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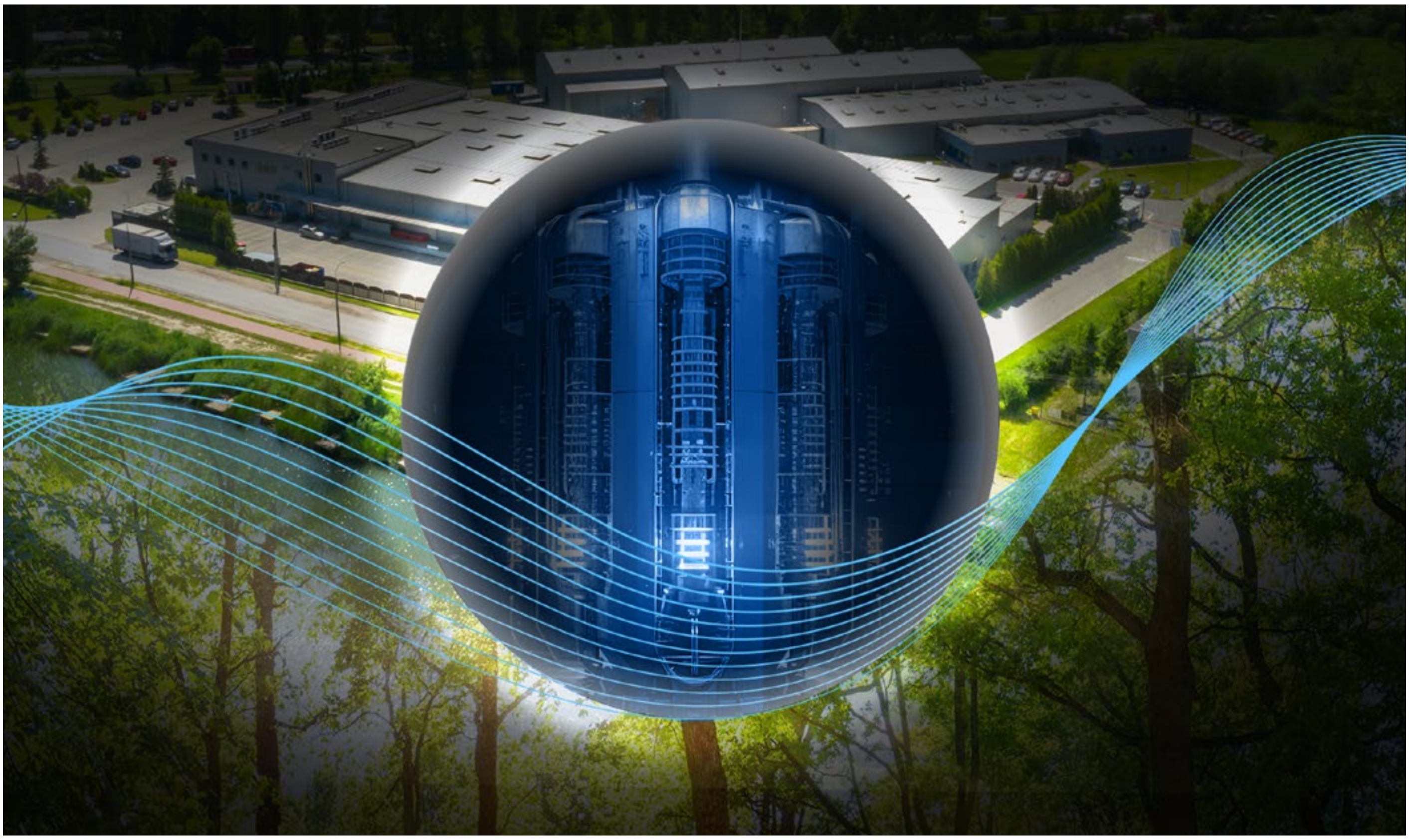

Small Modular Reactors

Winning the race in securing access to low-carbon energy

The time is now for organizations to act and lock in future energy supplies that will support their objectives to attract customers and sustain a competitive advantage. To win, organizations need access to reliable, safe, and decarbonized energy, all at favorable economics.

Small modular reactors (SMRs) are emerging as a serious contender to provide energy to various industrial applications, especially within hard to abate sectors. Demand for electricity is expected to rise globally, and to keep in line with climate goals, an increasing proportion of new generation capacity should be coming from low-carbon sources. With over 150 designs currently in development, the SMR landscape is ripe to leapfrog and play a significant role in making the energy transition a reality for all. In this paper, we outline how organizations can favorably position themselves to win the race by leveraging the abundant energy SMRs could provide.

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Introduction

While nuclear technology has been around for decades, it is only recently, in the last few years, that there has been somewhat of a global appreciation for the role of nuclear energy as a crucial pathway to realizing a net-zero world. COP28 was historic for nuclear, for the first time since 1995, when climate conferences began, nuclear energy was recognized by almost 200 countries, who have called for the acceleration of low-carbon energy sources to meet climate and decarbonization goals, including nuclear. (IAEA)

In addition to the recent announcement at COP28, more than 22 countries have committed to triple the production of nuclear energy by 2050 and in a bold move, the EU now classifies nuclear power as strategic green technology (EU taxonomy, ECEEE). These strong market signals should help to further boost the buildout of the nuclear industry, particularly small modular reactors (SMRs). Harmonization between countries on SMRs is achievable and arguably necessary if we are to realize the success of the global SMR ambition.

SMR technology has been gaining momentum for its differentiated and attractive features, offering more solutions flexibility, compared to traditional large nuclear reactors, including scalable market opportunities for decarbonizing power and heat generation applications for many industrial and hard to abate sectors. Through our research, Deloitte has identified over 150 designs under development around the world that can help to support the global market decarbonization demand. Of these designs, several are expected to be deployed in the 2030s time horizon, with more advanced designs beyond 2040.

Critical enablers to realizing a net-zero nuclear future include unlocking financial barriers and the capital constraints associated with the First of a Kind (FOAK) technology risk; harmonizing regulations among regional, municipal, and federal government agencies including alignment on disclosures and sustainability standards across the supply chains.

Future nuclear power plant using SMRs

This is particularly important with the integration of the Task Force on Climate-related Financial Disclosures (TCFD) into the International Sustainability Standards Board (ISSB) at COP28 (IFRS) and the increased push globally for adoption of the IFRS1 and 2, sustainability-related risks and climate-related disclosures.

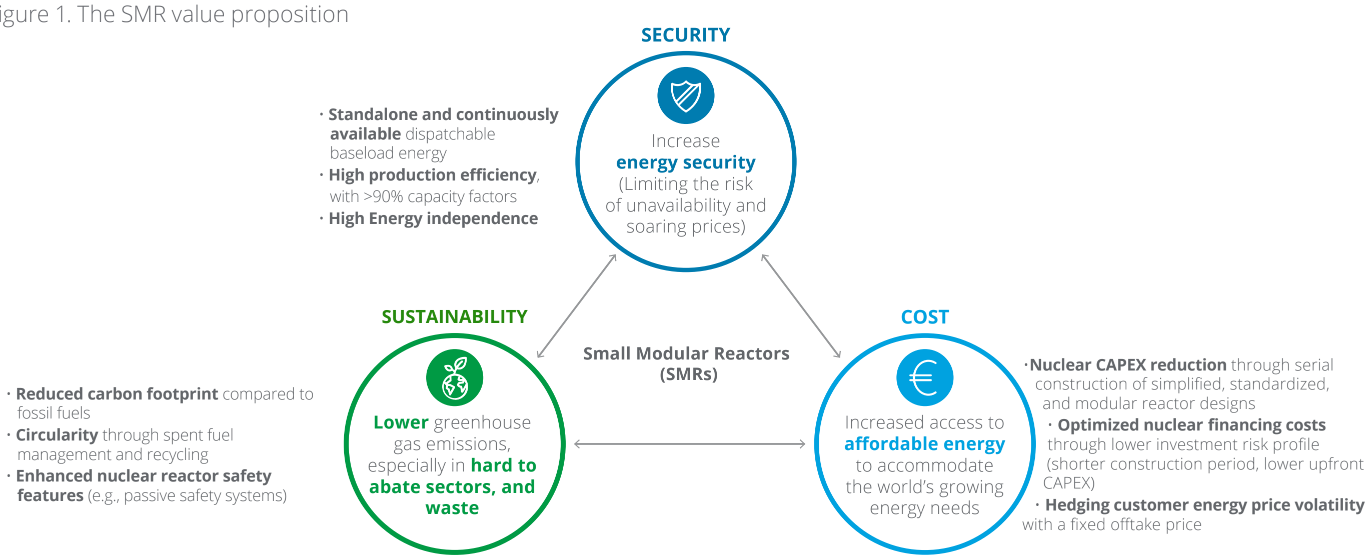
Of course, the ability for nuclear to increase its market share will come down to public acceptance, a historically sensitive topic. Industry experts cite a connection between regulation and social license. This point is illustrated in a regulatory approach whereby public participation is a foundational part of the regulatory process. Additionally, as regulators look to improve decision-making timelines, being able to demonstrate social acceptance will be critical to a more robust decision-making process.

The concept illustrates how brands well positioned to win the market today earn and enjoy favorable public opinion and support by creating value for multiple and diverse constituencies. Increasingly, industry finds itself challenged to succeed in the absence of cultivating strong relationships across varying interests. Coalition-building across constituencies is not only vital to building consensus; it is also critical for achieving business success. How you approach coalition-building to achieve broad support is crucial especially when opinions diverge.

Moreover, end-to-end value chains need to be in place while companies build specific capabilities to differentiate, optimize costs, and ultimately win the race. This includes ensuring enabled workforces and being able to manage geopolitical tensions that, as has been witnessed over recent months, have the capacity to constrain and redirect supply chains. While the future of SMRs is still uncertain, and a lot remains to be done to make it a sustainable and profitable business, there is hope that this can be nuclear's moment.

In this first article, we will delve into the dynamics of the SMR industry, review opportunities and challenges we foresee, and lay out a path forward for the technology to mature, scale, and deploy at a pace that will significantly contribute to the world's decarbonization challenge. Finally, we discuss what is needed to leapfrog the competition towards SMR commercialization and outline key capabilities needed to succeed.

Figure 1. The SMR value proposition



The need for nuclear to achieve the net zero target

In 2022, global energy-related CO_2 emissions grew by ~1% to over 36.8 Gt (IEA), driven mainly by the power (~40%) and the industrial sectors (~25%). The increase in energy-related emissions contradicts the Paris agreement to limit warming to 1.5°C and net zero targets by 2050 (UN). To get back on track, we must urgently make the necessary investments into decarbonization.

A successful energy transition requires a pragmatic approach to solving the components that make up the energy trilemma. The components include energy security; energy availability and reliability; energy sustainability; emissions generated from energy production and management of resources; and, perhaps most importantly for economic stability and investment, the cost of energy. Orchestrating a solution around these three components is complex, as advancements in one area can often pose challenges to another. For example, the ambitious rollout of intermittent supply can be cost effective, but can affect grid stability, and therefore negatively impact energy security and reliability which in turn would likely lead to contraction across economic sectors. In the journey to realize a tangible and practical solution for the energy trilemma, Figure 1 highlights how SMRs are emerging as a serious contender.

Nuclear energy has been around for over half a century and has demonstrated its ability to deliver reliable and secure baseload power with long-term price stability. Moreover, nuclear energy has a very low-carbon lifecycle footprint (from mining to decommissioning), with a low environmental impact (the smallest land-use footprint per megawatt-hour of electricity among available energy sources) (OurWorldinData).

Arguably, the main challenge for nuclear energy over the years has been the high capital requirements and time required to construct nuclear power plant. This is in part due to regulatory requirements and a large capital investment needed to commence buildout. SMRs, given the very nature of their size and scalability, are looking to address the cost and timing component through smaller sized units that are factory-built and road-transported for site-assembly, whilst maintaining the benefits of energy security and emissions reduction.

Nuclear energy has the potential to work alongside other low-carbon technologies and provide a solution that provides energy when it is needed, limiting the impact on the environment, at favorable economics. In fact, during COP28, world leaders recognized the critical role of nuclear technology to achieve the target set, and 22 nations pledged to triple nuclear generation capacity by 2050. In addition to nuclear energy now labelled as "green" investment under the EU Sustainable Finance Taxonomy since 2023 (EU taxonomy), the European Union confirmed the critical role of nuclear energy, and in December 2023, included nuclear energy in its list of "strategic" technologies to reach net-zero. Accordingly, nuclear energy will benefit from streamlined licensing procedures with full digitalization of procedures to ensure that authorizations can be obtained within 9 to 12 months (ECEEE).

These developments support the strong momentum that SMRs have experienced over the last couple of years as a key enabler to help meet global net zero targets. In addition, as more investment is drawn to the industry, together with a more favorable regulatory environment, the high cost of the technology can be reduced to make the technology more competitive to form part of the future energy mix.

SMR value proposition

SMRs are a class of advanced fission nuclear reactors, smaller in energy output and footprint than their conventional counterparts. SMR developers promise shorter time-to-market windows, thanks to factory-assembled modules. Additionally, many SMR designs have demonstrated an increased capacity for fuel efficiency and enhanced passive safety features. While SMR technology, including fuel fabrication, varies greatly among the designs, typically, SMRs have a power capacity of up to 300MWe per unit with thermal capacity to support industrial decarbonization. Micro reactors, or vSMRs, have smaller power outputs and their applications would support more site electrical and thermal requirements such as for mining or small industrial plants.

Figure 2 outlines a summarized comparison between low-carbon technologies (large nuclear reactors and SMRs) and renewables and demonstrates the differentiated value proposition of nuclear, and especially SMRs, as part of the broader energy mix.

While renewable energy can provide low-carbon energy generation at low cost (solar and onshore wind in particular) and a short time to market, it is location-specific, and intermittency can cause grid stability challenges.

Figure 2. Overview of clean energy portfolio solutions and the relative positioning of SMRs, in 2024 (indicative)

	LOW-CARBON		RENEWABLES				
	Large nuclear reactor	SMR	Geothermal	Hydropower	Solar PV utility[1]	Wind offshore	Wind onshore
Carbon intensity (min/max; median)	[4-110] gCO_2/KWh; 12gCO_2/KWh	[4-110] gCO_2/KWh; 12gCO_2/KWh	[6-79] gCO_2/KWh; 38gCO_2/KWh	[1-2,200] gCO_2/KWh; 24gCO_2/KWh	[18-180] gCO_2/KWh; 48gCO_2/KWh	[8-35] gCO_2/KWh; 12gCO_2/KWh	[7-56] gCO_2/KWh; 11gCO_2/KWh
LCOE[2] (min/max; median)	[42-102] US$/MWh; US$69/MWh	[76-134] US$/MWh[3]; Median not available. NOAK designs target cost-competitiveness with large nuclear reactors	[78-120] US$/MWh; US$99/MWh	[46-104] US$/MWh; US$68/MWh	[34-172] US$/MWh; US$56/MWh	[49-200] US$/MWh; US$88/MWh	[29-140] US$/MWh; US$50/MWh
Time to market[4] (min/max; median)	[5- +15] years; ~7.5 years	[3-4] years; Median not available	[1-3] years; Median not available	[4-10] years; Median not available	[1.5-2] years; Median not available	[2-4] years; Median not available	[1.5-2] years; Median not available
Power output (min/max; median)	[1,000-1,600] MWe Median not available	[10- +300] MWe Median not available	[10-1,600] MWe Median not available	[1-22,500] MWe Median not available	[1-1,200] MWe Median not available	[1-1,400] MWe Median not available	[1-1,500] MWe Median not available
Capacity factor (min/max; median)	[80-93] % ~86%	[80-95] % Median not available	[90-95] % Median not available	[30-55] % Median not available	[14-18] % Median not available	[35-45] % Median not available	[27-37] % Median not available
Power flexibility	Moderate	High	Limited	Limited	Limited	Limited	Limited
Land use (min/max; median)	~[0-1]m^2/MWh; 0.3m^2/MWh	~[0-1]m^2/MWh[5]; 0.3m^2/MWh	~[5-8]m^2/MWh; Median not available	~[10-18]m^2/MWh; 14m^2/MWh	~[8-25]m^2/MWh; 13m^2/MWh	~[8-250]m^2/MWh[7]; 99m^2/MWh	99m^2/MWh; ~[8-250]m^2/MWh[6]
Resource intensity (min/max; median)	Min/max not available ~1,200tn/TWh	Min/max not available ~1,200tn/TWh[8]	Min/max not available ~5,000tn/TWh[10]	Min/max not available ~15,500tn/TWh	Min/max not available ~2,500tn/TWh	Min/max not available ~6,000tn/TWh[9]	Min/max not available ~6,000tn/TWh[9]

Ranking: #1 #2 #3 Outside of top3

Notes: 1) Solar PV utility, without battery; 2) Median technology cost at discount rate of 7%; 3) i) Min corresponds to NOAK estimated LCOE; ii) Max corresponds to FOAK estimated LCOE; iii) Excluding US ITC; 4) From the start of construction to plant commissioning; 5) Nuclear used as a reference; 6) Include area between turbines; 7) Wind onshore used as a reference; 8) Nuclear energy used as a reference; 9) Offshore and onshore wind are assumed to have the same resource intensity; 10) Data based on 2015 US DOE and compared against 2021 World Nuclear Organization (WNO) for other energy sources due to lack of information

Sources: **Large nuclear reactor** (1: IPCC; 2: IEA; 3: i) ANSTO ii) WNO; iii) US DOE; 4: Press; 5: i) US DOE, ii) IAEA; 6: Expert interview; 7: OurWorldinData; 8: WNO); **SMR** (1: Nuward; 2: US DOE; 3: ANSTO; 4: WNO; 5: i) US DOE, ii) Nuscale; 6: Expert interview; 7: OurWorldinData; 8: WNO); **Geothermal** (1: IPCC; 2: IEA; 3: i) ISOR, ii) ESMAP, iii) Press; 4: Wikipedia; 5: US DOE; 6: Expert interview; 7: i) NREL), ii) Press; 8: DOE); **Hydropower** (1: IPCC; 2: IEA; 3: i) Press, ii) Research paper, iii) AQPER; 4: Wikipedia; 5: IRENA; 6: Expert interview; 7: OurWorldinData; 8: WNO); **Solar** (1: IPCC; 2: IEA; 3: i) SEIA, ii) Press; 4: Press; 5: IRENA; 6: Expert interview; 7: OurWorldinData; 8: WNO); **Wind offshore** (1: IPCC; 2: IEA; 3: Iberdrola; 4: Wikipedia; 5: IRENA; 6: Expert interview; 7: OurWorldinData; 8: WNO); Wind onshore (1: IPCC; 2: IEA; 3: IWEA; 4: Press; 5: IRENA; 6: Expert interview; 7: OurWorldinData; 8: WNO)

SMRs can be deployed where demand is needed and limit the requirement for extensive grid infrastructure due to remote off-grid capability. They also provide a continuous supply of energy, which means nuclear energy can complement intermittent energy and help to stabilize grid inertia while other large-scale storage solutions are uneconomical.

Inverters required to convert intermittent energy from direct current to alternating current, disrupt the synchronous generators on which the grid is built, which pose a risk to grid inertia and stability (Press). Nuclear energy, such as SMRs, provides continuous weather agnostic energy, thereby being able to fill in the energy demand gap, manage grid stability, limit investment in excessive grid infrastructure and facilitate the grid transition to renewable energy.

"Given their smaller size and portability, SMRs further optimize their environmental footprint by requiring less land and therefore less disturbance to ecosystems. This is especially important given the proposed locations for some SMRs, and vSMRs, providing energy to remote industrial applications or rural mining locations."

Within the low-carbon technology mix, SMRs offer a viable alternative to large conventional reactors across various dimensions, each of which is briefly discussed next.

(Potentially) cost competitive

Future deployment of SMR units could deliver a 30-40% reduction in Levelized Cost of Electricity (LCOE) between FOAK and Nth-of-a-kind (NOAK) units, through optimization of overnight capital cost and financing costs (US DOE). FOAK designs experience longer lead times (roughly twice as long as planned) with a high rate of component failure. NOAK designs, on the other hand, benefit from learning-by-doing, process standardization, reduced build time and supply chain development. On Levelized Full System Costs of Electricity (LFSCOE), defined as the costs of providing electricity by a given generation technology, assuming that a particular market has to be supplied solely by this source of electricity plus storage (Research paper), SMRs would likely outperform their peers thanks to their ability to locate on sites with no existing grid infrastructure and the absence of battery storage requirements.

Better time to market

Reactor modularization and factory-pre-assembly of components potentially reduce the construction time from typically 7.5+ years for large reactors to 3 to 4 years (WNO; ANSTO). Factory manufacturing allows operations to be carried out in a controlled environment, which allows the standardization of processes, procedures, and designs. The controlled environment enables higher quality output, less rework, and increased efficiency in construction, operation, and decommissioning (Research Paper).

Improved flexibility

SMR designs integrate higher power flexibility than conventional reactors to enable greater adaptation to demand variations. This is particularly useful when SMRs are integrated alongside intermittent supply, such as solar and wind, which supports grid stability through mutualization of different load profiles. Designs are also optimized to enable hybridization of energy supply and service both decarbonized electricity, and heat for various applications, such as district heating, industrial processes, and hydrogen production. Despite flexible power generation features, operators are expected to maximize asset utilization to amortize costs.

Reduced land use

Given their smaller size and portability, SMRs further optimize their environmental footprint by requiring less land and therefore less disturbance to ecosystems. This is especially important given the proposed locations for some SMRs and vSMRs, providing energy to remote industrial applications, distant community, or rural mining locations. Beyond the physical footprint of the asset, there is also a suggestion to reduce the emergency planning zone (regulatory approval pending) due to the lower energy output and additional safety measures from SMRs, such as enhanced passive cooling systems, and inherent safety characteristics of the design. Current SMR footprints range from ~1,500m^2 (Westinghouse AP300) to ~3,500m^2 (Nuward), which will easily fit into a football field (Westinghouse).

Infrastructure optimization

SMR technology could also potentially reuse existing fossil-based power plant infrastructure and repurpose it for nuclear power production. With a variable degree of plant reuse and integration strategy (from location to equipment reuse) (Research Paper), SMRs could facilitate repurposing a coal power plant by reusing existing infrastructure, ensuring more sustainable management of resources while maintaining jobs in local communities (US DOE).

Less spent fuel

Unlike conventional water-cooled thermal fission reactors, advanced reactors using fast fission allow spent fuel to be recycled at greater quantities, thereby reducing the amount of fuel that must be stored and managed. This in turn further limits environmental concerns associated with the storage of spent fuel (NewCleo). However, with a significant amount of reactors under development, the volume of spent fuel produced by SMRs varies as greatly as the technology used.

Enhanced safety

SMRs will continue to build on the global nuclear industry's safety record. Historical nuclear designs have seen improvements to safety features including the use of passive safety systems, which utilize natural forces or buoyancy driven flow to remove heat from the reactor core and containment to ensure ongoing stability of reactors in the event of an emergency or accident (SMRnuclear; Osti.gov).

SMRs have a strong value proposition to form part of the future energy mix while providing additional practical solutions to support off-grid applications to enable industrial decarbonization for mines, oil and gas operations, clean hydrogen production and even marine transport, including port decarbonization.

SMRs offer net-zero solutions where large conventional reactors have historically not been optimal given their size and operating requirements.

In addition to off-grid applications, the technology could work alongside renewable energy sources, offering support to intermittent energy through continuous, location-flexible energy supply and grid stability. Finally, the high temperature heat benefits extend beyond industrial decarbonization and offer opportunities for district heating, which can help to power everything from communities to local greenhouses. This in turn can help to address food insecurity and availability in climates where, due to weather conditions, remoteness, or cost, they are currently constrained.

The SMR market and applications

Driven by the urgent need to decarbonize, various players, such as research institutes, the power operators, and start-ups have set their sights on designing, building and commercializing SMRs and there is no shortage of SMR technology. In fact, globally there are over 150 SMR designs currently under development.

The SMR market is currently occupied by what the industry refers to as Generation III+ and IV reactors. Generation III+ reactors typically include water-cooled reactors, such as the pressurized water reactors (PWRs), integral pressurized water reactors (IPWRs) and boiling water reactors (BWRs).

Generation IV reactors, also referred to as Advanced Modular Reactors (AMR), are designs that typically make use of alternative coolants such as gas, metal, or salt. These reactors also showcase further safety enhancements, such as inherent safety characteristics and improved passive safety systems, use different fuel types at varying levels of enrichment (less than 20%), use different coolants and often operate at higher temperatures. Reactor technology typically includes high-temperature gas-cooled reactors (HTGCRs), lead-fast reactors (LFRs), sodium fast reactors (SFRs), or molten salt reactors (MSRs). As part of the broad spectrum of reactors under development, vendors are also designing different sizes of SMRs to meet the customers' varying needs, both on-grid and off-grid applications, such as decarbonization requirements, footprint restrictions, and energy output needs.

Water-cooled SMRs are the most mature technology, benefitting from the historic momentum achieved through the global rollout in both civil applications, where roughly ~95% of large reactors are water-cooled (IAEA), and military applications, where over 90% of the applications are water-cooled (WNO). As of today, only three SMR designs are in operation, which are two Russian water-cooled SMRs (WNO), and one Chinese gas-cooled SMR (Press).

The first, the RITM-200 SMRs, are IPWRs used to power the fleet of Russian nuclear ice-breaker (Press), whilst the second, the KLT-40S SMR of PWR technology, is a floating nuclear power plant and used to provide electricity and heat to the Pevek community in Siberia (Press). The KLT-40S SMR also provides a desalination capability (IAEA). The third, the Gen IV HTR PM of gas-cooled reactor technology, co-generates high-temperature stream, up to 500°C, and electricity to supply petrochemical industries and substitute the burning of natural gas and coal (Press).

The hybrid output functionality of some SMRs is of particular interest (Nuward). Some designs supply decarbonized heat for industrial processes (e.g., paper, chemicals, aluminum, and steel) and district heating. In particular, reactors such as the HTGCR are well suited to decarbonize carbon-intensive industries, given their ability to provide high temperature output heat (IAEA). Moreover, the need to produce carbon-free hydrogen can increase the production of e-fuels notably for aviation and maritime transport and provide flexibility and storage for electric systems.

SMRs can also provide electricity to power the low temperature electrolysis (LTE) process, but also high temperature electrolysis (HTE), which combines heat and electricity to achieve greater efficiency (Nuward).

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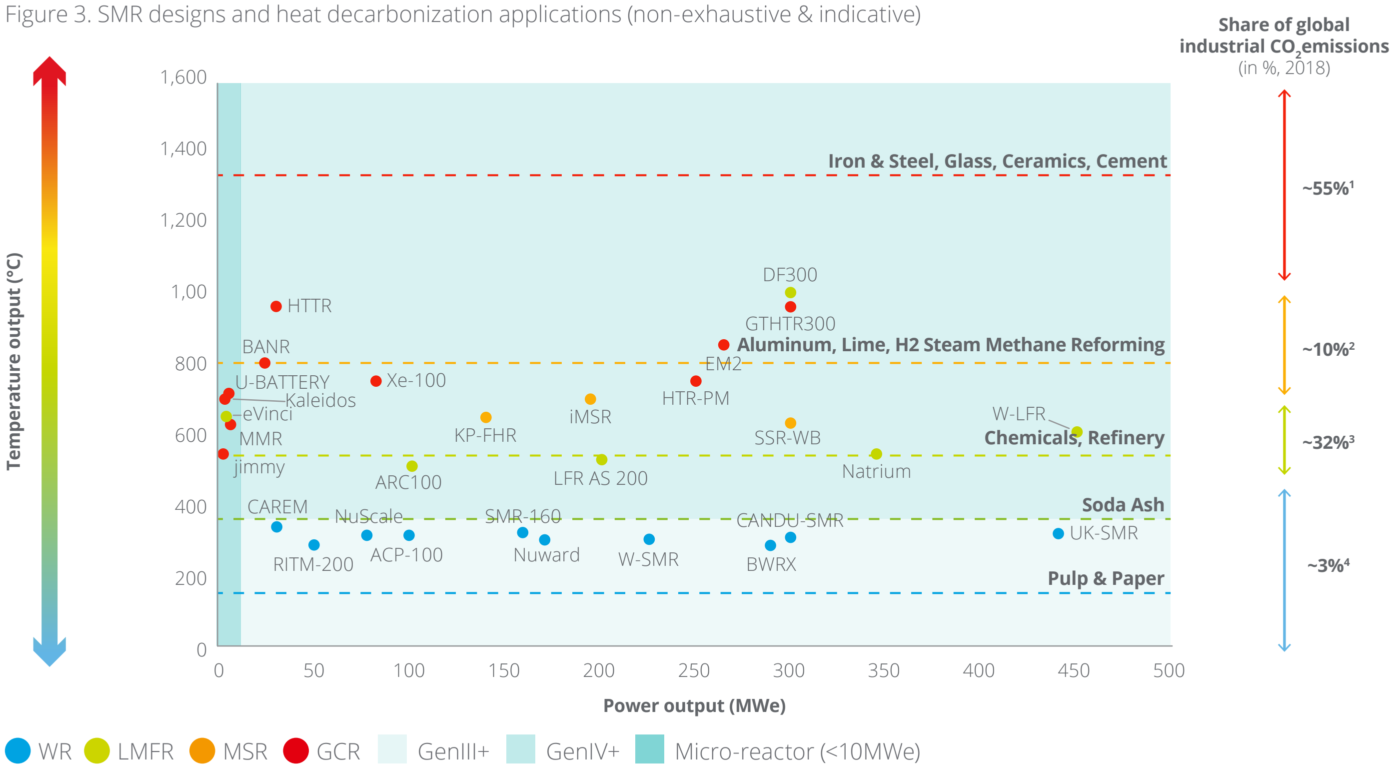
Figure 3. SMR designs and heat decarbonization applications (non-exhaustive & indicative)



Methodology for industrial CO_2 emissions breakdown calculations: 1) Assuming CO_2 emissions of Iron & Steel is ~2.1Gt, Cement ~2.2Gt, Ceramics ~0.4Gt, Glass ~0.1Gt CO_2; 2) Assuming CO_2 emissions of Aluminum is ~0.2Gt, H2 SMR ~0,5Gt and Lime ~0,1Gt; 3) Assuming CO_2 emissions of Chemicals is ~0.9Gt, Refinery is ~1.3Gt, and other sectors ~0.4Gt; 4) Assuming CO_2 emissions of Pulp & paper is ~0.2Gt and Soda Ash ~0.1Gt

Sources: NEA [Link1; Link2]; IAEA [Link]; ASME [Link]; Gemini Initiative [Link]; IEA [Link]; Chemicals CO_2 emissions [Link]; Refinery CO_2 emissions [Link]; Lime CO_2 emissions [Link]; Ceramics CO_2 emissions [Link]; Glass CO_2 missions [Link]; H2 SMR CO_2 emissions [Link1; Link2; Link3]; Soda Ash CO_2 emissions [Link1; Link2] Monitor Deloitte Research & Analysis

Figure 3 provides a summarized view of SMR reactor designs and applicability to decarbonize heat applications. The breakdown of industrial CO_2 emissions by temperature range is calculated primarily based on the International Energy Agency (IEA) data and supplemented by a bottom-up estimate of CO_2 emissions by sectors.

Water-cooled reactors predominantly provide output heat around 300 degrees Celsius, which is sufficient to provide heat for applications such as district heating and pulp and paper sectors. Advanced reactors (Generation IV) offer substantially increased thermal capacity, with a heat output of up to approximately 800 degrees Celsius, made possible by high-temperature gas reactors. While the pulp and paper sector accounts for a rather small share of the total industrial CO_2 emissions, almost half of the total CO_2 emissions from direct industrial processes could be addressed with advanced reactors.

The key addressable segment includes the decarbonization of industrial heat processes, with nearly half of global CO_2 emissions addressable. Innovative business cases are also under consideration by other energy-intensive industries, including the decarbonization of the shipping industry with nuclear technology (Newcleo), or powering data centers with nuclear energy (Press; Press).

Critical enablers for SMR industry take-off

As more commercial SMR models reach the market by 2030, the industry expects first movers to lock in market demand, capital investments funding to become less available, and less than 15 designs to become widespread by 2050. However, this path is still uncertain and the overall industry's success is contingent on a set of critical enablers that need to be collectively addressed.

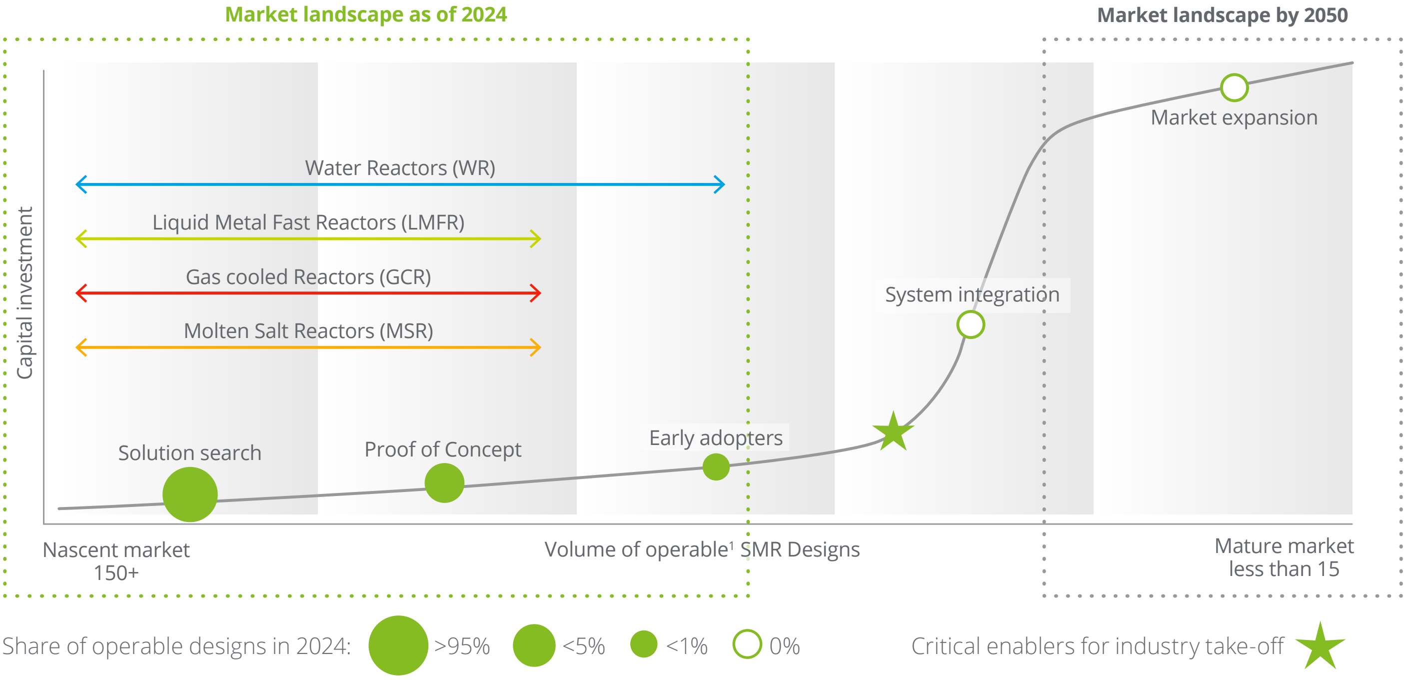
As per Figure 4, we expect an S-curve pattern of SMR adoption. At first, multiple designs are being developed and adoption is slow, driven by the low-carbon solution search and proof of concept stages. As more commercial SMR units hit the ground by 2030, early adopters will opt for licensed SMR designs.

Once the commercial units prove their value proposition, and subsequent units are mass-produced, the cost of SMRs will fall, and technology will gradually reach the mass market.

At that time, first-mover SMR developers will account for the largest share of installed units, driven by a successful track-record and large-scale production of their units.

Amongst winners, water-cooled reactors are expected to account for a sizeable share of the designs, being the most advanced and mature technology in the market today. However, the successful transition of the SMR industry from its nascent stage to a mature market is highly contingent on a set of critical enablers, including harmonizing international regulation, securing public acceptance, demonstrating safety designs, and reducing cost and unlocking funding. The list is not exhaustive and selected critical enablers are briefly discussed below.

Figure 4. SMR industry 2050 outlook (indicative)



Notes: 1. Operable design refers to designs under development in 2024 potentially operable by 2050
Sources: Expert interview [CEA, RR-SMR]; Monitor Deloitte Research & Analysis

Regulation

Harmonizing the international licensing process is critical to standardize safety protocols, speed-up regulator reviews and enable SMR developers to develop standardized designs to facilitate exports across borders. SMR vendors, operators and regulators around the world use different terminology to define the level of maturity of a design at the different design stages, which can be a source of misunderstanding or confusion when licensing the same reactor in different countries or regions (WNO). Harmonizing regulation across jurisdictions and regulatory authorities globally is even more imperative with the recent announcement of the TCFD being disbanded at COP28 and those disclosure principles being woven into the ISSB, which has announced the first two disclosure standards on climate and sustainability, IFRS1 and 2. As these standards move from voluntary to mandatory reporting elements for organizations and their supply chains, alignment will be even more critical for project success.

The International Atomic Energy Agency (IAEA) started the Nuclear Harmonization and Standardization Initiative consultation process in 2022, and brought together policy makers, regulators, designers, vendors and operators, to develop common regulatory and industrial approaches to SMRs and facilitate safe and secure international deployment (IAEA). While results are pending, SMR developers are actively working with regulators at regional level to progress towards a set of harmonized regulatory expectations related to safety, the use of passive safety systems and safety assessment approaches.

For example, Nuward, the French designed PWR SMR, has entered a Joint Early Review of its design. The review brings together the Nuclear Safety Authority (ASN) in France, the Radiation and Nuclear Safety Authority (STUK) in Finland, and the State Office for Nuclear Safety (SUJB) in Czech Republic and it aims to anticipate the regulator's expectations in the European countries where the technology will be deployed and to encourage international collaboration on nuclear safety and licensing (Nuward). Developing a harmonized international licensing process can reduce the overall SMR deployment cost and timelines, derisk investment and accelerate industry deployment (Nuward).

Social acceptance

Industry experts cite a connection between regulation and social license. This point is illustrated in a regulatory approach whereby public participation is a foundational part of the regulatory process. Additionally, as regulators look to improve decision-making timelines, being able to demonstrate social acceptance will be critical to a more robust decision-making process.

The concept illustrates how brands well positionned to win the market today earn and enjoy favorable public opinion and support by creating value for multiple and diverse constituencies. This includes nuclear. Historically, the nuclear industry has found itself challenged to succeed in the absence of cultivating strong relationships across varying interests.

Coalition building across constituencies is not only vital to building consensus, it is also critical for achieving business success. How you approach coalition-building to achieve broad support is crucial especially when opinions diverge. Companies and sectors that enjoy favorable public opinion and support are well-positioned to win the market by creating value for diverse and multiple constituencies. More and more, success is not simply a question of mastering the 'will-to-win' but garnering the kind of support where people 'want you to win'.

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Clear decision-making is crucial to move the broader public and targeted policy towards solutions-oriented outcomes. Broad-based support takes your organization's will to win and infuses it with the momentum of third-party support that 'wants you to win'. While human ingenuity may invent a perfect solution to climate change some day, we must build a plan based on what is known and proven today, leveraging the knowledge and technologies at hand. Nuclear's ability to support decarbonization efforts is well-documented, yet poorly declared. There is further opportunity to demonstrate the nuclear industry's positive social impact across communities, industries, and markets in addressing growing energy demands (both commercial and residential), while still contributing to decarbonization and ensuring a safe and sustainable future for society – a winning proposition that will attract capital and financing.

To succeed in this effort, the nuclear sector must methodically organize coalitions of support in a social movement.

Safety and environment

Nuclear energy is already one of the safest energy sources (OurWolrdinData). Building from an already safe technology, Generation III+ and IV SMR designs are intrinsically safer as the design was improved while retaining proven features. Conventional reactors are equipped with active-safety related systems requiring external power, force, action, or signal to function, and limited passive safety systems, while SMRs include passive-safety related systems inherent to reactor design and operation, further reducing the risk of nuclear incidents.

For example, due to the compact size of some SMRs, the entire reactor system can be encapsulated, which, together with other safety related systems, limits the spread of radioactive materials in the event of an incident.

Additional safety measures for Generation III+ water-cooled reactors include natural convection inside the reactor core to promote the removal of heat, and Generation IV reactors benefit from the inherent characteristics of the coolant, such as higher boiling points. For example, a metal-cooled reactor has a higher boiling point compared to water-cooled reactors, which increases the margin of safety in the event of an incident. SMRs also have a limited impact on the environment, with limited sized footprint, and the lowest land use-to-energy production ratio of all available energies (OurWorldinData). In addition, Generation IV fast reactors use spent fuel, which could help to meet the long-term challenge of nuclear repositories by looking at more sustainable management of nuclear fuel; recycling existing fuel rods and thereby reducing the spent fuel footprint; which will also limit the amount of long-lived radioactive materials. Although SMRs promise improved safety and lower environmental impact, and many of the constructs, including the fuel bundles, have taken existing proven technology and advancements in safety innovation over the past decades, uncertainty remains given the technology is FOAK.

Cost and funding

Arguably one of the greatest barriers to the nuclear dream is the FOAK challenge. FOAK can delay or inhibit advanced reactors altogether. In countries like Canada and the United States, historically, government has taken on the FOAK risk through various funding mechanisms to develop prototype and demonstration designs.

With SMRs thus far, the capital for prototypes has been lacking and vendors do not have capital for prototype spend; thus pushing for a commercial design out of the gate which shifts the FOAK risk to the first purchaser/operator of these units.

It is essential to reduce or remove this FOAK risk to get projects up and running; otherwise we risk having a lineup of fast followers all in cue, waiting for the FOAK risk to be absorbed and projects going nowhere.

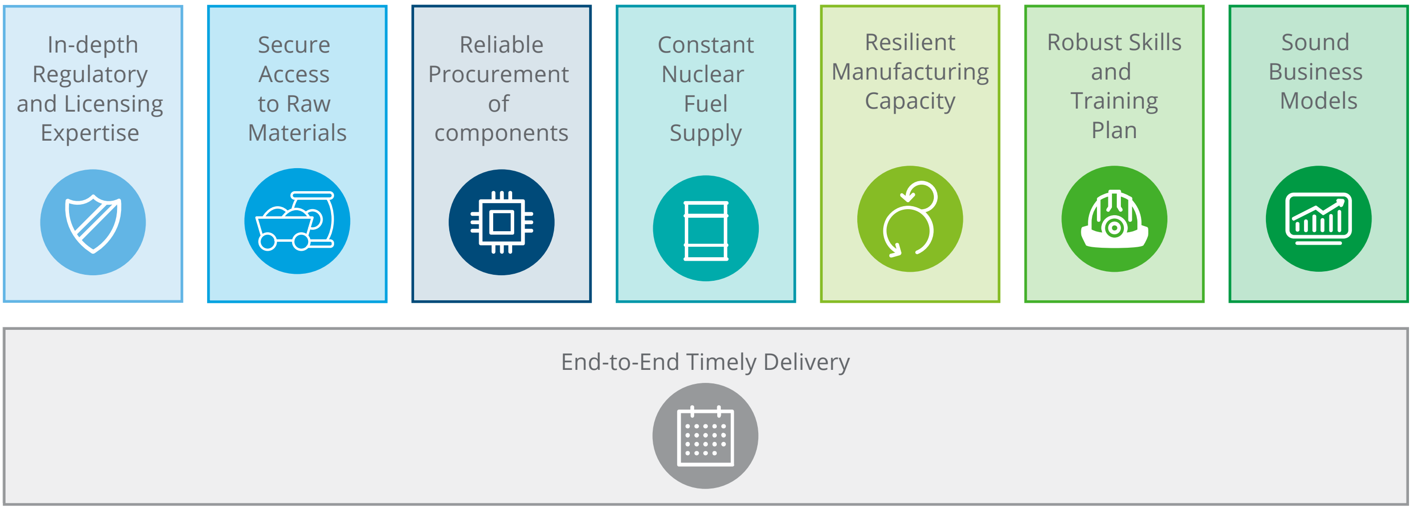
Providing investors with a clear and transparent account of the estimated cost is paramount as confidence in the technology of choice is developed. However, inherent uncertainty in the development of FOAK technology contributes to raising the overall risk profile of SMRs. Key actors, such as power utility companies and investors, have suggested that the initial set of SMRs could be difficult to fund due to this heightened FOAK risk. Private investors could be willing to take on more risk if the reward profile was more attractive, which will likely require governments to help shoulder some of the financial risk.

Nuscale, who received design certification from the US nuclear power regulator in 2022, initially pegged a target power price at $55/MWh back in 2016, which was subsequently increased to $58/MWh in 2020. However, following a detailed cost estimate in 2023, the company announced that the power price increased to $89/MWh, up by roughly 60% compared to the original estimate (IEEFA).

To support SMR developers, governments have introduced various funding schemes. For example, France pledged funding support of approximately €500 million in the 2030 plan for SMRs, of which €300 million is earmarked for Nuward (French government). Furthermore, the US Department of Energy invested US$4.6 billion in TerraPower, X-energy and NuScale (US DOE). The Nuscale 2023 power price of $89/MWh includes provision of the government subsidy, which is estimated to be approximately $30/MWh (IEEFA) – without the subsidy, Nuscale's power price will be well over $100/MWh.

In addition to funding schemes, reduction in taxes, longer-term grants, and allowing SMRs to qualify for sustainable finance are all part of driving the initial risk to investors down. Derisking SMR investment to attract private capital is pivotal to the development of the SMR industry, especially in a high interest, high inflationary and geopolitically charged environment and remains a key challenge for the industry to overcome.

Figure 5: Key Success Factors checklist to win the SMR race (non-exhaustive)



Who will win the race?

Provided critical enablers are achieved, with less than 15 designs to become widespread by 2050, the main challenge for developers is to take the lead in the competition and scale up production as quickly as possible to drive down cost and lock in market demand. As per Figure 5, critical capabilities are required to scale fast, including in-depth regulatory and licensing expertise, secure access to raw materials, reliable procurement of components, constant nuclear fuel supply, resilient manufacturing capacity, robust skills and training plan, and a sound business model to raise funds. These critical capabilities are underpinned and supported by an end-to-end delivery capability to ensure the program meets the envisaged objectives. Each of these capabilities are briefly discussed next.

In-depth regulatory and licensing expertise

Acquiring and maintaining regulatory and licensing capabilities are on the critical path for the commercial readiness of the FOAK reactor. Although time-to-market can be optimized (e.g., learning rate of regulatory processes, conducting reviews in parallel, etc.), the initial designs are expected to experience a longer lead time to obtain regulatory approval.

To overcome some of the regulatory barriers, developers prioritize the use of proven technologies that have already achieved regulatory approval, and limit design changes to enable a more efficient approval process, which supports a shorter time to market period. Others target developing countries (e.g., Asia-Pacific) to secure tailored agreements with the regulator. Critical barriers remain today that need to be addressed in collaboration with the regulator if the time-to-market is to be shortened. These include, amongst others, the size of the emergency planning zone (EPZ), capacity and capability of the regulator to effectively interact and manage the influx of SMR developer designs, and greater transparency on the overall requirements and timelines related to the regulatory approval process.

Secure access to raw materials

To construct a series of SMRs that support the climate goals, a large amount of raw material is required. As a result, long-term access to raw material for the manufacturing of components and equipment is critical to unlock the NOAK potential of SMRs. For example, high-alloy metals are needed to successfully construct SMRs, and developers and manufactures need access to a reliable supply of alloying elements. Amongst others, nickel and chromium are limiting alloying metals for new nuclear applications such as SMRs (Osti.gov). Sourcing strategies must therefore be wholistically defined and set up to achieve the production targets needed to achieve the desired efficiencies.

Reliable procurement of components

Roughly 20 million pieces are required to produce an SMR. While developers design SMR reactors with a maximum amount of "catalogue components" to minimize fluctuations in availability, other critical components cannot be accessed off the shelf. Long-lead time items, taking two or more years, are critical components, including nuclear-related components (e.g., reactor vessel, guard vessel, steam generator) and non-nuclear-related components (e.g., steam turbine, condenser, instrumentation, and controls). It is essential to assess the industrial supply chains for gaps and limitation that could hinder the production of FOAK and NOAK reactors. Supply chain risks include, amongst others, geopolitical factors, supply-demand imbalance, vendor and fabricator's reliability, and price fluctuations. Mitigation strategies must be properly planned to ensure a robust production at scale.

Constant nuclear fuel supply

Nuclear fuel can be classified into two categories – fuel that is more accessible in terms of supply and qualification and fuel that is more novel and requires more verification and longer lead times to get to market.

Generation III+ LWR SMR leverage existing globalized fuel supply chains for fuel needs, typically less than 5% enriched UO_2 pellets inside Zircalloy tubing, whilst Generation IV SMRs use advanced nuclear fuel types, requiring dedicated fuel supply chains to be built (both up and downstream from fuel usage). Advanced fuels include reprocessed spent nuclear fuel (MOX ceramic fuel), HALEU (e.g., Tri-structural Isotropic fuel (TRISO), Metallic fuel, and Molten salt fuel) (Orano) (Orano) and have the added challenge of qualification of materials at high temperature.

To scale SMR production, there is a high stake for the industry to mitigate the critical risk of advanced fuel supply. In some cases, advanced fuels like HALEU, the qualification issue is further complicated by supply issues due to geopolitics. For example, HALEU supply is strongly dependent on USA and Russia capacity.

The USA supplies HALEU from down-blending HEU declassified from US military stockpiles but advised that available volumes for domestic and foreign use will be exhausted by 2035-2040 (ESA) (Orano). In response, as recently as January 2024, the US Department of Energy sought proposals to help establish a reliable supply of HALEU (US DOE). The only commercial supplier of HALEU in Russia is Tenex (CRA).

TRISO fuel, used in Generation IV reactors, is structurally more robust and can withstand higher temperatures (US DOE). Tenex became a world leader in TRISO fuel; however, since the war in Ukraine, advanced reactor manufacturers are looking at alternative supplies. For example, US-based X-energy is constructing a Fuel Fabrication Facility that will manufacture TRISO fuel for SMRs. The project is supported by the US Department of Energy through its Advanced Reactor Demonstration Program (ARDP) (US DOE).

Reprocessed fuel (i.e., MOX) is dependent on France and Russia capabilities. Other countries, the USA, the United Kingdom, Japan and China, do not have, or no longer have, a complete cycle (SFEN). Along with securing reliable access to procurement of components, continuous access to next generation fuel is essential for sustained power generation. Nuclear fuel supply chains must be screened to properly assess degree of supply-dependency risk, stockpile volumes, geopolitical tensions, and potential environmental impacts.

Trained and skilled workforce working on an SMR plant

Resilient manufacturing capacity

With up to 60% of SMR power plants being factory pre-assembled (Research Paper), securing resilient manufacturing capability and capacity are paramount to deliver planned production targets, at competitive cost. Players plan to mitigate manufacturing capacity requirements by leveraging in-house assets (e.g. Rolls-Royce SMR is building a dedicated supply chain) or by a consortium approach (e.g. Nuward manufacturing is planned through cooperation between EDF and the consortium partners' supply chain). However, to enable series production to meet increasing demand, players must build resilient supply chains to minimize capacity fluctuation, production disruptions and scale up capability. The use of data analytics and artificial intelligence tools are valuable levers to optimize manufacturing.

Robust skills and training plan

Countries like China and Korea have arguably mastered the art of project construction with a workforce that is able to move from project to project with relative ease. This is in stark contrast to Europe and North America, where delays are more commonplace. To remove this barrier, having a workforce-ready population that can easily transition between projects will be just as vital as the raw materials needed to construct SMRs.

At the peak, up to 40 000 workers will be needed, across the plant and supply chain, to build the SMR plant (RR-SMR Program). To unlock the benefit of a full-scale production, SMR developers have a vital interest in securing the long-term, trained and skilled workforce needed to achieve the learning curve and in turn needed to lower costs and accelerate the pace of production. There is also an important role for post-secondary institutions to work alongside SMR employers to provide relevant skills and practical hands-on training to support workforce development, as well as to provide opportunities to existing employees.

Therefore, developers must establish resource management strategies to secure talents with extensive technical expertise and understanding of regulatory compliance to ensure safe and efficient operation. In addition, developers also need to focus on succession planning and knowledge retention to maintain expertise within the organization, especially as the demand for these skills is expected to become increasingly competitive. Beyond succession planning, companies will need to have robust Diversity, Equity, Inclusion and Accessibility (DEI&A) policies and programs in place if they are to attract and retain top talent.

Sound business models

Before contemplating any investments, public authorities and private financiers expect SMR developers to roll out sound business models, formulated out of good business principles. In the value chain, players can take different roles, such as technology developers, manufacturers, operators, or a combination of various roles (e.g., a player developing SMR technology with internal manufacturing capability). At the same time, operations can also be collaborative, ranging from an integrated capability to a joint venture or consortium shared capability, to an outsourced capability under contract. Accordingly, the lower the revenue intermediation along the value chain, the higher the return, but also the capital investment and project risk. Conversely, the higher the revenue intermediation along the value chain, the lower the return, but also the required capital investment and associated risk.

To formulate a sound business model, it is essential to understand how the value is distributed and captured along the value chain to derive a competitive advantage and strategic position compared to competitors. To build such a strategy, it is critical to assess core competencies, investments requirements and potential returns to make informed decisions on outsourcing or integration of capabilities.

End-to-end timely delivery

To bring a complex SMR program to life and ensure all moving parts are effectively and efficiently managed, strong delivery expertise is required. Key metrics include the proactive management of cost, schedule and integration, partners, risk, and the use of digital tools to drive a differentiating value proposition in the market. Moreover, it should also include robust engagement dialogues with various interested parties, such as investors, regulators, partners, and community leaders, including indigenous elders and knowledge holders. Since shorter delivery time, compared to large reactors, is a key value proposition for SMRs, it should remain a high priority for SMR programs to connect, converse and collaborate to deliver on promises. Key expectations are for developers to establish mitigation strategies to address identified risks, including proactive financial planning to buffer against unexpected expenses, contingency plans for schedule deviations, and robust engagement plans that require early and frequent engagement in order to drive successful coordination with partners.

> "It should remain a high priority for SMR programs to connect, converse and collaborate to deliver on promises."

Conclusion

Nuclear energy will play a significant role in the energy transition by providing affordable, reliable and secure energy as well as numerous other opportunities to support deep industrial decarbonization, including lower-carbon fuels like hydrogen. While most SMRs are in the early stages of development and regulatory approvals, water-cooled reactor technology is the most advanced currently and is therefore poised to likely offer such benefits in the short to medium term.

Generation IV reactors, such as metal cooled reactors, molten salt reactors, sodium fast reactors, and high temperature gas cooled reactors offer viable decarbonization solutions in the medium to longer term, for hard-to-abate energy intensive industrial processes in everything from mining operations to petrochemical production, steam methane reforming hydrogen, marine transport, and steel production.

It is a critical requirement if the world wants to get back on track to meet the 1.5 degrees Celsius warming target and stave off the worst of climate change. While there is global interest among many organizations to develop SMR technology, to date there have been varying levels of success. The adoption trend is anticipated to follow an S-curve trajectory, where initial adoption is slow as the market assesses the best technical solutions.

A swift acceleration in adoption is required and anticipated as early adopters acquire licensed designs.

To win the race, organizations need to prioritize access to in-depth regulatory and licensing expertise, secure access to raw materials, and set up processes to ensure reliable procurement of components, including fuel. Organizations also need to prioritize the setup of their manufacturing capacity, train and retain talent, and leverage fit-for-purpose business models. Finally, a strong end-to-end delivery capability is needed to orchestrate cost, schedule and quality across the value chain.

SMR is a promising technology for addressing the energy trilemma many countries and industries are dealing with. The window of opportunity is now and leaders and decision makers need to create the momentum needed to make it a reality.

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