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Analysis for the nuclear energy community

Small Modular Reactors
A Global Perspective

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Contents

Overview

The International Atomic Energy Agency (IAEA) defines small sized reactors as having the capacity to generate electricity of up to 300MW and with modules manufactured in dedicated facilities before being shipped to and installed on site. The concept of the small modular reactor (SMR) and its applications to generating electricity has been discussed by researchers, governments and the nuclear industry for many years, and reactor design and technology breakthroughs in the last decade are starting to prove the feasibility of deploying an SMR.

Supported by workable investment and capital costs, more recent global energy imperatives have emerged that are edging commercial SMR operations closer: increasing demand for electricity to drive economic growth, increasing demand for energy security and generating low-carbon power to tackle climate change. SMR developers, the nuclear industry and governments have also accelerated drives to be the first to deploy an operational unit in order to exploit opportunities to export technology under proven licensing, safety and regulatory regimes into the global market place.

The IAEA estimates there are around 50 SMR designs at various stages of development.[1] Argentina, China and the Russian Federation are expected to begin commercial operations of the first SMRs between 2019 and 2020, with around twelve more deployments of SMRs advancing through licensing and construction to follow. North America is likely to be the next to deploy a unit with the US looking at 2026 to start commercial operations and Canada pursuing a progressive regulatory regime to accommodate deploying demonstration reactors in the same year.

The UK National Nuclear Laboratory's SMR feasibility study concluded SMRs could fulfil a significant global market estimated at 65-85GW by 2035 and valued at GBP£250-400bn (USD$300-500bn).[2] The US Energy Information Administration (EIA) projects world energy consumption will grow by 28% between 2015 and 2040.[3] Most of that growth expected to come from countries outside the Organisation of Economic Cooperation and Development (OECD) where electricity demand is driven by strong economic growth. Non-OECD countries in Asia, including China and India, are expected to account for more than 60% of this global consumption over that 25-year period.

Total electricity production in OECD member countries in 2016 was 10,158.2TWh (net), of which nuclear power generated 18.5% (net).[4] Although the share of electricity production from nuclear power plants (NPP) in the OECD area increased from 18.3% on the previous year, total NPP capacity declined by 0.6%. There are many alternatives to nuclear power that would increase electricity production to meet growing demand, although SMRs bring additional advantages over traditional large NPPs: SMRs can be integrated into a diverse energy mix; they can be deployed on- and off-grid; and they also have applications such as process heat, desalination and hydrogen production.

This report evaluates the SMR market by country, looking at the designs, technology and the research and development (R&D) progress towards licensing and commercial operations, while potential domestic market and opportunities for export are also summarized.

Developers and Markets

Argentina

Electricity consumption in Argentina has increased over the last 13 years, with per capita consumption rising from just over 2000 kWh/yr in 2002 to around 3,000 kWh/yr in 2015.[5] In 2017, gross electrical energy production totalled 136,436.27 GW, of which nuclear power generated 6,161 GW (4.52%).[6] A total of 51% of electricity is generated by natural gas, with 26% generated by hydroelectric power, 14% from oil and 2% from coal.[5]

Argentina has two NPPs with a combined power output of 1,632MW: the Atucha 1 340MW Pressurized Heavy-Water Reactor (PHWR) and Atucha 2 692MW PHWR plant in Lima (Buenos Aires province), as well as the eponymous 635MW PHWR in Embalse (Córdoba province).ibid Construction of the 33MW CAREM (Central Argentina de Elementos Modulares) water-cooled, land-based SMR began at the Atucha site in February 2014.

The government is pursuing an energy policy that will facilitate building more renewable energy infrastructure, including developing the country's significant hydroelectric power, and reduce the country's greenhouse gas (GHG) emissions.[7] A program launched in 2016 aims to boost the 2% share in renewable energy production (excluding large hydroelectric units) to 20% by 2025.

Energy contributes 43% of the country's overall GHG emissions, with the next largest source agriculture and animal husbandry (28%).[8] In its Intended Nationally Determined Contributions (INDC) at the 2015 United Nations Climate Change Conference (COP21), the government pledged to unconditionally cut the country's emissions by 15% by 2030.

Nuclear power is included in the criteria for selecting actions that have the potential to reduce or capture GHG emissions, as well as the possibility of applying nationally developed technology. The government created the Under Secretariat of Nuclear Energy with the Ministry of Energy, which has a remit to improve efficiency in the nuclear sector and assist in the local management of peaceful uses of nuclear energy and radioactive materials.[9]

The Agencia Argentina de Inversiones y Comercio Internacional (AAICI) reiterates the national priority to secure sufficient power supply as a demand grows, while simultaneously lowering the cost of electricity and reduced carbon CO2 emissions.[10] Its 2018 report on investment opportunities highlights the potential USD$3 bn construction and finance opportunity offered by the CAREM reactor by 2023.

Developed by the Comisión Nacional de Energía Atómica (National Atomic Energy Agency or CNEA) and its primary partner INVAP S.E., CAREM-25 reactor and plant have evolved from domestic technology as a national project. The supply chain has also been developed by domestic vendors. At least 70% of plant inputs, including components and related services supplied by national companies, have been certified by the CNEA under international quality standards.[11]

The design is based on an integral Light Water Reactor (LWR) with an electrical capacity of 30MW and a thermal capacity of 100MW.[12] Some of the significant design characteristics include an integrated primary cooling system, a self-pressurized reactor, core cooling by natural circulation, in-vessel control rod drive mechanisms and safety systems that rely on passive features. CAREM's design reduces the number of sensitive components and the risk of interaction with the external environment.

Figure 1: The plant site at Atucha for the CAREM reactor.
Credit: the CNEA.

Figure 2: Construction works at the CAREM installation site.
Credit: the CNEA.

Once deployed commercially, the reactor is expected to generate around 120 MWe, with four modules built in one power plant generating 480 MWe.[11] Target markets include supplying power to domestic regions with smaller electricity demands, as coastal sites since CAREM supports desalination processes that supply water and energy to end-users.[12]

IN 2015, INVAP announced that a joint venture had been agreed with the Saudi Technology Development and Investment Company (TAQNIA) in the Kingdom of Saudi Arabia (KSA).[13] The joint venture company, INVANIA, was set up to develop technology for the KSA nuclear power program, with CAREM is under consideration for desalination application.

Australia

Total electricity generation was 248TWh in 2013 to 2014, with 61% from coal, 22% from gas and 15% from renewables including wind, solar and hydroelectric power.[14] Australia prohibits NPP construction and operation and has no nuclear power reactor, although the 20MW nuclear scientific research reactor OPAL operated by the Australian Nuclear Science and Technology Organisation (ANSTO) produces medical isotopes.[15] Australia has almost a third of the world's known uranium resources and is the third largest producer.[16]

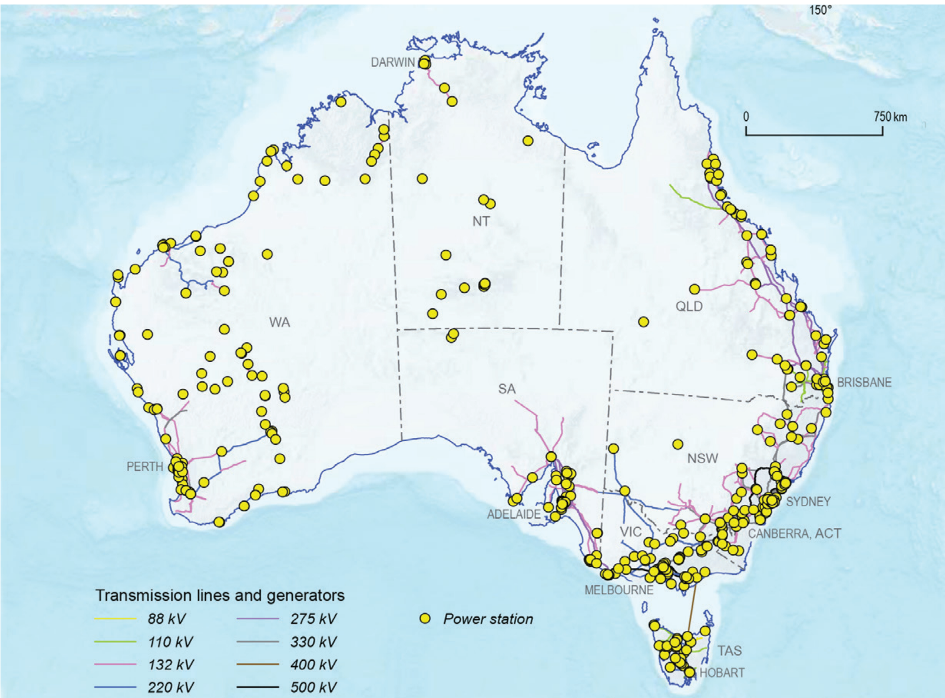


Figure 3: Australia's electricity infrastructure.
Credit © Commonwealth of Australia (Geoscience Australia) 2018.

In its INDC submitted to COP21, Australia pledged to reduce GHG emissions by 26-28% below 2005 levels by 2030.[17] Under Australia's Renewable Energy Target scheme, more than 23% of the country's electricity is expected to be generated by renewable energy sources by 2020. Recently renewed interest in overturning the NPP ban Australia is mainly driven by reducing GHG emissions and its inherent costs, especially as SMRs would generate emissions-free electricity while complementing renewable energy sources.[18]

In 2017, SMR Nuclear Technology Pty Ltd published a roadmap for the deployment of SMRs in Australia, which commences with community consultation exercises in 2018 and moves through licensing to commercial operation by 2030. Existing infrastructure would support a nuclear energy program, as Australia is a signatory to the Non-Proliferation Treaty (NPT), is party to the Convention on Nuclear Safety and has the Australian Radiation Protection and Nuclear Safety Agency (ARPANSA), an independent nuclear regulator.

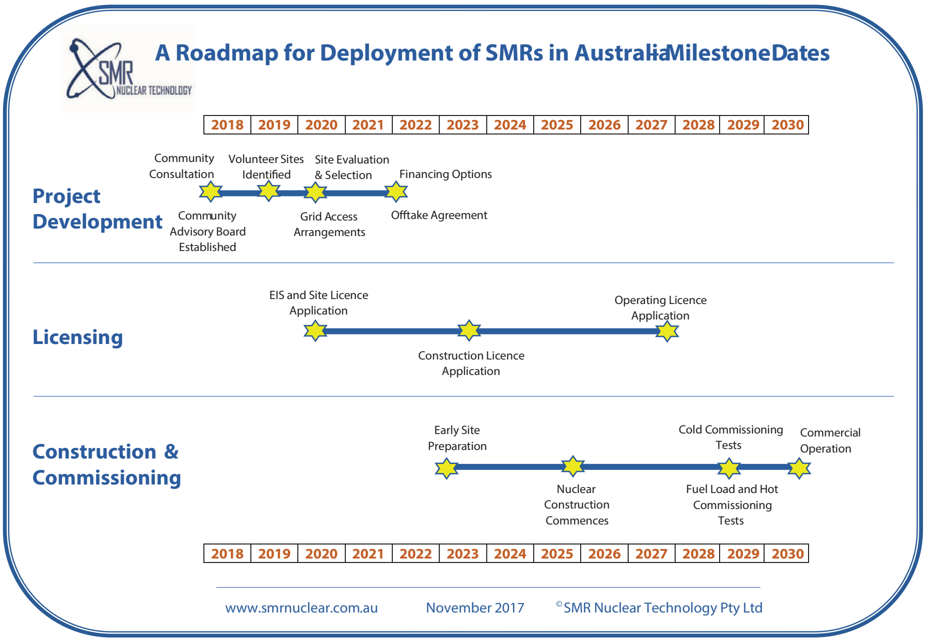


Figure 4: A Roadmap for Deployment of SMRs in Australia.
Credit: SMR Nuclear Technology Pty Ltd.

Advancing SMR programs in Canada and the USA are being closely followed, particularly for their safety, low-carbon emissions and regulatory aspects. Deploying SMRs would improve energy reliability and security in remote regions of Australia, in which many communities rely on expensive diesel, while diversifying baseload power and contributing to the reduction of GHG emissions. In addition, SMRs have the potential to ignite innovation and develop new industries.

*With acknowledgements to Tony Irwin, Technical Director, SMR Nuclear Technology Pty Ltd.

Canada

Canada's annual electricity use is one of the highest in the world.[19] Electricity generated in 2015 totalled 670 TWh, of which 380 TWh was from hydroelectric power and 101 TWh from nuclear power. Although nuclear energy currently represents 15% of Canada's total electricity supply, more than 60% is generated in the province of Ontario and 33% in New Brunswick.[20]

Currently, there are 19 operational NPPs in Canada, with a total net capacity of 13,553 MW.[19] Provincial governments and utilities have taken the decision to extend the lifespan of several of the Canadian Deuterium Uranium (CANDU) reactors by undertaking an extensive refurbishment program, which is part of an overall goal to meet future electricity demand.

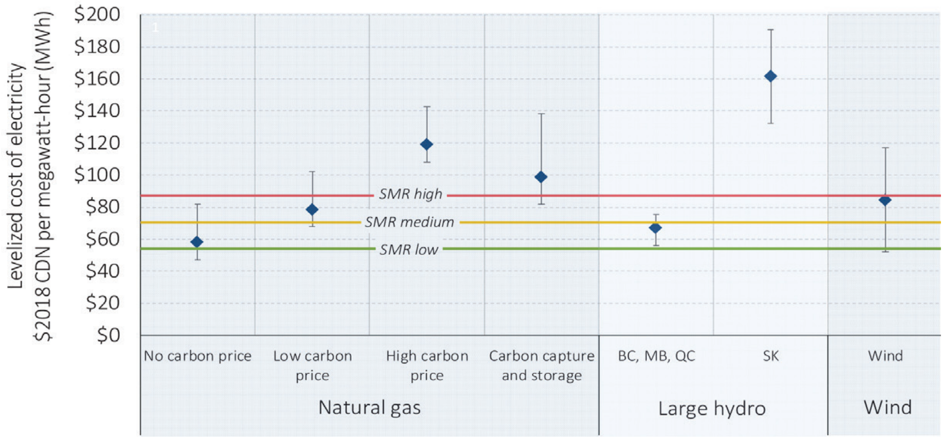


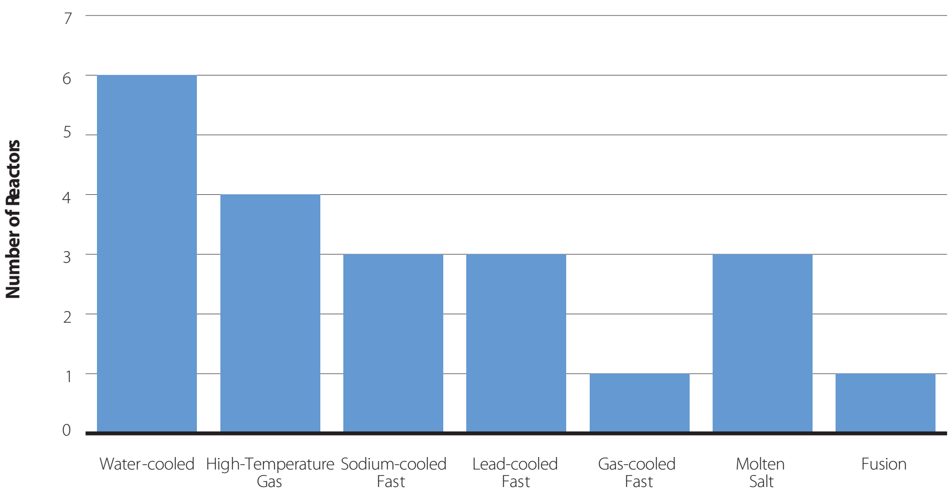
Figure 5: Comparison of levelized cost of electricity from on-grid SMRs with other options: Best case (6% discount rate, more innovative technology)
Credit: Canadian Small Modular Reactor Roadmap Steering Committee.

The Government of Canada also recognizes the role of nuclear power in the country's transition to low-carbon and non-emitting energy sources when setting domestic energy policy. In its INDC pledge in 2015, electricity and transportation were acknowledged as the largest GHG emitting sectors of the Canadian economy.[21]

Although the INDC also states that almost 80% of the country's electricity generation is already non-carbon emitting, Canada has pledged to reduce its GHG by 30% (on its 2005 level) by 2030. In 2017 the Canadian Nuclear Laboratories (CNL) put out a Request for Expressions of Interest (RFEOI) to stakeholders to determine whether SMRs could be part of a future decarbonized energy landscape that included nuclear power.[22]

In its summary report, Perspectives on Canada's SMR Opportunity, the CNL stated its goal to have an SMR installed on one of its sites by 2026. The RFEOI received feedback and comments from 80 organisations and individuals in Canada and from overseas, including SMR developers who have submitted licence applications to the nuclear regulator, the Canadian Nuclear Safety Commission (CNSC).

Respondents noted the use of cost-effective SMRs to power off-grid mining operations would improve revenue margins. Respondents also articulated the possibilities for communities living in the remote north of Canada to have greater energy independence that would enable economic growth for small businesses and improve the standard of living. These communities rely on expensive diesel fuel, which is difficult to transport across harsh terrain in severe weather conditions resulting in energy insecurity.



Reactor types being developed by respondents. RFEOI Summary Report.
Credit: Canadian Nuclear Laboratories.

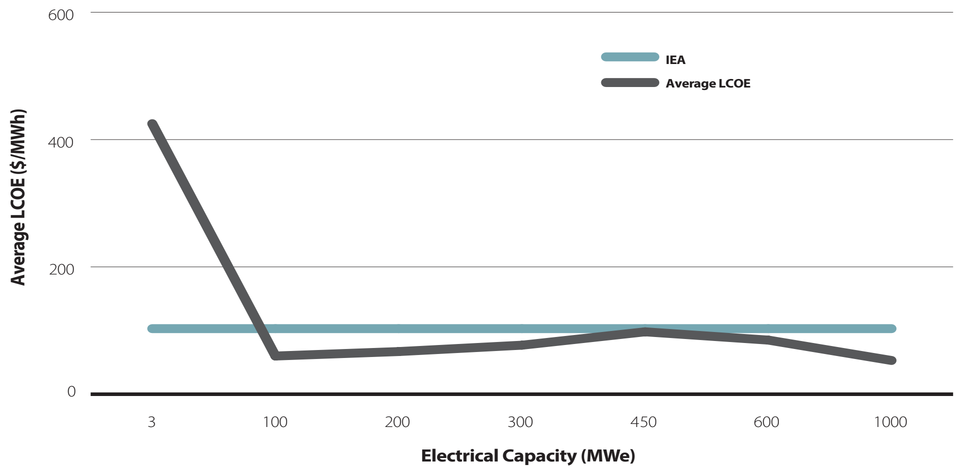


Figure 7: Average expected commercial LCOE, $/MWh by MWe plant size. RFEOI Summary Report.
Credit: Canadian Nuclear Laboratories.

Natural Resources Canada (NRCan) began a series of pan-Canadian consultations and engagement with SMR stakeholders. The resulting A Call to Action: A Canadian Roadmap for Small Modular Reactors was launched by the Canadian Small Modular Reactor Roadmap Steering Committee in November 2018.[20] It has four themes framing the recommendations to take the Roadmap forward.

The first outlines the need for federal and provincial government cost- and risk-sharing initiatives to build and deploy demonstration units. The second calls on the federal government and CNSC to work on policy, legislation and regulatory matters that includes nuclear liability, security and waste management.

The third revolves around capacity, engagement and public confidence, and specifically identifies further Indigenous engagement. The fourth pillar calls for enabling international frameworks to position Canada as a leader in international partnerships and SMR markets.

Details from meetings with end-users such those living and working in remote off-grid mining projects and the far north of Canada are also documented in the report. Consultations with the mining industry concluded that there was a demand for high quality steam and energy security including heat as well as power, as well as the necessity to have a successful SMR demonstration project. The industry also wants to partner experienced nuclear operators that will be responsible for operations.

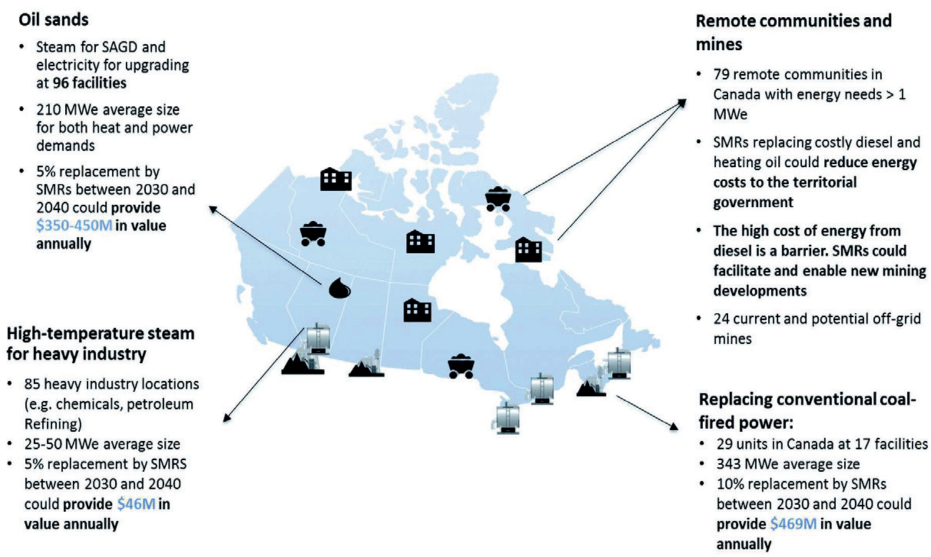


Figure 8: Domestic Market Potential.
Credit: Canadian Small Modular Reactor Roadmap Steering Committee.

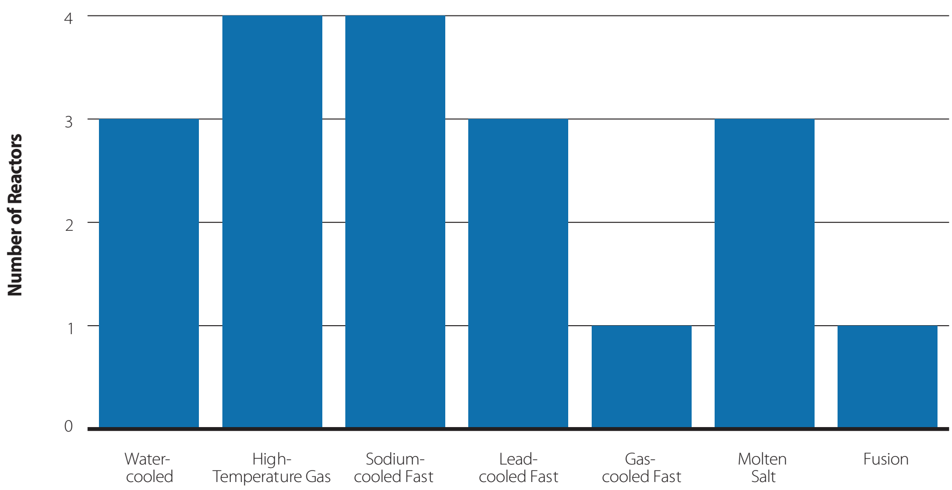


Figure 9: Proposed demonstration reactors. RFEOI Summary Report.
Credit: Canadian Nuclear Laboratories.

The Roadmap concludes that, as a first mover in the high-tech innovation sector, Canada could secure in-country jobs, Intellectual Property and supply chains. Ontario's CAN$26 bn investment in reactor refurbishments will strengthen a robust supply chain, while the CAN$1.2 bn federal investment in CNL infrastructure will boost Canada's leadership in nuclear science and technology.

Canada also has the potential to take a leadership position on policy and standards in the international community and use its strategic influence to deliver on climate change and clean energy commitments.

Canada's SMR development program is advancing at a significant rate, as developers respond to ambitious research initiatives and a variety of deployment opportunities. Having an internationally recognised regulator with a framework that accommodates new technology and a well-established nuclear supply chain are also attractive to developers.

Priorities for reactor technology developers are the economics of SMRs and securing the financing for a prototype or demonstration plant.[22] A total of 19 different SMR concepts were put forward as demonstration candidates, with 16 of these keen to site their reactor at a CNL facility and three considering commercial deployment in Canada.

The CNSC offers a Pre-Licensing Vendor Design Review (PLVDR) service to domestic and international developers considering applying for a license to build and operate a new NPP and assesses the plant design based on the vendor's reactor technology.[23] The review does not guarantee approval of a design.

Phase 1 of the PLVDR takes around 12-18 months to complete and indicates whether the design is set to meet Canadian regulations, codes and standards, with Phase 2 taking a further 24 months and looks at potential fundamental barriers to licensing. Phase 3 allows the vendor to follow up on finding from Phase two. According the CNSC, ten developers have applied for a PLVDR:

Terrestrial Energy Inc.	**Phase 1 review start April 2016 (completed)**
Integral Molten Salt Reactor (ISMR) 200MW	**Phase 2 review start December 2018**

The ISMR is the first SMR design to complete the PLVDR. After Phase 2 is completed (around end 2020), the first plant site and first customer will be selected in the early 2020s. Licensing and construction will follow, taking the timeline to the first operational deployments to the late 2020s.[24]

In addition to electricity generation, the ISMR also supplies a 600C heat from hot molten

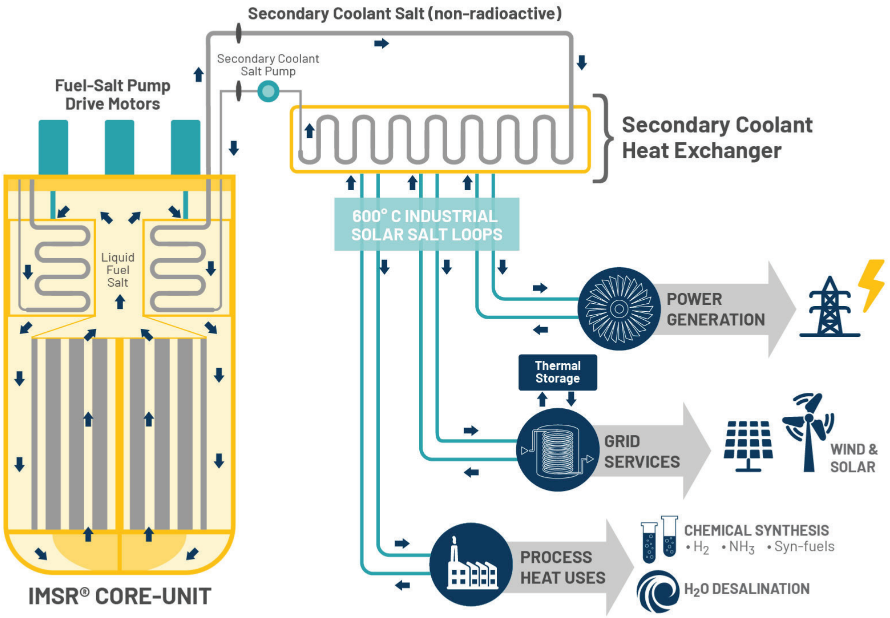


Figure 10: The ISMR: How it Works.
Credit: Terrestrial Energy Inc.

salt that widens its applications to include energy-intensive processes such as desalination, hydrogen production, petrochemical refining and clean synthetic transport fuels. The ISMR can also partner renewables as it rapidly load-follows thus remove the need for grid storage.

Ultra Safe Nuclear Corporation	**Phase 1 review start December 2016**
MMR-5 and MMR-10 High Temperature Gas	**Phase 2 review pending late 2018**

The Micro-Modular Reactor (MMR) is a cogeneration High Temperature Gas-Cooled Reactor (HTGR) that generates electricity and processes heat and has an operational lifespan of 20 years.[25] Target markets include mining concerns and remote communities in northern Canada.

LeadCold Nuclear Inc.	**Phase 1 review start January 2017 (on hold)**
SEALER Molten Lead 3MW	

Figure 11: The SEALER.
Credit: LeadCold Nuclear Inc.

The Swedish Advanced Lead Reactor (SEALER) designed to produce 3M of electrical power for up to 30 years without the need to refuel.[26] It is intended to replace diesel-power in off-grid locations and meet demands for commercial power production in the Arctic regions including remote communities living in the Nunavut and North-West Territories and the mining industry. LeadCold aims to have a construction license in Canada by the end of 2021 and to have its first SEALER unit ready for operation in 2025.[27]

Advanced Reactor Concepts Ltd.	**Phase 1 review start Fall 2017**
ARC-100 Liquid Sodium	

The ARC-100 is designed for a long lifespan with proliferation-resistant fuel cycle in order to open new markets to nuclear energy[28] Factory fabricated modular components can be shipped to the plant site for rapid assembly. Key applications include distributed power, base load and load-following ability and water desalination with the Shale Oil Extraction industry a target customer.

In July 2018, ARC agreed to collaborate with New Brunswick Power in exploring the potential future deployment of the ARC-100 at the Point Lepreau NNP with a view to deploying at other sites across Canada and internationally.[29]

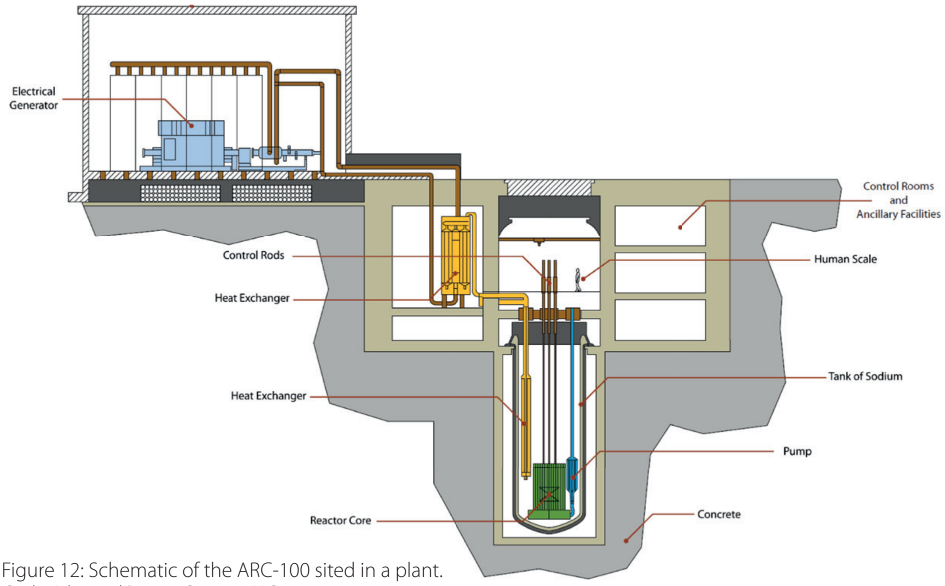


Figure 12: Schematic of the ARC-100 sited in a plant.
Credit: Advanced Reactor Concepts LLC.

Moltex Energy **Phase 1 and 2 reviews start December 2017**

Stable Salt Reactor Molten Salt 300MW

The Stable Salt Reactor (SSR) replaces solid pellets used in conventional fuel assemblies with molten salt fuel.12 The reactor is a low cost peaking power plant rather than a base-load operation as it outputs its heat as a stream of molten nitrate salts that can be stored in large volumes at low cost.

The Wasteburner (SSR-W) is fuelled with very low purity reactor-grade plutonium recycled from stocks of spent uranium oxide fuel produced by a Waste to Stable Salt process. Thus, the design has applications in countries with significant stocks of spent nuclear fuel and meets a demand for a low carbon power that complements intermittent renewable energy sources.

In July 2018, Moltex Energy was selected by New Brunswick Energy Solutions Corporation and New Brunswick Power to progress the development of the SSR-W with a view to deploying the SMR at the Point Lepreau NPP before 2030.[30]

SMR, LLC. (A Holtec International Company) **Phase 1 review start July 2018**

Pressurized Light Water SMR-160

The preliminary SMR-160 design is due to be completed in 2019 with completion of pre-application activities and starting commercial licensing scheduled for 2020.[12] Initial operation of the first deployed reactors is expected by the mid-2020s.

Electricity production is the primary application although there is optional cogeneration equipment capacity for hydrogen generation, district heating and desalination. Capable of isolated operation, the SMR-160 is appropriate for off-grid locations and areas with unstable power grids.

In February 2018, Holtec International, SMR LLC., Global Nuclear Fuel and GE Hitachi Nuclear Energy signed a Memorandum of Understanding (MoU) to develop, design, license, deploy and service globally the SMR-160.[31]

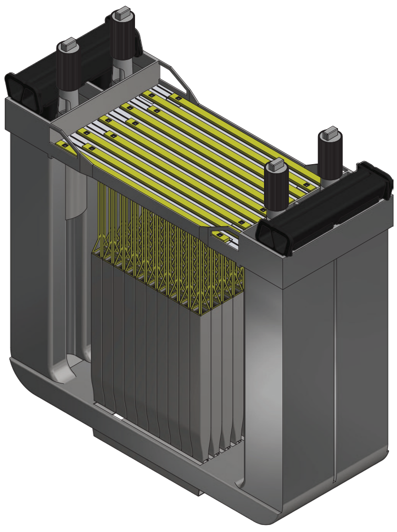


Figure 13: Moltex SSR Module.
Credit: Moltex Energy

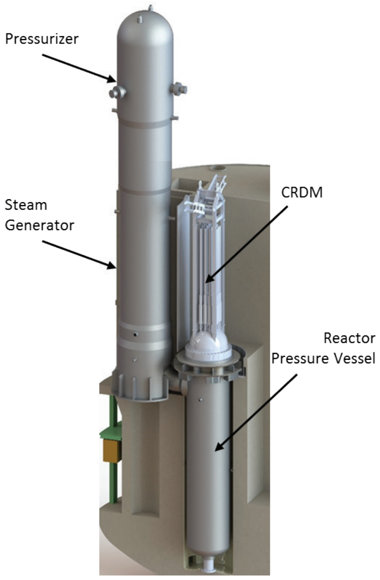


Figure 14: SMR-160 reactor.
Credit Holtec International, USA.

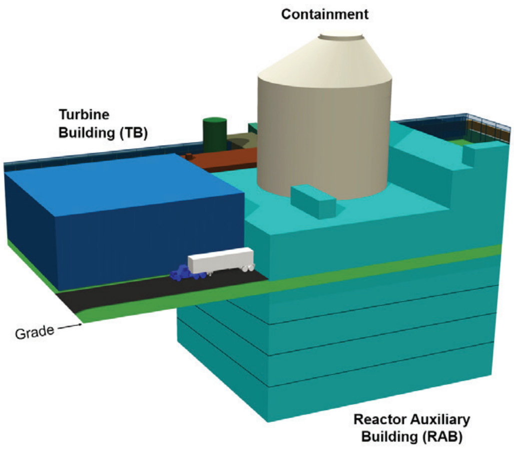


Figure 15: SMR-160 reactor island.
Credit Holtec International, USA.

Westinghouse Electric Company, LLC.	**Phase 2 review start pending early 2019**
e-Vinci Micro Reactor up to 25MW	

The e-Vinci Micro Reactor is designed energy consumers in remote locations as it aims to create affordable, reliable sustainable power that requires minimal maintenance and, with an operational lifespan of more than 10 years, refuelling is infrequent.[32]

Figure 16: e-Vinci micro-reactor.
Credit: Westinghouse Electric Company, LLC.

According to the Westinghouse e-Vinci roadmap, the first major milestone is developing a full-scale electrical demonstration unit by 2019. A system integral test with nuclear fuel will be constructed and demonstrated to quality the reactor for commercial deployment by 2024.[33]

NuScale Power, LLC.	**Phase 2 review start April 2019**
NuScale IPWR 50MW	

The NuScale Power Module (NPM) can be deployed in 50MW module increments up to a 12-module (600MW) configuration of a single plant.[34] The flexibility facilitates diverse markets from powering urban areas to smaller communities in remote locations. The NPM also has several applications including desalination, as well as base-load flexibility that allow integration with renewables.

In 2017, NuScale became the first developer to submit its Design Certification (DC) application to the US Nuclear Regulatory Authority (NRC). The NRC completed its Phase 1 review of the DCA in 2018 and DC approval is expected in 2022. NuScale is targeting 2026 for its first commercial and operational plant in Idaho, US.12

In November 2018, NuScale announced that it had signed a MoU with Bruce Power L.P. to develop a business case to bring NPM technology into the Canadian market.[35]

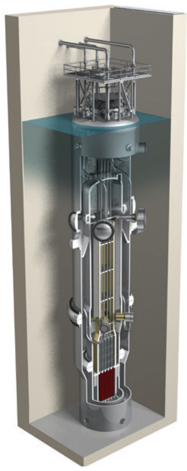


Figure 17: NuScale Power Module in cross section.
Credit: NuScale Power, LLC.

Figure 18: NuScale Power plant schematic.
Credit: NuScale Power, LLC

URENCO	**Phase 1 review start to be determined**
U-Battery High-Temperature Gas 4MW	

The U-Battery project was initiated in 2008 by URENCO, with the concept design developed by the Dalton Nuclear Institute, University of Manchester (UK), and the Technology University of Delft (The Netherlands). A U-Battery demonstration unit is planned for operation by 2026. A single unit produce 10MWt that can be delivered in a cogeneration configuration generating up to 4MW or 750C process heat.[36]

Target markets are industrial power and off-grid locations. Applications of U-Battery include power and heat supply to heavy industry, desalination and hydrogen generation for hydrogen-powered vehicles. In 2017, URENCO signed a MoU with Bruce Power to accelerate the development, licensing and deployment of U-Battery across Canada.

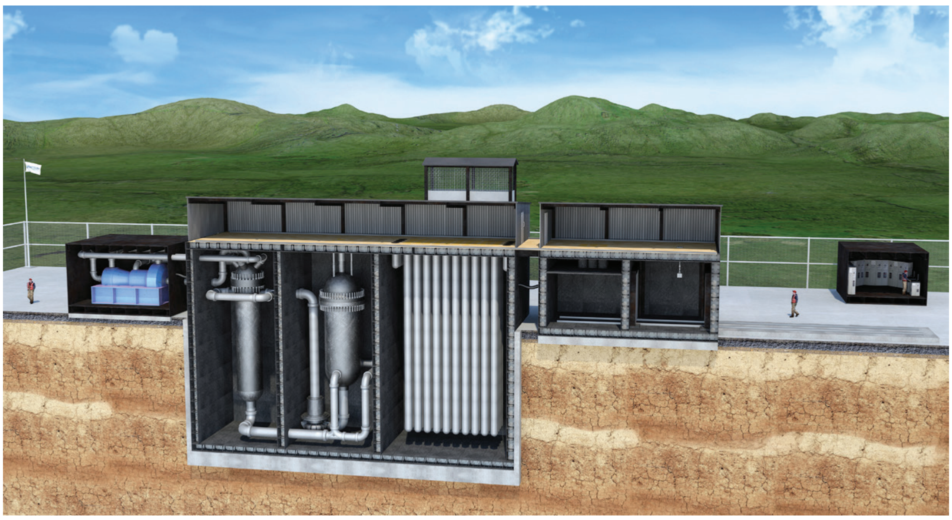


Figure 19: U-Battery reactor and plant schematic.
Credit U-Battery.

StarCore Nuclear	Phase 1 and 2 reviews start to be determined
StarCore Module High Temperature Gas 10MW	

A standard module of this HGTR has a five-year lifecycle, produces 20MW / 36MWt that expands to 100MW, and is capable of base-load and load-following generation.[37] StarCore Nuclear will build, own, operate and decommission each plant, and customers will execute a power purchase agreement. The module is designed for remote communities, mining and refining operations, as well as back up for renewable power.[38]

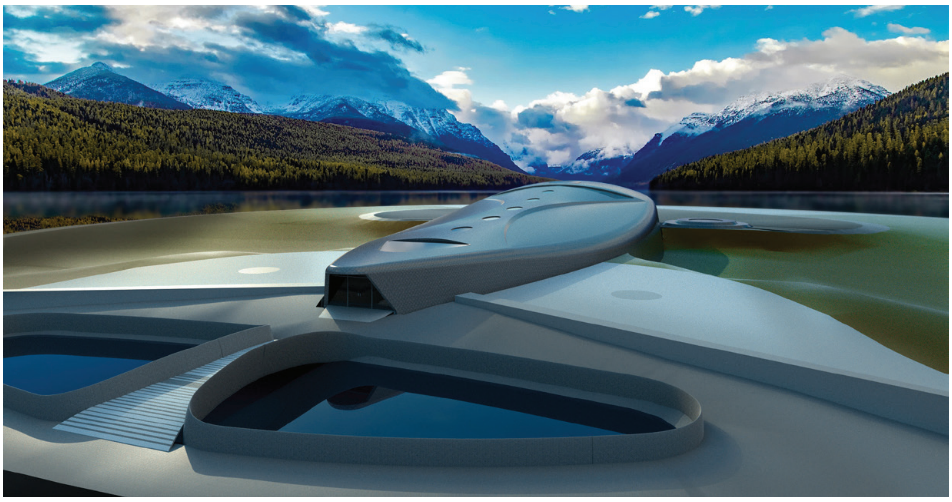


Figure 20: StarCore plant view schematic.
Credit: StarCore Nuclear (Canada)

People's Republic of China

According to the China Nuclear Energy Association (China NEA) electricity consumption in 2015 totalled 4,100 KWh, more than quadruple the total in 2000.[39] Coal is the primary generator of power accounting for 74.37%, with 17.79% generated by hydroelectric power and 3.56% from nuclear power.

China contributes 23.75% of the world's total GHG emissions.[40] In its INDC submitted to COP21, China pledged to peak its CO2 emissions by 2030, with 'best efforts' to peak earlier. In addition, it pledged to cut emissions per unit of GDP by 60-65% on 2005 levels by 2030, which would potentially put emissions on course to peak by 2027.

In recognition that China's energy consumption has been dominated by fossil fuels, the government set a target of 15% of primary energy consumption derived from non-fossil fuels by 2020 rising to 20% by 2030. Power generation by renewable and nuclear energy, as well as natural gas, will be gradually increased.[39]

By the end of 2016, 35 NPP units were operational and further 21 units were under construction. According to China's 13th Five-Year Plan set out in 2016, 30 million KW of new nuclear builds (NNB) will come online bringing the total installed KW nuclear power to 58 million by 2020. The total number of NNB units will have reached 25-30 with an annual investment of RMB 100 million.

Several nuclear reactors have been in development in efforts to meet the government's energy policies and goals. SMRs including the HTR-PM (211 MW / 250MWt), ACP100 (125MW / 385MWt), CAP200 (200MW / 660MWt) and ACPR50S (50MW / 200MWt) are part of China's nuclear development program.[12]

The gas-cooled High Temperature Reactor - Pebble-bed Module (HTR-PM) SMR has been developed by the Institute of Nuclear and New Energy Technology (INET) at Tsinghua University

Figure 21: HTR-PM reactor.
Credit: Professor Yujie Dong, Nuclear Engineering, Tsinghua University

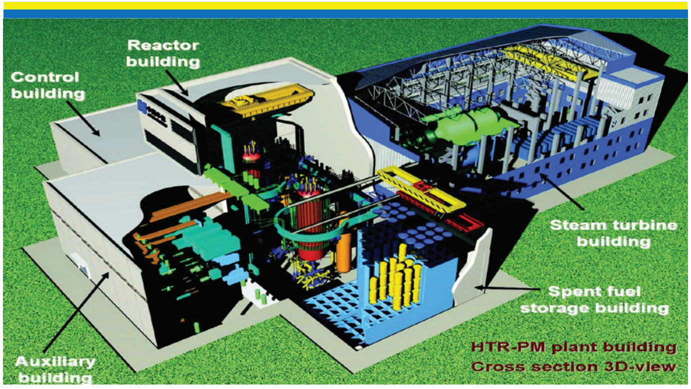


Figure 22: HTR-PM plant schematic.
Credit: Professor Yujie Dong, Nuclear Engineering, Tsinghua University

in cooperation with CHINERGY and Shandong Electric Power Engineering Institute. It is in an advanced stage of construction and is due to start power generation in 2019.[12,41]

Work on the conceptual design began in 2001 and implementation planning was approved in 2008 after completion of a feasibility study.[41] The basic design of the demonstration plant was also completed in 2008, with approval of the preliminary safety analysis report (PSAR) by the National Nuclear Safety Administration (NNSA) in 2009.

In 2008, excavation of the HTR-PM site began in Rongchen City, Shandong Province, in preparation for the construction of the nuclear island buildings. In 2016, the two reactor pressure vessels (RPV) were installed, with the first ceramic internals installed and graphite pebbles loaded a year later in 2017. By December 2017, the head of the first RPV was in place.

The China National Nuclear Corporation (CNNC) began construction on its commercial fuel plant in 2013 and had produced 300,000 fuel pebbles by December 2017. Next steps are to deploy a six-module 600MW unit coupled to one steam turbine that would supplement electricity generation by PWRs. These NPPs can then be a viable replacement for coal-fired power plants.

In 2010, the CNNC also began development of the ACP100 IPWR in collaboration with Nuclear Power Institute of China (NPIC) and China Nuclear Power Engineering Co. (CNPE).[12] The plant design accommodates the installation of one to eight modules, depending on the required electrical and/or thermal output.

The ACP100 is at an advanced design stage and development is in a near-term deployable timeframe.[42] It was the first SMR to complete the IAEA Generic Reactor Safety Review (GRSR) in 2016 and, a year later in 2017, the basic design was completed and Changjiang nuclear power site on the island province of Hainan was chosen to build the first-of-a-kind (FOAK) ACP100 demonstration project. The PSAR was completed in 2018.[12]

The ACP100 is designed for deployment in remote areas that have limited energy supply options or a lack of industrial infrastructure. Applications include cogeneration, district heating, steam production or desalination.

Potential domestic markets include the Three Northeastern Provinces (Liaoning, Jilin and Heilongjiang) where there is demand for heat and power, coastal provinces such as Zhejiang, Fujian and Hainan to address demand for power, steam and desalination, as well as supplying power and steam to provinces including Hunan and Jiangxi. A floating plant in the Bohai Sea is also being considered. Overseas markets include North Africa and the Middle East to meet these regions' demand for power, heat, steam and desalination of sea water.

Figure 23: The ACP100 reactor.
Credit: China National Nuclear Corporation and Nuclear Power Institute of China

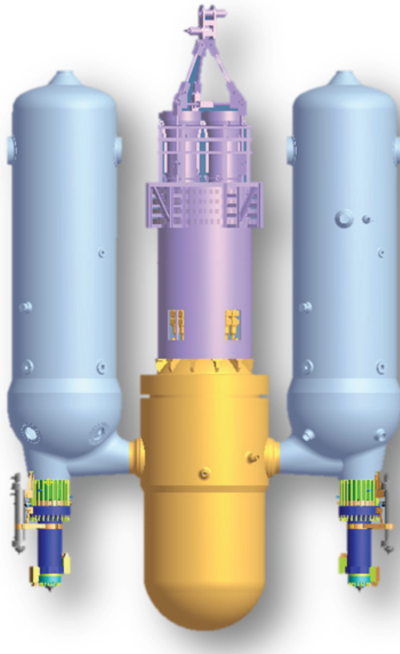


Figure 24: The CAP200 reactor.
Credit: The Shanghai Nuclear Engineering Research and Development Institute

The conceptual design of the CAP200 reactor, developed by the Shanghai Nuclear Engineering Research and Development Institute (SNERDI) in collaboration with the State Nuclear Power technology Company (SNPTC), was completed in 2015.[12]

The design is based on the PWR while adopting SNERDI's passive engineered safety features. CAP200 applications include nuclear cogeneration and can be deployed to supplement large NPPs, as well as replacing retired fossil-fuel fired power plants in urban areas.

In 2009, the China General Nuclear Power Corporation (CGN) began a conceptual study of its floating, off-shore ACPR50S reactor with the overall design completed in 2014.[12] In late 2015, the SMR was approved for entry into the government's 13th Five Year Plan as part of a program to develop experimental reactors.[43]

The PSAR review is scheduled to be completed in 2018-2019, along with starting construction planning and obtaining permits to build. The plant construction and installation of the ACPR50S is expected to be completed by 2010, with commissioning and connection to the grid due a year later in 2021.[12]

The ACPR50S is designed for deployment in marine environments such as islands, off-shore oil drilling platforms in the Bohai Sea, nuclear powered shipping and deep-water oil and gas development in the South China Sea.[43] It offers a stable, economical and green energy source that can also supply heat and has desalination applications that can deliver fresh water to island residents and an off-shore work force.

Marine-based SMRs has different siting requirements to land-based ones, including the need to consider navigation safety and running aground.[44] Severe weather conditions will also need to be avoided and appropriate sites for mooring will also need to be considered. Legalities surrounding the ocean-going transportation of nuclear materials in international waters are also being reviewed.

Russian Federation

Russia is the world's largest producer of crude oil and the second largest producer of dry natural gas.[45] As Russia's economic growth is driven by energy exports, it is also a major exporter of oil and natural gas. In 2016, electricity production was 1,091 TWh, of which 48% was generated from gas, 18% from nuclear, 17% from hydroelectric and 16% from coal.[46]

In its 2015 INDC at COP21, the Russian Federation pledged to limit its GHG emissions to 25-30% below 1990 levels by 2030, with this target including the contribution of its national forests as carbon sinks.[47] The pledge is also contingent upon the IDNCs of major GHG emitter nations and the outcome of UN climate negotiations.

Currently, there are 35 operational reactors with a total capacity of 26,983MW.[46] Russia's latest Federal Target Program aims to increase the share of nuclear power in electricity generation by 25-30% by 2030 and has 11 units under construction due to be completed in that timeframe.[48] Russia is still understood to be steadily expanding the role of nuclear energy, which includes the development of new technologies underpinned by fast reactors to close the fuel cycle.

Russia has a significant SMR program, with three reactors developed by Afrikantov OKBM (a subsidiary of Rosatom) at near-term deployment: the KLT-40S, RITM-200 and RITM-200M. (6) The KLT-40S is a floating power unit is in an advanced stage of construction and due to start operations between 2019 and 2022. Four RITM-200 reactor units have already been installed in the Sibir and Arktika icebreaker vessels, which are scheduled to go into service in 2020.

Afrikantov OKBM KLT-40S (35MW / 150MWt)

KLT-40S PWR was developed for deployment on a floating nuclear power plant, particularly icebreakers that sail in severe weather conditions. The reactors are assembled, tested and readied for operations in the shipyard and can be moored in any coastal region.[12] Target markets and applications include cogeneration of power and heat to remote, off-grid communities, power generation on oil rigs and desalination.

Rosatom announced that, after completing mooring tests in May 2018, the floating NPP Akademik Lomomosov was transported from Murmansk to an Atomflot Federal State Unitary Enterprise site where it loaded nuclear fuel. The Lomomosov is expected to replace the NPPs Bilibino and Chaunskaya that are scheduled for decommissioning in 2019-2021.[49]

Afrikantov OKBM RITM-200 (50MW / 175MWt)

The RITM-200 is on schedule for near-term commercial deployment, with its optional modular assembly able to supply power to meet lower demand of 100MW or to scale up to meet higher demands of 300MW.48 Originally designed for deployment on icebreakers with four units already installed on two vessels, land-based RITM-200 units are being developed for generating electricity, district or industrial heating, as well as desalination.

The conceptual design for a land-based plant was completed in 2018 and the detailed design is expected in 2020. First construction is due to start in 2022, with commissioning expected in 2025.

South Africa

In 2016, electricity production totalled 253TWh, with 90% produced from coal, 6% from nuclear and 4% from solar, wind and hydroelectric power.[50] Eskom Holdings SOC Ltd owns South Africa's only NPP, the Koeberg plant that has two PWR reactors with a combined capacity of 1,830MW. The reactors are scheduled to shut down 2024-2025. The South African government abandoned plans for NNBs that would have generated an additional 9,600MW by 2030.

In its INDC pledge submitted to COP21, South Africa acknowledged its heavy dependency on coal while highlighting the challenges it faced as developing nation to make any transition to a low-carbon society and economy.[51] As such, South Africa is taking a peak, plateau and decline approach to reducing its GHG emissions. Emissions will aim to peak in the 398-614 million tonnes CO2 equivalent range between 2020 and 2025, and then plateau until around 2035 before levels begin to fall.

South Africa is only country in Africa that has an NPP due to significant obstacles to faced by many developing nations looking to develop a nuclear energy programme. The IAEA advises that grid capacity should be ten-fold the capacity of any planned NPP and few countries in Africa currently have such grid capacity. There are also challenges securing the financing and investment necessary to build, operate and decommission an NPP, as well as the required regulatory and safety oversight.[52]

The smaller size, capacity, passive safety features and simplified design of SMRs could provide a feasible option for financing, constructing and operating a unit in African countries. SMRs are already being designed to meet the power, heat and desalination needs of remote, isolated communities in northern Canada and these designs could be appropriate for small off-grid communities in Africa living in similar environments. SMRs could be built where needed without grid infrastructure or capacity and units added as required to meet increasing energy demand.[53]

Eskom had been considering developing a pebble-bed design SMR since the early 1990s, an idea that was shelved due to financing challenges and demand for large NPP.50 In 2016 Eskom began looking again at the design with a view to simplifying it and adding in features that would allow heat process applications and follow-on loading with intermittent renewables.

A new concept emerged for an advanced high-temperature reactor (AHTR-100) generating 50MW / 100MWt to be deployed in the 2030s. Version 1 concept of the AHTR-100 was completed in 2017 and R&D activities continued throughout 2018.[12]

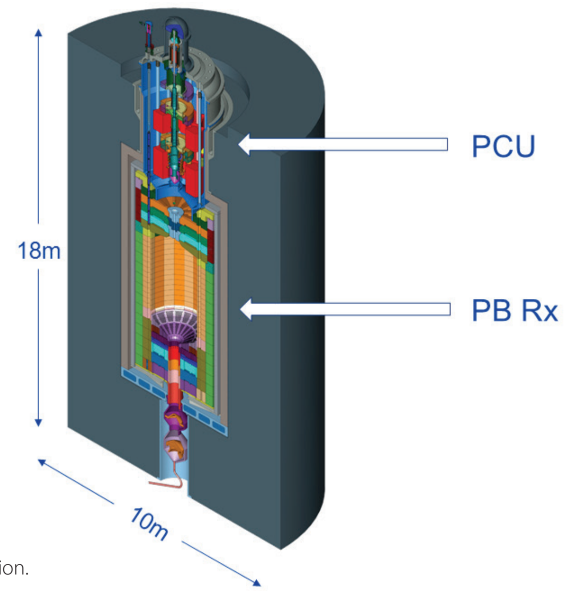


Figure 25: AHTR-100 in cross-section.
Credit: Eskom Holdings SOC Ltd

HTMR Ltd, a sister company of Steenkampskraal Thorium Ltd (STL) that owns the rights to the thorium at the Steenkampskraal monazite mine, is designing the High-Temperature Modular Reactor, HTMR-100.[54] The HTGR pebble-bed reactor has a thorium or uranium fuel cycle that generates 35MW / 100MWt electricity and high quality steam. Target markets are remote areas or islands and applications include hydrogen production, fertilizer production, desalination, metals processing and process heat in petrochemical plants and oil refineries.[55] The conceptual design is scheduled to be completed in 2019.[12]

United Kingdom

In 2016, gross electricity production totalled 336 TWh, with gas contributing 42%, renewables 21.4%, nuclear 21%, gas 9% and hydroelectric 8%.[56] Fifteen reactors, seven twin-unit advanced gas-cooled reactors (AGR) and one PWR, remain operational with a combined 9.5GW capacity. The AGRs are scheduled shut down between 2023 and 2030, and PWR is expected to close in 2025. Eight NNBs with a combined capacity of 12.2GW are planned as replacements for the ageing fleet.

The European Union, of which the UK is one of 28 members*, contributed 8.97% of the world's total GHG in 2012.[40] In its INDC under COP21, the EU pledged to reduce domestic GHG emissions by at least 40% by 2030. A 2018 report by the UK Committee on Climate Change stated the country's GHG emissions had been cut 43% compared to 1990 levels, which put the UK on target for a reduction of at least 80% by 2050.[57] Since 2012, 75% of emission reductions were made in the energy sector.

The UK Nuclear Industry Council proposed a Nuclear Sector Deal to the UK Government in 2018, which included a call for clarity on the future of SMRs.[58] In response, the Government is setting out a new framework to prepare for SMR R&D, supply chain development and regulator support.[59] This support is designed to challenge the industry to propose technical and commercially viable propositions for the deployment of new reactors, which would attract investors and be cost competitive additions to the energy system.

The Department for Business, Energy and Industrial Strategy (BEIS) is to invest GBP£44m in an advanced modular reactor (AMR) feasibility and development project.[60] Eight vendors have been awarded contracts of up to GBP£300,000 to produce feasibility studies under phase one of the project.[25] Among the technology that has SMR potential are SSRs (Moltex Energy Limited), SEALER (LeadCold), U-Battery (U-Battery Developments Ltd), ARC-100 (Advanced Reactor Concepts LLC.) and MMR (Ultra Safe Nuclear Corporation).

According to BEIS, nuclear energy has an important role in the transition to a low-carbon economy and SMRs offer the potential to reduce costs though modularization while leveraging skills and expertise in the UK.[61] In addition to power generation, target applications include power peaking and load following, industrial grade heat, low grade heat, hydrogen production and desalination.

A GBP£4.5m study is set to explore the potential of SMRs with a view to mature technologies deployed in the UK by 2030. BEIS acknowledges that more work will be needed to ensure existing licensing and design assessment process do not present unnecessary barriers to the commercial deployment of SMRs.

The regulatory process could take six or more years prior to construction and comprises three phases and, in 2017, the UK Government announced it would provide regulators GBP£7m to build capability and capacity.[62] Pre-licensing requires the Office for Nuclear Regulation (ONR) and Environment Agency (EA) to carry out the Generic Design Assessment (GDA). Next, a suitable site is assessed and finally regulators continue to monitor during construction.

The UK SMR Consortium, led by Rolls-Royce, is developing the power plant design for the UK.[63]

Figure 26: Artist's impression of the UK SMR consortium's power station design.
Credit: Rolls-Royce,

A study by the UK National Nuclear Laboratory suggests demand from the domestic market will be around 7GW by 2035. The international market could be GBP£400m by 2035 and, in 2017, Rolls-Royce signed an MoU with Jordan to conduct a feasibility study of the construction of its SMR.[64]

The UK 400-450MW SMR is based on a PWR design being primarily developed for electricity generation with heat generation and co-generation applications.[65] The planned FOAK commercial operation is in 2030.

United States of America

In 2017, electricity generation totalled 4,015TWh with 32% derived from natural gas, 30% from coal, 20% from nuclear, 7.6% from hydroelectric and 7.6% from renewables (solar and wind).[66] The main energy consuming sectors are electric power (38.1%), transportation (28.8%), industrial (22.4%), residential (6.2%) and commercial (4.5%). The USA has a population of just over 325 million and annual electricity demand is projected to increase to 5,000 TWh in 2030.

The US contributes 12.1% of the world's total GHG emissions.[40] In its INDC submitted to COP21, the US pledged an economy-wide target of reducing its greenhouse gas emissions by 26-28% below its 2005 level in 2025, with best efforts to reduce its emissions by 28%.[67] The US plans to withdraw from the Paris agreement and not meet this pledge.

The USA is the largest producer of nuclear power and accounts for more than 30% of the world's total nuclear generation of electricity.[66] A total of 98 NPPs operation in 30 states by 30 different utility companies, although the average age of these reactors is 37 years and NNBs have been put on hold for more than 30 years. No more than two units will be online by 2021. The dominant technology is the Light Water Reactor (LWR), which is deployed in units with 1,000MW capacity.[68]

In 2018, the US Department of Energy (DOE) announced USD$60 million research and development (R&D) funding for advanced nuclear technology.[69] The DOE awarded USD$40 million matched funding to finalize NuScale's NPM design and ensure the supply chain is ready for the first commercial operation in 2026. This is NuScale's third DOE award, as it successfully bid for funding in 2013 and 2015 to develop the technology and prepare a combined Construction and Operating License Application (COLA) for the Carbon Free Power Project (CFPP) of its first customer, the Utah Associated Municipal Power Systems (UAMPS).[70]

The NRC has engaged in pre-application activities with SMR (LWR) developers and completed


Figure 27: SMR reactor.
Credit: Westinghouse Electric Company, LLC

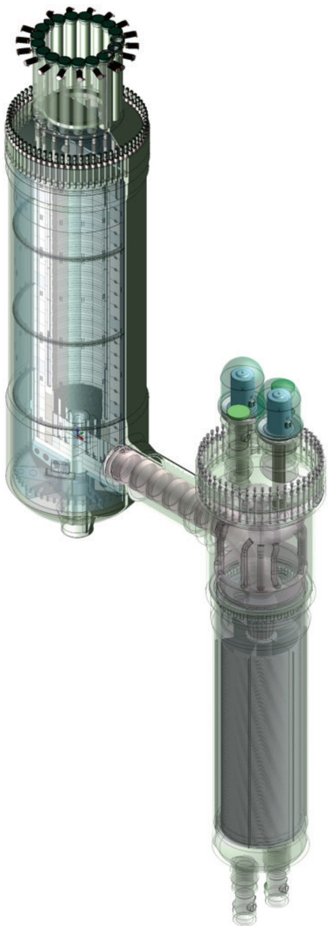


Figure 28: Xe-100 reactor and steam generator.
Credit: X-energy, LLC.

its Phase 1 review of NuScale's 50MW NPM.[71] A Pre-Application has also been submitted by SMR Inventec, LLC, (a Holtec International Company) for its SMR-160. Both SMRs are discussed above in the section on Canada.

Other US developers are also actively pursuing designs with a view to commercial deployment in the domestic and overseas markets:

Westinghouse Electric Company, LLC. **Westinghouse SMR (<225MW / 800MWt)**

The SMR is an IPWR that will target markets where there is energy insecurity. It has the ability to provide process heat, district heat and has off-grid applications such as generating power for liquid transportation of fuel from resources such as oil shale and coal-to-liquid applications.[72] The conceptual design was completed in 2015 and the company focus is on finalising the design in preparation for submitting a DC application to the NRC.

FRAMATOME INC. **SC-HTGR (272MW / 625MWt)**

The Steam Cycle High-Temperature Gas-Cooled Reactor (SC-HTGR) developed for applications including industrial process heat, hydrogen production and moderate electricity generation applicable for micro-grids and load-following.[73] The steam cycle will also facilitate cogeneration of electricity and heat process, which could be supplied to major industrial processes in petrochemical, ammonia and fertilizer plants, as well as refineries. In 2017, the pre-conceptual design plant technical requirements documents were completed.[12]

X-energy, LLC. **Xe-100 (75MW / 200MWt)**

The Xe-100 is a pebble-bed HTGR deployed as a four-module plant generating approximately 300MW.[74] Designed for a 60-year operational lifecycle, the Xe-100 can be operated as a base-load or load-following power source and accommodates a diverse range of applications for electricity production, chemical processes, desalination and hydrogen production. Commercial deployment is targeting the mid- to late-2020s.

The conceptual design is due to be completed in 2019, which will be followed by submitting the DC application to the NRC in 2021.[12] Construction is due to start in 2025. In 2017, X-energy signed an MoU with the Jordan Atomic Commission to explore the potential for deploying the Xe-100 in Jordan.[75]

General Atomics **EM2 (265MW / 500MWt)**

The Energy Multiplier Module (EM2) is a high-temperature helium-cooled fast reactor that uses existing nuclear reactor waste as fuel and is being developed for electricity generation and high temperature use.[12,76] The reactor converts fertile isotopes to fissile and burns them over a 30-year core life. The unit is designed as a modular, grid-capable power source.

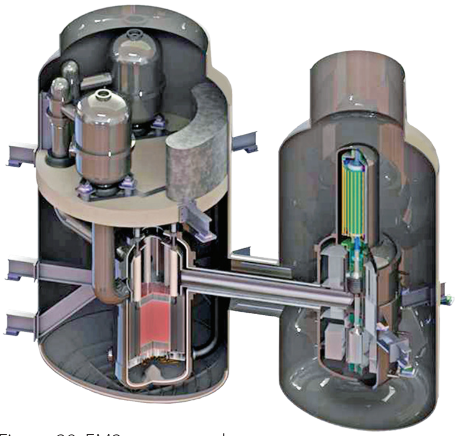


Figure 29: EM2 reactor pods.
Credit: General Atomics

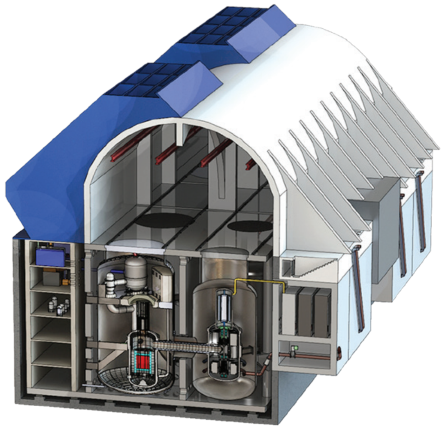


Figure 30: EM2 reactor housing.
Credit: General Atomics

Argonne National Laboratory **SUPERSTAR (120MW / 300MWt)**

The Sustainable Proliferation-resistance Enhanced Refined Secure Transportable Autonomous Reactor (SUPERSTAR) used molten lead as a coolant, has load following capability and is being developed for international or remote deployment on growing electrical grids such as those found in developing nations.[77]

Flibe Energy, Inc. **Liquid Fluoride Thorium Reactor (250MW / 600MWt)**

This Molten Salt Reactor (MSR) is being developed to produce electricity at low cost by efficiently consuming thorium.[12] The design is still in an early stage of development and licensing procedures have not yet started. In July 2018, Flibe Energy was awarded USD$2.6 million by the DoE to fund its work on Fluorination of Lithium Fluoride-Beryllium Fluoride (FLiBe) Molten Salt Processing.[78]

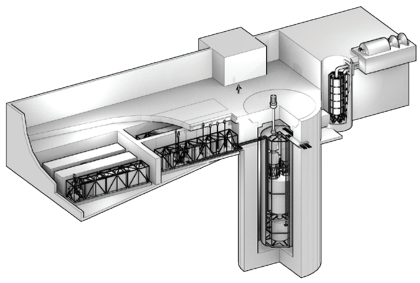


Figure 31: The Liquid Fluoride Thorium Reactor.
Credit Flibe Energy

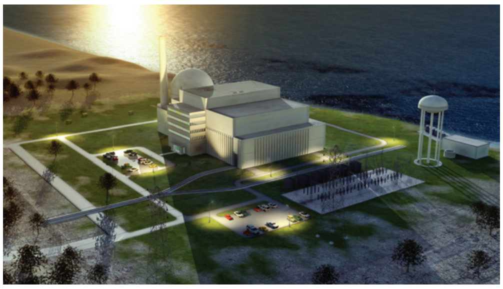


Figure 32: The Liquid Fluoride Thorium Reactor plant schematic.
Credit Flibe Energy

University of California, Berkeley **Mk1 PB-FHR (100MW / 236MWt)**

The Pebble-Bed Fluoride Salt-Cooled High Temperature Reactor is designed to produce 100MW base-load electricity, a power output that can be increased to 242MW using gas co-firing for peak generation.[12] This capability provides a new value proposition, as the Mk1 PB-FHR can provide flexible grid support services to meet rising demand for peak power.

A 12-unit plant would produce 1,200MW of baseload electricity and up to 2,900MW when using natural gas co-firing during periods of peak electricity demand.[79] Further work is being undertaken into the plant design, as well as devising licensing strategies for deploying commercial prototypes in the US and internationally.[12]

Elysium Industries, USA and Canada **MCSFR (50MW / 100MWt)**

The Molten Chloride Salt Fast Reactor ((MCSFR) has the capability to generate up to 1,200MW.[80] The modular construction allows deployment in new and existing nuclear markets. As the preferred fuel is spent nuclear fuel, primary initial target countries are the US, Canada, UK, and Japan where there are significant quantities of spent fuel that need to be consumed.[12]

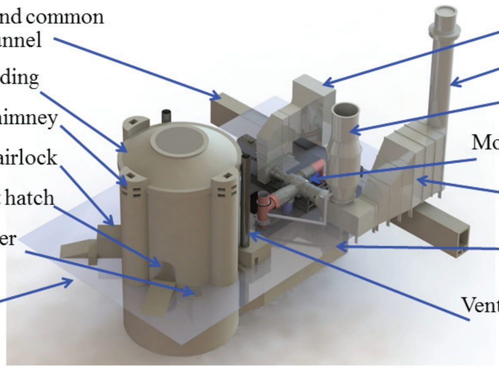


Figure 33: Plan of Mk1 PB-FHR plant.
Credit: Thermal Hydraulics Laboratory, Department of Nuclear Engineering, U.C. Berkeley

The pre-conceptual design is near completion and large scale testing is aiming to start in 2020. BA feasibility study conducted between 2020 and 2025 will involve building a very low power prototype that would facilitate fission testing to begin in 2025. Licensing is scheduled for 2021-2027, with commercial operation aiming for 2030.

Elysium was awarded USD$3.2 million under the 2018 DOE round to fund the development of the computational fluid dynamics models needed to stimulate and optimize the flows of chloride molten fuel in a reactor and heat exchangers for the MCSFR design.[81]

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Acronyms

AAICI	Agencia Argentina de Inversiones y Comercio Internacional
AECL	Atomic Energy of Canada Limited
AGR	Advanced gas-cooled reactor
AMR	Advanced modular reactors
ANSTO	Australian Nuclear Science and Technology Organisation
ARIS	(IAEA) Advanced Reactors Information System
BEIS	(UK) Department for Business, Energy and Industrial Strategy
CANDU	Canadian Deuterium Uranium (reactor)
CAREM	Central Argentina de Elementos Modulares
CFPP	Carbon Free Power Project
CGN	China General Nuclear Power Corporation
China NEA	China Nuclear Energy Association
CNEA	Comisión Nacional de Energía Atómica (National Atomic Energy Agency, Argentina)
CNL	Canadian Nuclear Laboratories
CNNC	China National Nuclear Corporation
CNPRI	China Nuclear Power Technology Research Institute
CNSC	Canadian Nuclear Safety Commission
CO2	Carbon dioxide
COLA	Construction and Operating License Application
COP21	United Nations Climate Change Conference (Paris 2015)
DC	Design Certification
DOE	(US) Department of Energy
EIA	(US) Energy Information Administration
EA	(UK) Environment Agency
FOAK	First-of-a-kind
GDA	Generic Design Assessment
GHG	Greenhouse gas
GRSR	Generic Reactor Safety Review
HTGR	High Temperature Gas-Cooled Reactor
HTR-PM	High Temperature Reactor- Pebble-bed Module
IAEA	International Atomic Energy Agency
ISMR	Integral Molten Salt Reactor
INDC	Intended Nationally Determined Contributions
INET	Institute of Nuclear and New Energy Technology
IPWR	Integral Pressurized Water Reactor
KSA	Kingdom of Saudi Arabia
LCOE	Levelized Cost of Electricity
LWR	Light Water Reactor
MCFR	Molten Chloride Fast Reactor
MoU	Memorandum of Understanding
MSR	Molten Salt Reactors
NDT	Non-destructive testing
NEA	Nuclear Energy Agency
NEI	Nuclear Energy Institute
NNB	New nuclear builds
NNSA	(China) National Nuclear Safety Administration
NOAK	Nth-of-a-kind
NPM	NuScale Power Module
NPP	Nuclear power plant
NPT	Non-Proliferation Treaty
NRC	(U.S) Nuclear Regulatory Commission

NRCan	Natural Resources Canada
OECD	Organisation of Economic Cooperation and Development
ONR	(UK) Office for Nuclear Regulation
PHWR	Pressurized Heavy-Water Reactor
PLVDR	Pre-Licensing Vendor Design Review
PRIS	(IAEA) Power Reactor Information System
PSAR	Preliminary safety analysis report
PWR	Pressurised Water Reactor
R&D	Research and development
RFEOI	Request for Expressions of Interest
RPV	Reactor pressure vessels
SC-HTGR	Steam Cycle High-Temperature Gas-Cooled Reactor
SMR	Small Modular Reactor
SNERDI	Shanghai Nuclear Engineering Research and Development Institute
SNPTC	(China) State Nuclear Power technology Company
SSR	Stable Salt Reactor
SSR-W	Stable Salt Reactor-Wasteburner
STL	Steenkampskraal Thorium Limited
UAMPS	Utah Associated Municipal Power Systems
WNA	World Nuclear Association

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