 4. Basic data on the DHR400 design

Design	Module Power	Coolant/ Moderator	FOAK ETA	Applications	Safety Approach
Pool-type water reactor	400 MWth	Light water	2021	District heating	Intrinsic safety features. Large volume of water in the reactor pool

The DHR-400, also called Yanlong, is a pool-type light water reactor for district heating designed by CNNC. The reactor can also be used in other industrial processes, such as desalination and radioisotope production. [13] The design itself is extremely simple, mostly comprising a deep reactor pool and a core. The reactor is inherently safe due to the safety systems in place and the large amount of water in the pool. The combined effort of the shutdown systems, negative temperature feedback and the pool can keep the reactor submerged for up to 26 days without intervention. At the same time, the design does not include a containment building. While not necessarily required due to the safety of the plant, this could be an issue when licensing the plant outside of China. [13]

The design is for one module per heating plant, but scalability would be unnecessary for the DH-use case, as 400 MWth is already fairly large for a single DH installation. The concept is, however, strongly modular. The simplicity of the design means that the onsite activities are reduced to include virtually only the final installation. Due to the simplicity, the plant should also be economical, producing heat at about 20-30€/MWh. This simplicity is also reflected in the schedule, as the FOAK plant is scheduled to come online in 2021.

It's important to note that as a pool-type reactor in atmospheric pressure, the DHR400 can only produce heat at about 90°C, meaning that for DH networks that require a temperature above 100°C, the steam will require priming. Nevertheless, the plant seems extremely promising for producing CO_2-free baseload district heating.

2.3.5 HTR-PM

Table 5. Basic data on the HTR-PM design

Design	Module Power	Coolant/ Moderator	FOAK ETA	Applications	Safety Approach
Pebble bed high-temperature gas-cooled reactor	250MWth/ 105 MWe	Helium / Graphite	2019	Electricity production, process heat	Active and passive

The High-Temperature Reactor Pebble Bed Module, the HTR-PM, is a pebble-bed type high-temperature, helium-cooled reactor originally designed by INET. The commercial-scale demonstration nuclear power plant consists of two modules feeding one steam turbine generating electric power of 210 MWe. Originally scheduled to start production in late 2018, the plant is currently under commissioning and expected to come online in late 2019. While the FOAK plant is mainly meant for electricity generation, the plant is also aimed at decarbonising process heat generation. [14]

The reactor's inherent safety is characterised by the low power density, good coated-particle fuel performance and strong negative temperature reactivity coefficient. While the design seems promising in terms of safety and performance, there is a lack of public information regarding the manufacturing/deployment and economics of the plant. Nevertheless, the Chinese sources have raised the options of building a fleet of HTR-PM plants and of using the same design for a plant that would include 6 reactor modules running a single steam turbine. [15]

HTR-PM uses tristructural isotropic-type particles (TRISO) as fuel. The particles are graphite-coated and dispersed in 6 cm diameter graphite spheres. The pebble bed and TRISO fuel configuration also allows for continuous fuel loading and discharging while the reactor is online (as opposed to many other designs that only allow for refuelling when the reactor is shut down). While the TRISO fuel is advantageous for the inherent safety of the design, it is still an expensive fuel type to manufacture and the production has been small on a global scale despite the Chinese having ramped up their own production. [16]

If more information becomes available regarding the economics and if the fuel manufacturing can be expanded into a larger scale, the HTR-PM could very well become an important tool in decarbonising industrial heat production.

2.3.6 IMSR

Table 6. Basic data on the IMSR design

Design	Module Power	Coolant/ Moderator	FOAK ETA	Applications	Safety Approach
Molten salt pool type	400 MWth / 190MWe	Fluoride fuel salt / Graphite	Late 2020s	Electricity and/or heat production	Active with passive backup

The Integral Molten Salt Reactor IMSR is a graphite-moderated, molten fluoride salt reactor designed by Terrestrial Energy Inc. aimed at electricity generation as well as process heat for various industrial applications. [17]

IMSR entered the second phase of a vendor design review by the Canadian Nuclear Safety Commission in October 2018. The design was the first advanced reactor to complete the first phase of the CNSC's regulatory pre-licensing review. [6] [18]

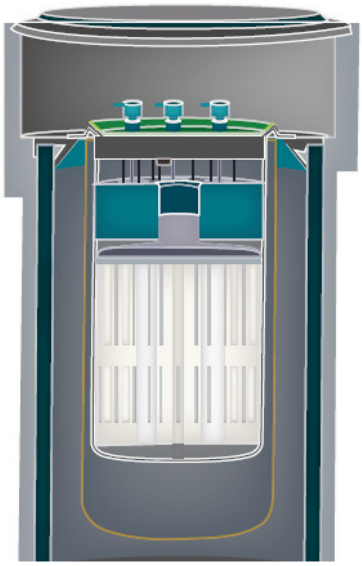


Figure 4. The core, primary containment and silo of the IMSR [19]

The IMSR is a fully integrated design with all of the primary systems such as the main coolant pumps, heat exchangers and shutdown rods, sealed inside the reactor vessel. The reactor uses molten fluoride salt for its primary fuel salt and can be refuelled online. After 7 years of operation, an identical IMSR core unit replaces the old unit. This replacement strategy both allows the IMSR to sidestep some of the issues regarding material technology common with molten salt reactors and removes the need to open and service the reactor vessel at the plant site.

IMSR's safety features rely on the inert, stable properties of the salt, inherently stable nuclear core, fully passive backup cooling systems for core and containment and integral reactor architecture. The reactor operates at low pressure of < 0.4 MPa due to the inert fuel mixture and the absence of water or steam in the system. This approach eliminates stored energy from the reactor system.

The vendor claims a 4-year build time for the plant, which is achieved by high modularity and mass manufacturing of the components. The vendor aims for an LCOE of 50 $/MWh but does not clarify if this refers to a FOAK or a NOAK. Overall, there are promising aspects to the IMSR, but it should be noted that the design will be among the first commercial MSRs to be built and there are certainly challenges to overcome in the development.

2.4 OVERVIEW ON SAFETY APPROACHES

As noted earlier, all of the SMRs considered in the case studies are fairly mature designs. This applies especially to the technology and safety design. While the licensing of these approaches will take a while, the safety approaches presented in Table 7 can most likely be considered up to par, licensable and provide the safety levels expected of SMRs and nuclear installations in general.

Table 7. Safety approaches of the shortlisted SMRs

	Integral design	Approach to safety	Cooling without human intervention
NuScale	Yes	Primary side coolant circulation is completely passive, there is no reactor coolant pumps, passive DHRS*	Indefinite time
ACP100	Yes	Inherent and passive safety features Passive DHRS, ECCS, CCS, CACS* and automatic reactor depressurisation system	Up to 72 hours
UK SMR	No	Passive and active (The emergency safety systems are passive) Passive and redundant DHRS and ECCS*	-
DHR400	No	Intrinsic safety features Large volume of water in the reactor pool, two sets of reactor shutdown systems, pool water cooling system and DHRS*.	Up to 26 days
HTR-PM	No	Combination of active and passive	Requires very limited intervention
IMSR	Yes	Active (pumps) with passive (heat loss) backup, no safety injection systems required (low-pressure passive pool-type design)	Indefinite time

* Decay Heat Removal System (DHRS), Emergency Core Cooling System (ECCS), Containment Cooling System (CCS), Containment Air Cooling System(CACS)

3 Markets

3.1 OVERVIEW AND SUMMARY OF THE MARKETS

The push towards SMRs in multiple markets is fairly clear. This is especially visible in dominant nuclear countries like the US, China and Russia, which see the plants and an early presence in the SMR market as an opportunity to build a strong export industry. At the same time, many countries look at SMRs as a potential tool to decarbonise their energy systems. This is especially true for sectors of energy consumption that cannot necessarily utilise renewable resources as easily. District heating and industrial process heat take up large parts of energy consumption in many countries, and nuclear is one of the few options that could potentially be used to replace fossil fuels in these use cases.

While the interest is clear in smaller countries, it's fairly clear that the FOAK plants will have to be supported by governments or by other sources. It's fairly hard to believe that any western country, at least, would build a new FOAK plant after the experiences of OL3, Flamanville and the various UK projects without a clear business case to continue on.

At some point, the timing of SMR deployment will also become critical. Many of the markets explored here have a clear slot in their energy systems for SMRs, but based on older plants coming to the end of their lifecycle or due to strict deadlines regarding decarbonisation, the timeframes of potential SMR deployment are limited – at least in the first wave. Even if some of the SMR designs can squeeze the deployment timeframe down to 3-4 years, renewing nuclear laws to accommodate SMRs, licensing the design and building public support all take time. This could clearly push the potential wider SMR deployment back in the UK, Poland and Finland, for example.

As noted the licensing takes time and is a significant question in many of the markets studied. Since the SMR designs depend highly on being built as originally designed and replicated over multiple sites, modifying the designs for each site and customer is not necessarily viable. This would require countries and regulators to both deepen their relationships and co-operation and, if there is interest in deployment, to be pro-active regarding the harmonisation of local licensing environments.

3.2 CURRENT DEVELOPMENTS

The interest in SMRs has been rising steadily, but this interest has not yet been translated to a significant number of projects. Clear deployment plans for SMRs can be seen in e.g. US, Canada, UK, China and Russia. When considering the deployment of new SMR designs, the FOAK plants become significant for the future, as they can be deemed, in some cases, to stand in as demonstration plants, especially for non-LWR designs. The number of actors willing to take a risk on an FOAK SMR is fairly limited, if there is not a clear, for example, national-level interest in the project. Governments in e.g. US and UK have signalled their interest in supporting a new-build and then exporting the technology. Without this level of support, it is presumable that many of the designs will die in the so-called innovation-valley-of-death. In this light, many of the various publicly announced MoUs between different utilities/countries and vendors seem extremely preliminary. These still give a good understanding of where there is interest and need for the technology. One clear region is Northern and Eastern Europe. Many Eastern European countries have fairly recently signed MoUs with various vendors to work towards SMR deployment. These include Estonia, Romania and Ukraine [20].

Meanwhile, the public discussion about SMR DH has been significant in Finland in recent years.

Alongside the larger countries, SMRs have also been considered beneficial from the point of view of developing countries wishing to expand into nuclear power. The smaller-sized reactors would be easier to incorporate into smaller-scale electricity grids. At the same time, applications like desalination are becoming more relevant. These factors could potentially open up SMR markets in areas like the Middle East and South East Asia. [21] [22]

There are plenty of forecasts on the number of SMRs expected to be deployed in the future with capacity levels ranging between 1 to 75 GW between various low and high scenarios; the overall average ranges to about 20 GW of SMR capacity by 2035. For traditional large NPPs, this number would be fairly low, but for the size range of SMRs, even this would mean a fleet of over 60 plants.

The US support for SMRs has been ongoing on a larger scale since 2012 when the Department of Energy (DOE) allocated $450 million for the development of an advanced US-based LWR. Originally, the support was awarded to the B&W mPower design that was later mothballed [2]. The DOE has supported multiple different plant designs, but at the moment the design furthest along with the largest funding behind it is the NuScale 60 MWe SMR. NuScale is currently in the process of going through the NRC design certification, aimed to be completed by 2022, and the first fully commercial 12-module and 720 MWe plant is scheduled to come online by 2027 at DOE's Idaho National Laboratory site. [23] The plant is meant for both commercial operation as well as a test bed for SMR technology as DOE will own one of the modules. The rest will be owned by the UAMPS, which represents a number of power companies and other similar interests in an organisation similar to the Finnish Mankala principle. The NRC is also in the process of going through the early site permit process for the Clinch River Nuclear Site for up to 800 MWe of SMR capacity. [24]

The NRC process is also important as the US regulator is often seen as a reference point for other regulators around the world. This does not necessarily apply as strongly in Europe any longer, but there is still some importance for SMRs, as the process for NuScale is fairly far ahead and the NRC has approved a number of important design aspects already. These include, for example, the decision that the NuScale SMR would not require a back-up power for emergency cases, but the passive solutions are deemed robust enough. Similarly, the decision by the NRC to reduce the emergency planning zone is important when considering the utilisation of SMRs for district heating and other industrial applications where the distance to the end-user becomes critical. [25]

The DOE is also backing multiple other SMR-related activities, including microreactors, advanced low-enriched uranium fuel manufacturing, other gen IV SMR designs etc [2]

Russia is a very prominent player in the SMR field with a long history of using reactors to power icebreakers. They have several SMR designs for land and offshore applications, but there is significant uncertainty around which of these are potentially commercial and how fully is the state-backed Rosatom focusing on offshore/remote locations with SMRs. Similarly, the role of Rosatom raises some questions on the potential political risks of deploying Russian SMR designs abroad.

Russia’s first official SMR, Rosatom's Floating nuclear power station Akademik Lomonosov, equipped with two KLT-40S reactor units generating a combined 70 MWe, completed construction and testing in July 2019 and immediately began the preparations for transportation to its permanent location. [26] Similarly, Rosatom is also developing the RITM-series SMRs both for on- and offshore use. The series has already seen successful deployment on icebreakers. [27]

China is extremely active in the field of SMRs, with a fleet of designs, competition between various manufacturers and multiple projects in the preparatory and construction phases. China also seems to be widely interested in utilising SMRs for a variety of use cases including electricity production, process and district heat. China sponsors a series of programs to research, develop and demonstrate advanced reactors, including Generation III and IV reactors for commercial and sustainable development. In general, nuclear power has grown dramatically in China in the last decade as a result of political decisions to promote the technology, and the size of the potential market for SMRs seems significant inside China. How well this will translate to export potential for the SMR designs remains to be seen, as currently the only Chinese NPP build abroad is in Pakistan and different regulatory and other issues could potentially be seen as roadblocks. [11]

Figure 5. Akademik Lomonosov, the Russian floating nuclear power station [28]

3.3 CASE STUDIES

The markets chosen for this shortlist are meant to give both a Nordic view on the subject as well as a deeper look into areas of potential deployment. The initial data in Table 8 should not be read as definitive, but as a basis for where the countries have expressed initial interest in or have been deemed as promising for utilising SMRs.

Table 8. Basic data of shortlisted countries

		Potential interest in utilising SMRs for:			
	Maturity of nuclear ecosystem	**Electricity**	**CHP/ DH**	**Process heat**	**Off-grid**
Finland	Mature		I		
Sweden	Mature	P	P		
Poland	Requires effort		P	I	
UK	Mature	I	P		
Canada	Mature	I	I	I	I

*I - Initial interest expressed, P - Deemed potentially promising

3.3.1 Finland

As a country that is trying to completely eliminate coal from its energy system by 2029, Finland is currently scrutinising options to replace it. The country's electricity production is largely decarbonised, but the heating sector still faces a multitude of challenges in this regard. SMRs have been recognised even in the public discussion as one of the ways of potentially producing carbon-free district heating. This is further supported by Finland's long history with nuclear. The country currently has four nuclear reactors in operation, which covered 32% of the electricity production and 25% of the electricity consumption in Finland in 2018. There are two new on-going NPP projects: Olkiluoto 3, which is currently scheduled to come online in July 2020 [29], and Hanhikivi 1, which is expected to receive a construction license in 2021. [30]

When it comes to licensing SMRs, STUK, the Finnish nuclear regulator, has given no assurances, but it has indicated that the organisation is interested in the technology and would be willing to work towards ensuring that the regulation would recognise the special characteristics of SMRs, thus allowing for a potential new-build SMR to be deployed in Finland. Interest in SMRs is also backed by fairly strong public support of nuclear power.

There is no clear indication of the actual market size for SMRs in Finland, but if used for e.g. replacing district heat from fossil fuels, there is potential. As an example, there are currently around 8 DH/CHP plants of over 200 MWth using natural gas or coal as fuel and another 15 similar plants between the size range of 100-200 MWth.

While the potential does exist, the same hurdles that generally apply to nuclear everywhere apply in Finland as well. Heating plants would need to be fairly close to the DH networks, resulting in a significant challenge when it comes to public acceptance. The financial development of SMRs and the timetable will have a large impact on these plants becoming reality. The 2029 coal ban is fairly soon for a new nuclear installation, and the potential other replacement installations for the coal plants will most likely have a lifetime of at least 20 years. This would most likely lock down the heating plant investments until 2040-2050.

3.3.2 Sweden

Sweden seems fairly mixed in reception when it comes to the potential of SMRs in the country. Currently, the country has 8 active nuclear power units producing about 40% of its electricity and 4 units in decommissioning. Moreover, 2 units out of the 8 active are scheduled to be shut down in 2019 and 2020. Combined with the 4 units closing between 2015 and 2020, 2.7 GWe will be removed from Swedish production capacity. [31]

This could be considered as leaving room for the possible replacement by SMRs, but there are some limitations to new nuclear reactors. They must replace an older reactor that has been permanently shut down on the existing sites [32]. How this would be interpreted in regards to SMRs is interesting as, for example, a single NuScale plant could be considered to include 12 reactors. Similarly, this would most likely mean that SMR DH is not an option, as the required investment in the heat distribution infrastructure would be too large due to the distances to significant cities and DH networks.

While currently any SMR development might seem unlikely, the Swedish nuclear policy has been subject to a significant number of changes over the years. Sweden does have a mature nuclear ecosystem that could most likely accommodate SMRs well and a fairly decent amount of public support behind the technology. At the same time, the energy system is already fairly far along in terms of decarbonisation both in electricity production and heating, so the need for new CO_2-free energy sources is not as clear as in e.g. neighbouring Finland.

3.3.3 Poland

Poland is an interesting case with regard to SMRs. The country has had plans to build its first traditional NPP for years and has also expressed clear interest in HTGR technology to support its industry. At the same time, the Polish energy system is almost fully based on coal, including its district heating system.

While there has been a clear push towards a nuclear new-build, the plans have been pushed back multiple times. The May 2019 energy policy includes the first of six 1-1.5 GW units to be completed by 2033 with subsequent units coming online every two years. This would require a clear investment in the plants and in nuclear regulation, as the only Polish nuclear installation at the moment is a 30-MW research reactor. The current non-fixed state of nuclear regulation does leave a position open for SMRs. [33]

The clearest push towards SMRs in Poland has been the interest in HTGRs for providing process heat in industry. The clear drivers behind this for Poland are the uncertainties regarding gas imports and the price of CO_2 emission allowances as well as the potential of being an early adopter and exporting the technology. The Polish Ministry of Energy's report on the subject presumes room for about 10-20 HTGRs in Poland. The same report from 2018 outlines a plan to build a 10-MWth pilot plant by 2026 and a full-scale 165-MWth plant by 2031. [34]

While not given much room, the same report does note the chance of using light water reactors for district heating. Coal currently comprises about 85% of Poland's DH production and the majority of these plants are fairly old and in need of replacement investments. This would mean replacing between 16 and 23 GW of capacity over the next 20 years and the government has outlined support for the expansion of CHP. It remains unclear if this could potentially be utilised by SMRs, but there is clear market potential to be explored in the area, especially if rising CO_2 costs keep pushing fossil fuel-based production out. The public opinion about the expansion towards nuclear is overall fairly positive in Poland. [35]

3.3.4 United Kingdom

The United Kingdom is experienced in the nuclear field, with 15 operational nuclear power reactors generating over 20% of the country's electricity. However, almost half of the UK's nuclear capacity is to be retired by 2025, which means SMRs could have an opportunity to replace the retiring capacity. The government aims to have 16 GWe of new nuclear capacity operating by 2030. This goal has been challenged recently, as a combined 9.2 GW of new nuclear reactor capacity has fallen through. SMRs could be partly used to fill this void. The TEA reports, for example, see room in their modelling for 10 GW of SMRs by 2050, 14 GW if there is the possibility to utilise SMRs in a CHP configuration in combination with district heating. [36][37][38]

There is a lot of interest in SMRs in the UK. In 2016, the government launched a Small Modular Reactor competition to identify the best SMR design for the UK. A wide range of nuclear technologies entered the competition, including, for instance, the Rolls-Royce's design, UK SMR. In December 2017, the Department for Business, Energy & Industrial Strategy announced that the SMR competition had been closed. Instead, a new two-phased advanced modular reactor competition was launched to incorporate a wider range of reactor types. Total funding for the Advanced Modular Reactor Feasibility and Development project is up to £44 million. In September 2018, eight organisations were awarded contracts to produce feasibility studies for the first phase of the project. Besides Rolls-Royce with their design, among the other interested parties were NuScale with a five-point UK-focused action plan and CNNC with their ACP100 reactor.[38]

In 2016, the UK decided to leave the European Union. It is still unclear exactly how Brexit will affect SMR development, as the implications are far-reaching. For instance, cost and availability of certain supplies or goods may change, and cross-border transits may face additional hurdles. New regulations are likely to replace EU law, and legal uncertainty will most likely exist until those changes have been made.

3.3.5 Canada

Canada has emerged as one of the leading markets for SMR development with supportive regulatory regimes and deployment opportunities. The Canadian Nuclear Safety Commission (CNSC) regulates the entire life-cycle of nuclear plants and conducts pre-licensing vendor design reviews. In March 2019, the CNSC received the first siting license application for a micro-SMR from Global First Power [2]. The Micro Modular Reactor in question already completed the first phase of CNSC's pre-licensing vendor design review. This is a part of Canadian Nuclear Laboratories drive to build a new SMR by 2026 at its Chalk River site. Other options for the site include Terrestrial Energy's IMSR. [39]

In November 2018, the Canadian government released its SMR Roadmap, which concludes the three major areas of application for SMRs and some potential domestic market sizes: [40]

- On-grid power generation phasing out coal plants
  - × 29 plants of, on average, 343 MWe
- On- and off-grid combined heat and power for heavy industry
  - × 85 heavy industry locations requiring, on average, 25 - 50 MWe equivalent of high-temperature steam
  - × 96 oil and gas facilities of, on average, 210 MWe requiring both heat and power
- Off-grid power, district heating and desalination in remote communities,
  - × 79 remote communities with needs of over 1 MWe currently supplied by diesel
  - × 24 current and potential off-grid mines requiring, on average, 5 - 30 MWe

Perhaps the most promising market for SMRs at the moment is the country's large mining sector, which is typically supplied by diesel-fired plants. Canada also has plans to close coal-powered units in the 2020s; the capacity of these units is approximately 10,300 MWe. SMRs have the potential to play a role in Canada's transition to clean electricity and to be a part of the non-GHG-emitting power supply. [39] [41]

Overall, Canada's interest in SMRs is clear and the country sees a clear case for SMRs both domestically and for export. The country also has the background for it, with a long history in nuclear energy and research that has continued up to this day. The domestic industry is strong and, as noted, the regulator is friendly and proactive towards new kinds of reactors with licensing efforts continuing to advance. The country is therefore fairly likely to be one of the first to see large-scale application of SMRs. The market is especially interesting, as the identified use cases range from very small-scale electricity production to large-scale process heat generation. The strategy the country adopts for broader application in the future can have wider repercussions depending on whether any of the designs become dominant

4 Conclusions and Discussion

SMRs are a clear reality and an important part of the future of the nuclear industry. While they seem poised to meet many of the hopes pinned on the technology – easily deployable and economical NPPs that are flexible in terms of use cases and employing advanced safety solutions – there are still plenty of hurdles to overcome. From the technical point of view, design and safety, SMRs seem to be fulfilling the expectations. Most of the plants reviewed here, especially the most mature ones, all fulfil at least part of the hopes attached to SMRs, in terms of technology. Almost all of the designs use passive safety systems made possible by the smaller size of the designs. These result in reactors that are often safe for extended periods without the need for operator intervention.

While the technology itself seems fairly solid, the manufacturing processes are a bit more open to critique. Most SMR designs utilise a similar process of aligned site works and factory manufacturing, but these also most likely contain the largest uncertainties regarding TRLs. Many of the SMR vendors are experienced nuclear manufacturers, but modularising nuclear plants is still not a simple process. While there are multiple companies in the SMR business that could be considered startups, the vendors with mature designs have combined forces with more experienced companies and have built up supply chains with enough expertise to fulfil the goals of the SMR designs.

The uncertainties regarding manufacturing and deployment are also translated into uncertainties regarding the economics of SMRs. As the low-cost energy produced by these plants is often presumed to be based on the modularisation and on the fast deployment and learning rates associated with the designs, there cannot necessarily be certainty regarding how well SMRs fulfil these promises until the FOAKs are deployed. Even so, learnings from multiple other industries prove that the methods used by these designs do produce learning rates that could make SMRs competitive energy sources, if the designs make it from FOAK to NOAK.

The FOAKs are also a significant question in terms of the market analysis. The first countries deploying SMRs are most likely also the countries where they are being developed. This is already true with China and the HTR-PM and with Russia and the KLT-40. Building a new kind of small-scale NPP is a significant economic risk and requires an additional incentive beyond the energy produced. The export opportunities are one clear example, but SMRs do offer multiple other incentives as well. The technology could easily be utilised in multiple fields, from off-grid power production to district and process heat. Many of these fields are currently heavily based on fossil fuels, and SMRs could be an important tool for decarbonisation. This has been recognised in e.g. Finland, Poland, Canada and multiple other countries. The market sizes are significant as well, and some presumptions see fleets of over 60 plants being built by 2035 worldwide. This is, of course, heavily reliant on the overall development of energy markets, commodity prices and the success of the FOAK plants.

5 Additional Information

The two best starting points for reading about SMRs are World Nuclear Association's (WNA) SMR page and the International Atomic Energy Agency's (IAEA) SMR handbook:

- https://www.world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/small-nuclear-power-reactors.aspx
- https://aris.iaea.org/Publications/SMR-Book_2018.pdf

While there is not really a single primary source for SMR news, the Nuclear Energy Insider's (NEI) SMR section and the World Nuclear New's (WNN) New Nuclear provide a starting point. NicobarGroup's weekly Chinese Nuclear News roundup is a limited but useful resource for stories on Chinese SMRs not picked up elsewhere.

- https://analysis.nuclearenergyinsider.com/small-modular-reactors
- https://www.world-nuclear-news.org/New-Nuclear
- http://www.nicobargroup.com/news-views-1

The conferences fully focusing on SMRs are fairly limited, as the designs are often considered as parts of larger nuclear energy conferences. NEI does host an International SMR and Advanced Reactor Summit in the US.

- https://www.nuclearenergyinsider.com/international-smr-advanced-reactor/

There are numerous smaller scale conferences and events for SMRs, but these generally tend to be fairly local. As an example, the Finnish Ecomodernists held an SMR district heating seminar in Helsinki in March 2019; the presentations can be found online:

- https://www.youtube.com/watch?v=bhDUa16gWvc&list=PLFSpRcbeapkiwbfw7LKfY49oHZ3fOlwhL&index=2

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Appendix A: Glossary

Below The Grade - Reactor is installed below ground level
BWR - Boiling Water Reactor
Commercial Deployment and Licensing- Process for non-demonstration/research reactor
Deployability - How easily a plant is deployed in regard to licensing, construction, financing etc.
DH - District Heating
EPZ - Emergency Planning Zone - The area around a nuclear facility requiring prepared protective actions
Fast Reactor - Reactors in which the fission chain reaction is sustained by unmoderated fast neutrons
Fuel Salt - A fuel type in which the nuclear fuel is mixed with a molten salt to produce the coolant/fuel mixture
GEN III+ - Advanced (primarily) Light Water Reactors designed based on the learnings of Gen II/III, first completing construction in 2016
GEN IV - The next generation of nuclear reactors currently primarily in the R&D phase and mostly focusing on more novel approaches compared to the LWR designs of GEN III/III+
Heat Pipe Reactor - Nuclear reactor utilising passive heat pipes for heat transfer instead of coolant
Heavy Water Reactor - Nuclear reactor utilising heavy water as coolant allowing for the use of unenriched uranium as fuel
HTGR – High-Temperature Gas Cooled Reactors (GEN IV)
Innovation-Valley-Of-Death - The stage between R&D development and full-scale commercialisation where new products/designs often fail
Internal Redundancy - Provision of multiple alternative systems to ensure function in the case of a single-point failure
LWR - Light Water Reactor
LNPP - Large Nuclear Power Plant
LOCA: Loss-Of-Coolant-Accidents - Accident in which the reactor coolant is lost partly or fully due to a line break or other causes
Microreactors - Generally an SMR-type nuclear reactor producing 1-20 MWth
MSR - Molten Salt Reactors (MSR) (GEN IV)
NPP - Nuclear Power Plant
Nuclear Inventory - The amount of nuclear material in a facility. In plants, primarily the nuclear fuel in the core
IPWR - Integral Pressurised Water Reactor - a PWR with e.g. coolant pumps, steam generators etc. integrated into the reactor pressure vessel
Passive System - Not requiring external control signals nor an external power source
Power Density - The amount of power produced per unit of volume
PWR - Pressurised Water Reactors
Thermal Reactor - Reactors in which the fission chain reaction is sustained by moderated thermal neutrons
TRL - Technological Readiness Level

Appendix B: SMR Data Sheet

	Design	Module Power	Coolant/ Moderator	FOAK ETA	Applications	Integral design	Approach to safety	Cooling without human intervention
NuScale	Integral pressurised water reactor	200 MWth / 60 MWe	Light water	2026	Electricity and/or heat production	Yes	Primary-side coolant circulation is completely passive, there are no reactor coolant pumps, passive DHRS*	Indefinite time
ACP100	Integral pressurised water reactor	385 MWth / 125 MWe	Light water	2025	Electricity and/or heat production	Yes	Inherent and passive safety features Passive DHRS, ECCS, CCS, CACS* and automatic reactor depressurisation system	Up to 72 hours
UK SMR	Pressurised water reactor	1276 MWth / 443 MWe	Light water	2030	Electricity and/or heat production	No	Passive and active (The emergency safety systems are passive) Passive and redundant DHRS and ECCS*	-
DHR400	Pool-type water reactor	400 MWth	Light water	2021	District heating	No	Intrinsic safety features Large volume of water in the reactor pool, two sets of reactor shutdown systems, pool water cooling system and DHRS*.	Up to 26 days
HTR-PM	Pebble bed high temperature gas-cooled reactor	250MWth/ 105 MWe	Helium / Graphite	2019	Electricity and/or heat production	No	Combination of active and passive	Requires very limited intervention
IMSR	Molten salt pool type	400 MWth / 190MWe	Fluoride fuel salt / Graphite	Late 2020s?	Electricity and/or heat production	Yes	Active (pumps) with passive (heat loss) backup, no safety injection systems required (low pressure passive pool type design)	Indefinite time

SMALL MODULAR REACTORS

This report gives a brief overview of the basics of SMR-technology and the current status of the market as well as a deeper dive into a few shortlisted SMR designs and markets.

Many of the more mature SMR designs seem poised to fulfil the hopes placed on the technology. These designs are meant drive advances in economics, modularity, flexibility and deployability, and to eventually produce reliable, low-cost zero-carbon energy.

While there are plenty of uncertainties before these goals can be deemed as being fulfilled, plenty of countries have expressed clear interest in the technology. To overcome these uncertainties, some actors will need to take risks with first-of-a-kind plants. If these succeed, there is a clear, wider market for SMRs.

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