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Research Article

Global outlook on large-scale nuclear power development strategies

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Abstract

As of today, nuclear power together with hydropower provides three-quarters of global low-carbon electricity generation. Over the past 60 years since the time of its inception, the use of nuclear power has reduced CO_2 emissions by over 60 gigatonnes. There is no doubt that nuclear power can play a major, and maybe even a decisive role in decarbonizing the electricity sector, as it is evident from the current energy mix of some European countries, especially France, and major economic powers like the Unites States, Russia and South Korea. It is also evident that in most advanced economies nuclear power has entered a phase of gradual decline with little new investment coming into new projects, regardless of the world's desperate need for more low-carbon electricity. Although existing reactor and their corresponding fuel cycle technologies have enabled the global nuclear power fleet to reach ~ 400 GWe of net installed capacity, there is growing concern that the scale of NPP shutdowns expected in Europe and North America could offset new capacity additions in Asian markets. Theoretically, renewable energy could fill the void left by reactors taken offline but there is strong evidence that the potential of wind and solar for global decarbonization is limited by material, land and economic constraints. Large-scale renewable systems would also require massive energy storage capacity that would hamper economic sustainability of the energy supply for developing countries. Taking into account the potential benefits of developing nuclear power, some countries are determined to expand its share in their energy mix through technological innovation and application of new strategies, directed at improving or completely resolving current issues related to economics, environmental concerns or non-proliferation of nuclear weapons. There are many states in the world today pursuing some sort of nuclear power development. A limited number of countries envision expanding or transforming their nuclear energy system using truly game-changing strategies based on innovative reactor, fuel cycle and waste management technologies. The focus of this paper is to give an overview of the approaches to large-scale nuclear power development being applied today in Russia, China, USA and India.

Keywords

Nuclear power, development strategy, fast reactor, closed nuclear fuel cycle, Proryv Project

Russia

Today Russia can be considered as a well-established international leader in nuclear energy development, building NPPs not only in the Russian Federation, but on foreign soil as well. Russia's NPP total net installed capacity in 2021 reached 28,5 GWe with 38 reactors in operation and 3 under construction. An additional 35 units are under various stages of development and construction in foreign countries. Russia has extensive experience with

fast reactor technology, operating two commercial sodium-cooled fast reactors (BN-600, BN-800) with plans to expand its FR fleet in the future. Recently the country has achieved several milestones in advancing its innovative nuclear reactor portfolio. In 2020 Russia was the first country in the world to commission a floating nuclear power station – the Akademik Lomonosov, supplying heat to the Pevek port town and electricity to the regional Chaun-Bilibino power system. In June 2021 within the industry-wide "Proryv" project framework significant progress was made with construction starting on the 300 MWe lead-cooled BREST-OD-300 fast reactor as part of the Pilot Demonstration Energy Complex (PDEC) in Seversk, Russia's Tomsk region. Besides the aforementioned reactor, PDEC will feature on-site fuel fabrication and reprocessing facilities, which will in essentially demonstrate Russia's capability of closing the nuclear fuel cycle locally, within the confines of a nuclear power plant site.

The fundamental principles that constitute energy security based on analyzing previous experience gained from nuclear power development in the world were outlined in 2000 in the «Russian atomic energy development strategy up to the first half of the XXI century» document:

- Complete autonomy from natural resource availability;
- Increased share of renewable energy sources (mainly nuclear energy based on fast reactor and closed nuclear fuel cycle technology);
- Environmental sustainability of energy;
- Efficient and rational use of fossil fuels.

In 2018 these principles were expanded upon in detail in the «Russian nuclear power development strategy through 2050 and long-term outlook to 2100» (Strategy-2018). This document defined the key long-term goals, tasks and policy recommendations at industry level for nuclear power not only to successfully compete with alternative generating technologies, but also to emerge as a dominant force for decarbonizing the electricity sector in Russia. In order for that to happen, the following requirements must be met:

- Guaranteed safety of nuclear power generation and related fuel cycle facilities and operations, including waste management with minimal negative impact on the environment;
- Economic competitiveness of nuclear power for national and foreign consumers;
- Diverse product portfolio from nuclear energy (electricity, heat, water desalination, hydrogen and alternative fuels production, etc.);
- No of foreseeable limit to resource availability;
- Guaranteed safety of final radioactive waste isolation;
- Technological assurance of sustaining non-proliferation at all times.

The work on Strategy-2018 showed that Russia's natural uranium reserves, although vast, are still insufficient for supporting large scale NPP capacity development up to the end of the XXI century if only open fuel cycle technologies are considered (Fig. 1). Available resources would limit total thermal reactor capacity and the nuclear authorities would still have to deal with a significant amount of spent nuclear fuel accumulated over time – a financial and radioecological burden for many generations to come. Reprocessing thermal reactor spent nuclear fuel with the intention of producing MOX fuel for VVER type reactors could theoretically yield uranium savings up to 20–30%, but this would constitute an insignificant improvement for large-scale nuclear systems in terms of resource availability and present a new problem for the back-end of the NFC – MOX spent nuclear fuel and more MA accumulation.

A different approach based on deploying fast reactors and closed nuclear fuel cycle technologies could resolve these issues by recycling U-Pu-MA and utilizing the full potential of the uranium element through U-238 within a two-component nuclear energy system (NES). Total uranium requirements in the XXI century for a NES gradually transitioning to FR reactors in Russia would not exceed 230 000 t (excluding exports). Project «Proryv» is actively developing next-generation reactor and closed nuclear fuel cycle technologies to transition to a more sustainable and competitive nuclear energy system in Russia. These technologies include a new line of fast reactors for power generation (BN-1200M, BR-1200), fuel fabrication (mixed nitride fuel), spent fuel reprocessing and waste management facilities. Large-scale adoption of fast reactors operating in a closed nuclear fuel cycle as envisioned by the «Proryv» project would in effect lower demand on mining and enrichment capacities due the fact that these fast reactors start up using Pu obtained from thermal reactor spent fuel and then operate on regenerated FR fuel throughout their entire lifecycle. A full-scale transition to a closed nuclear fuel cycle would ultimately eliminate the need for any uranium mining or enrichment in the front-end and as a result significantly improve nuclear power's position from an environmental and resource sustainability standpoint (Fig. 1).

Another advantage of this strategy is the effect a closed nuclear fuel cycle would have on waste management and radioecological safety. In an open nuclear fuel cycle, spent fuel is transferred to interim storage or deep geological disposal. For many countries this is undesirable for political, environmental and safety reasons. The radiotoxicity of spent fuel does in fact gradually decrease in time but it would take hundreds of thousands of years for it to match the level of radiotoxicity of natural uranium. The «Proryv» project's goal in this regard is to use the U, Pu and MA in thermal reactor spent fuel in a fast reactor fuel cycle so that only HLW (mostly fission products) is shipped for final disposal. The radiotoxicity of this HLW would gradually decrease and match that of natural uranium in a few hundred years, which is ultimately much more preferable to the open fuel cycle option. Furthermore, recent studies on radiological equivalency show

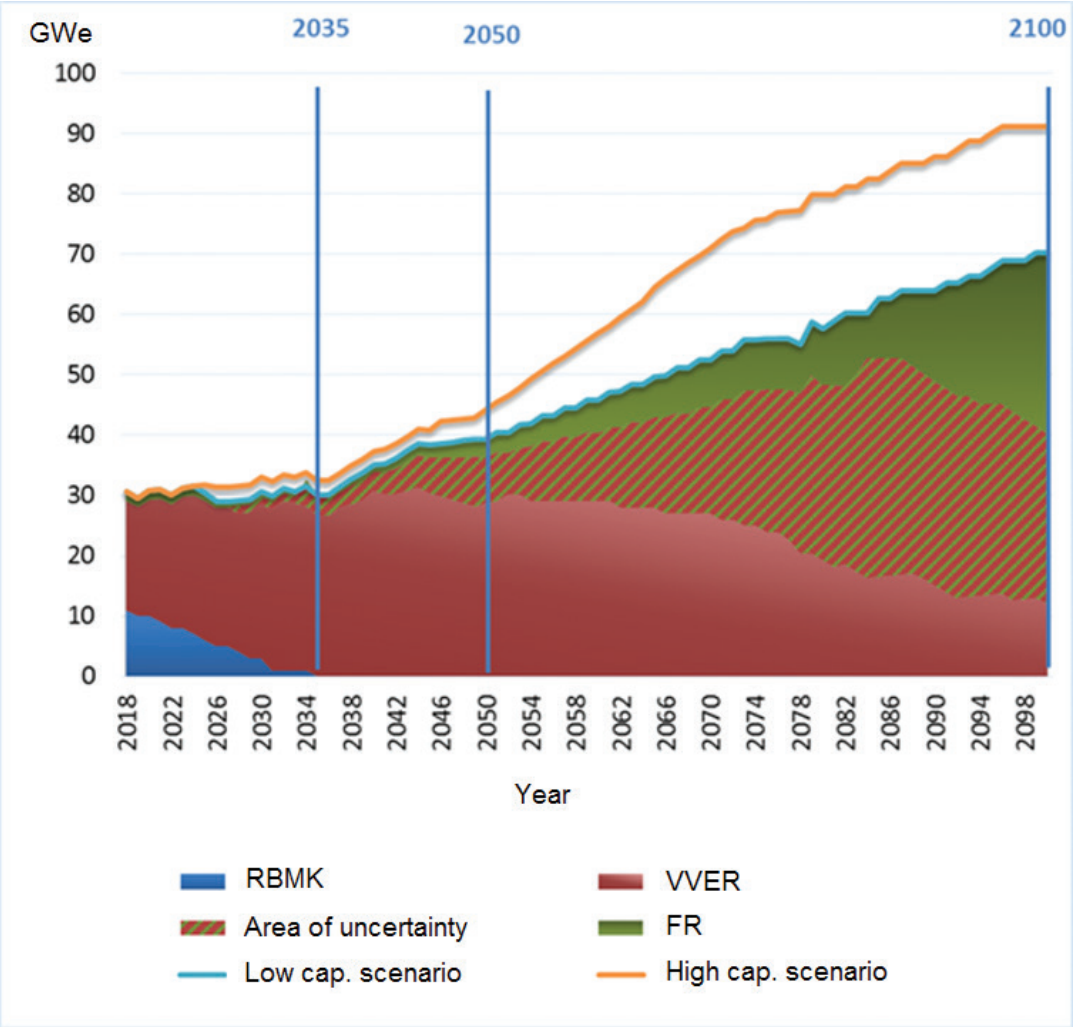

Figure 1. Nuclear power development scenarios under different assumptions regarding NPP capacity additions and FR deployment scale (source: Strategy-2018).

that lifetime attributable risk of cancer (LAR) for HLW after reprocessing is equal to LAR for initial raw uranium after a period of 100 years (Ivanov and Spirin 2021).

Many approaches to using FRs in conjunction with the existing and newly forming thermal reactor fleet have been examined, with different assumptions regarding the role of FRs in such systems. Some of these imply using FRs for breeding Pu in blankets and providing extra fissile material for manufacturing MOX fuel for a new line of VVER reactors. This «symbiotic» relationship between FRs and TRs could theoretically be possible if FR capital costs exceed VVER capital costs. In any case, it is important to consider FR competitiveness not only in relation to newly developed VVERs, but to CCGT power plants as well. Natural gas reserves in Russia are currently the largest in the world, a factor that positively affects natural gas power economic efficiency. In order for FRs to be competitive, it was estimated that their capital costs must be 20% lower than for current VVER-TOI projects. Furthermore, the FR fuel cost component of the electricity cost, which includes reprocessing and waste management operations, must not exceed the same parameter for current VVERs operating in an open cycle. If these requirements are met, FRs can successfully compete with CCGT plants, especially if long-term natural gas price increases and possible carbon tax regulations are taken into account. As a result, Russia could obtain a safe, competitive and ecologically friendly technology for carbon-free electricity generation that would in effect transform its energy mix with a much larger nuclear share.

China

China currently has 51 operational nuclear power units and 13 nuclear power units under construction. The development of China's nuclear industry over the last decade has been remarkable – it is the main source of growth for nuclear power across the world (Fig. 2). China has prioritized developing nuclear power technologies since the mid-1980s. Since its inception, China's large-scale nuclear power program has adapted foreign technologies and actively pursued domestic research and development of innovative types of nuclear power reactors. By studying various advanced technologies and gaining experience from imported NPPs, China has managed to

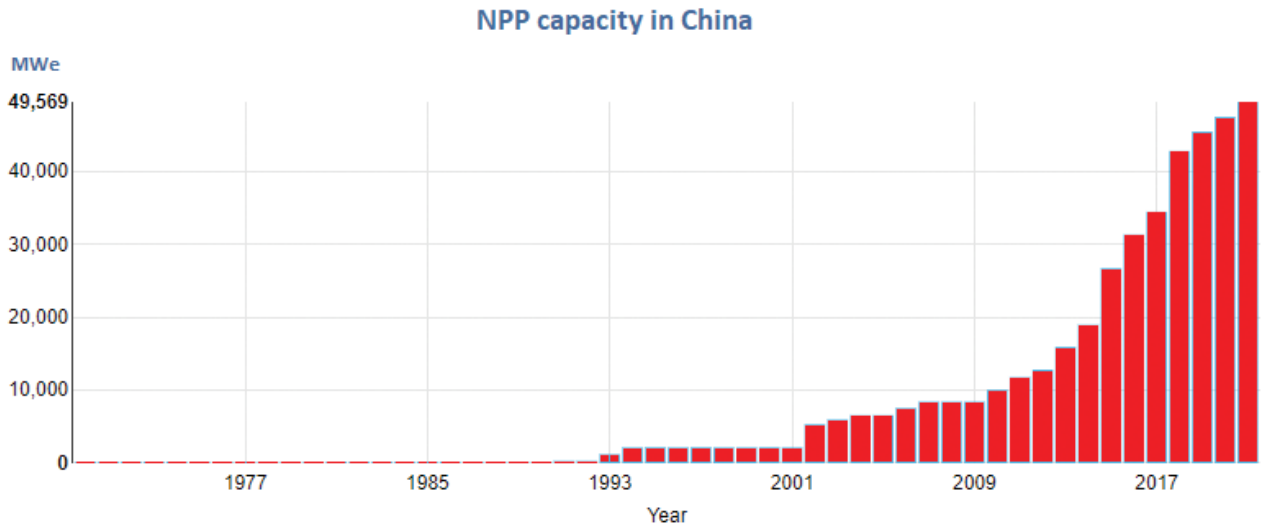

Figure 2. NPP capacity increase in China.

develop its own range of nuclear power reactors and is actively looking to export these technologies to potential foreign buyers.

At this rate, China is poised to become the largest global nuclear power in terms of nuclear power capacity in the coming decades, surpassing France and the United States. The incentive for increasing nuclear power share in China is understandable for obvious reasons. Currently coal is the main energy source and most reserves are in the north or northwest regions of the country. This presents problem from the point of view of logistics (Rioux et al. 2016) – nearly half the country's rail capacity is used for transporting coal. There are also strong environmental concerns regarding air pollution and climate risks, all of which are major drivers for increasing carbon-free energy sources.

For the present, China's impressive nuclear development has relied on technologies based on thermal reactors, mainly PWR. Nevertheless, China aims to replace these light water nuclear power plants with advanced systems based on fast neutron reactor technology, which is in line with its three-step nuclear power development scenario envisioned in 2005. This scenario calls for China to develop its PWR fleet through 2020s, transition to fast breeder reactors replacing legacy PWRs from 2020 through 2050, and, finally, start adding nuclear fusion reactors in the second half of the XXI century (although there is still much uncertainty regarding practical application of thermonuclear technology).

In order to succeed, deep industrial expertise is needed for these new systems to make the transition from R&D to commercial deployment. For a fully closed nuclear fuel cycle, China must also develop advanced spent nuclear fuel reprocessing and fabrication technologies for using recycled plutonium. Although there is no clear consensus regarding how many more nuclear power plants China will build long-term, various analytical agencies and state organizations project capacity figures for 2050 in a broad range between 150 GWe and 500 GWe (Hibbs 2018; IAEA 2019).

There are several reasons for taking the route of reprocessing SNF:

1. Recover valuable fissile materials for use in advanced nuclear power reactors;
2. High costs of uranium, processing and enrichment;
3. Disposal of HLW instead of SNF is safer;
4. Potential value in recovering TRU and FP (neptunium, americium, curium, palladium, rhodium).

With considerable assistance from Russia, China has connected one FR to the power grid – the Chinese Experimental Fast Reactor (CEFR) rated at 20 MWe. The project took 20 years to complete and its main purpose was to gain experience for later deployment of FRs at an industrial scale. A new CFR600 FR sodium-cooled fast reactor is currently under construction with the intention of gradually expanding the breeder reactor fleet within the XXI century. A proponent of the breeder reactor program, the China Institute of Atomic Energy envisions China building fast reactors at a rate so that over 100 FR units would be operating in the country by the second half of the XXII century (Hibbs 2018). These plans have yet to be confirmed by Chinese officials.

The speed at which China transitions to a system relying more on fast reactors than thermal reactors depends on many factors: advanced fuel fabrication and SNF reprocessing capabilities, growth rate of electricity demand, economics, climate policy, etc. Another major factor in driving FR deployment is the goal of partitioning and transmutating TRU. China recognizes the value in disposing nuclear waste that decay in a few hundred years compared to disposing untreated waste (SNF) that would remain radiotoxic for several hundred thousand years. To solve these issues, which undoubtedly present significant challenges not just for local nuclear industry specialists, but for the global nuclear science community as well, China is developing advanced fuel fabrication and reprocessing techniques, including pyrochemical processing, to supply recycled fuel for future fast reactors. How fast

these technologies can be deployed at an industrial scale in China remains open for debate.

In addition to sodium-cooled fast reactors, China is exploring a portfolio of reactor technology options: molten salt, ADS, thorium, high-temperature gas-cooled, lead-cooled and supercritical water-cooled reactors. For niche applications of supplying power and heat to remote locations, SMR technologies are also being developed.

Following large-scale deployment of thermal reactors, China has plans to develope its third stage of nuclear power based on nuclear fusion, which could take place between 2050 and 2100. Although the technical and economic challenges for commercializing fusion are recognized to be formidable, international cooperation in this field could possibly reduce the time needed for deploying these advanced systems.

United States

Today the US is the world's largest producer of nuclear power with 95 GWe net installed capacity accounting for more than 30% of worldwide nuclear electricity generation. Following a 30-year hiatus in which few new reactors were built, it is expected that two more units will come online soon after 2020. A major challenge for the US is maintaining the level of NPP capacity, since no new projects of GW-scale capacity are planned as of yet after commissioning units Vogtle-3 and 4. This situation presents a major obstacle for decarbonizing the energy sector in the United States (Fig. 3).

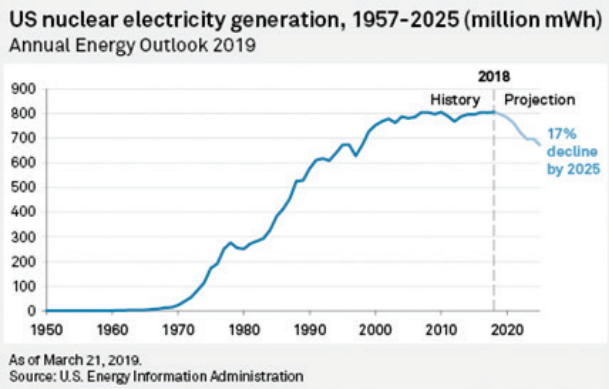

Figure 3. Short-term outlook on nuclear power in the USA (EIA forecast).

Renewable energy sources like solar and wind have grown faster than expected and their respective industries have had considerable success; together with hydroelectric, they surpassed coal for the first time ever in 2019 and now produce 20% of electricity in the United States. With liberalized wholesale electricity markets, financing capital-intensive nuclear power projects has proven extremely difficult. Moreover, low gas prices have put the economic viability of some existing reactors and proposed projects in doubt. Although total nuclear capacity remains high, there is an evident downtrend, which is going to hamper climate-related goals for individual states and the country as a whole. One measure for prolonging high nuclear capacity level that is being considered in the United States is reactor lifetime extension. The original 40-year licenses were always intended to be renewed in 20-year increments, as they had more to do with amortization of capital rather than design or structural issues limiting their lifespan. Currently R&D programmes focused on assessing major mid-life refurbishment and power plant component replacement are actively being developed by the US nuclear industry.

Judging by recent activity in the US nuclear academic, expert and energy policy community (NIA 2021; ANS 2021), the future of nuclear power in the United States is now linked to the success of various SMR programs under development. The reasoning is that in order to be competitive with fossil fuel and renewable power, new nuclear power units must dramatically reduce their capital costs using the modular approach and take advantage of the scaling effect.

As outlined in (NIA 2021), several requirements must be met for this transition to be successful:

1. Utilization of public-private partnerships for incentivizing American innovation.
2. Rapid commercialization of advanced reactors
3. Incorporation of advanced nuclear energy into a broader U.S. climate, innovation, and infrastructure agenda.
4. Cooperation with U.S. allies and trading partners to compete in global markets for nuclear energy while furthering non-proliferation objectives.
5. Development of a proactive whole-of-government export strategy for advanced reactors.

By taking advantage of the recently acquired support of the government for advanced nuclear technology development (Clean Energy for Biden 2020), the US nuclear industry is pursuing several projects on a federal level:

- The Versatile Test Reactor to support research and industry;
- Two reactor projects to support defense energy security (Project Pele and 2019 NDAA microreactors);
- Several space reactors, including a commercially developed reactor for NASA to flight test on the Moon.
- Several research reactors, including the Transformational Challenge Reactor and MARVEL.

With four commercial projects underway, including Oklo, X-Energy, Terrapower and Nuscale, the United States has the widest product range of nuclear projects under development (Fig. 4). Other projects like Terrestrial Energy and Ultra Safe Nuclear Corporation are conducting pre-application activities with the US NRC, arranging first customers, and pursuing demonstration projects. The

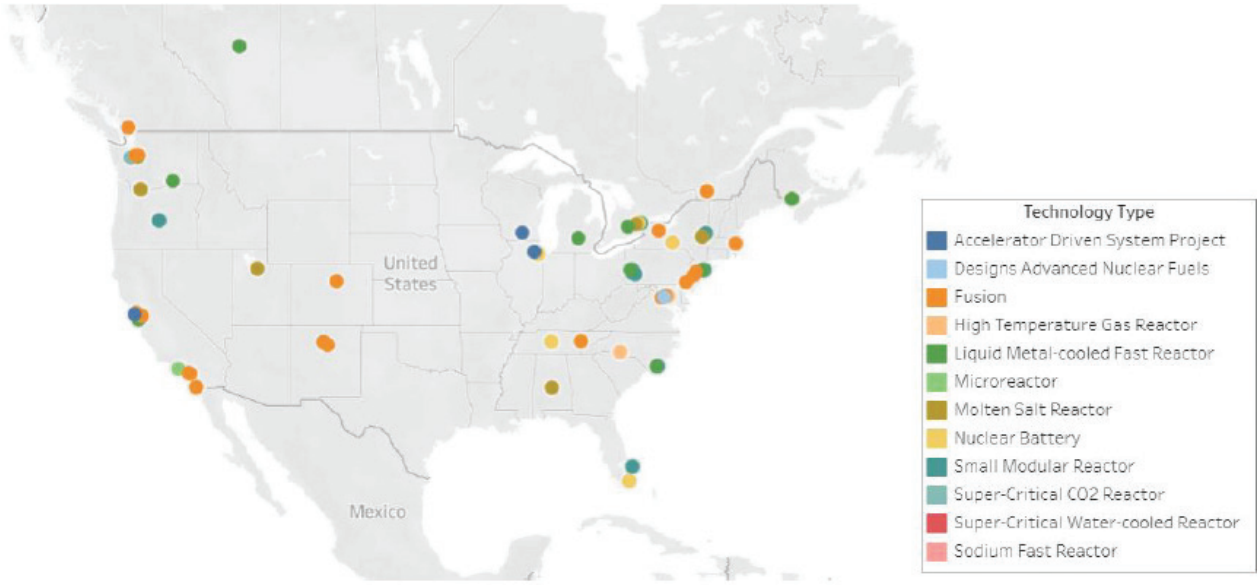

Figure 4. Advanced reactor companies in North America by reactor type. (source: Third Way, national think tank).

US strategy at present is set for close coordination of the nuclear industry with the government in order to advance new demonstration projects during the 2020s, achieve commercialization, cost competitiveness, and rapid global deployment in the 2030s and beyond.

Another important factor recognized in nuclear innovation in the US is the need for revising the regulatory framework for advanced nuclear technologies. There is a consensus in the scientific community that current regulatory regimes are designed around the characteristics of traditional light water reactors and need to be updated for taking into account new and diverse characteristics of advanced reactor designs. Appropriate action can reduce application time, eliminate redundant processes, minimize paperwork while maintaining rigorous standards and requirements.

The relatively recent shift in nuclear policy can also be explained by the success of the Russian and Chinese nuclear programs (Nakano 2020). There is growing sentiment in the United States nuclear industry that in the event of a US retreat from global nuclear energy, Russian and Chinese suppliers would completely dominate existing and emerging nuclear export markets due to their advantageous position as State Owned Enterprises. In light of this, US think tanks recommended taking action to counter foreign dominance in nuclear power:

1. Enable government support for the private-sector effort to develop and commercialize advanced reactor technologies;
2. Remove the current restrictions on the U.S. government financing for NPP projects overseas;
3. Support safety and security work that would position the United States as the continued leader in SMRs and advanced reactor technologies.

It is evident that despite recent stagnation in the competitiveness of its nuclear industry, the government, numerous nuclear enterprises, national labs and think tanks aim at restoring US leadership in nuclear innovation though a coordinated effort spanning the industry, state, labor, and civil society community. If successful, the program could jump-start global SMR innovation and deployment with significant benefits for national climate and sustainable development goals.

India

Since its inception in India in the 1960s, nuclear power has been thought of as one of the major energy sources for the future of the country. India's nuclear industry has been directed towards complete independence in the nuclear fuel cycle after it was excluded from the 1970 Nuclear Non-Proliferation Treaty (NPT) due to it acquiring nuclear weapons capability. As a result, fuel or technological assistance from other countries was not possible for a very long time period, until the Nuclear Suppliers Group agreement was achieved in 2008 and the possibility of sourcing both reactors and fuel from outside suppliers finally opened up. Currently India operates 6.9 GWe NPP net installed capacity and is building 4.2 GWe. The government has set ambitious targets to grow nuclear power but issues in construction and alternative energy options have somewhat delayed these plans.

India has always pursued a three-stage strategy (Banerjee and Gupta 2017) to developing its nuclear power capabilities with the aim of utilizing its vast thorium resources to power a large-scale energy system. In the first stage, it is implied that Pressurized Heavy Water Reactors (PHWRs) produce energy from natural uranium and accumulate Pu-239 in their respective SNF as a by-product. In the second

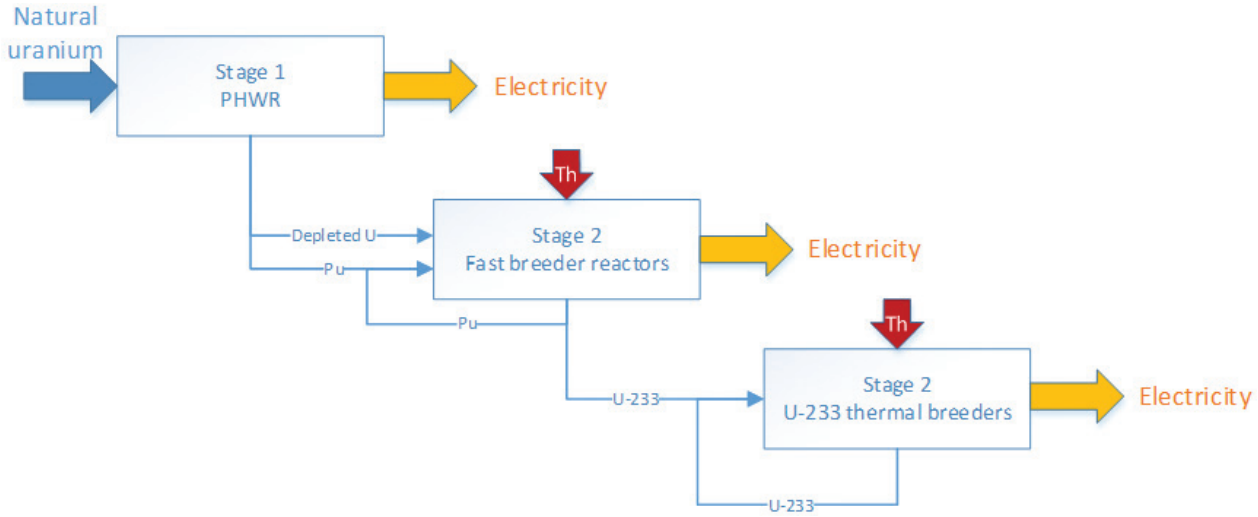

Figure 5. India's three stage nuclear energy development plan.

stage, fast breeder reactors fueled by Pu-239 from reprocessed PHWR SNF produce energy and more Pu-239. Once the inventory of Pu-239 is adequate, thorium can be introduced as a blanket material and be transmuted to uranium-233. In the final stage, India plans on transitioning to an advanced nuclear power system operating in a self-sustaining breeding cycle of thorium-232-uranium-233. The result, if all other steps are successful, is a thermal breeder reactor system that is refueled using only naturally occurring thorium after its initial fuel charge (Fig. 5).

According to the Nuclear Power Corporation of India Limited (NPCIL), the energy generation targets after 2004 were to provide 20 gigawatts (GW) by 2020 and 60 GW by 2032. These figures was revised and later increased to 63 GWe in 2011. Later in 2018, the government stated that nuclear capacity would fall well short of its initial target and total nuclear capacity is likely to be about 22.5 GWe by the year 2031. Latest discussions in the Indian parliament indicate that large scale thorium deployment is expected 3–4 decades after the commercial operation of fast breeder reactors. Because of this delay, the country is now looking at reactor designs that allow more direct use of thorium in parallel with the sequential three-stage programme, including the Indian Accelerator Driven System, Advanced Heavy Water Reactor (AHWR), Compact High-Temperature Reactor. Although the AHWR is technically ready for installment, no specific plans for construction have been announced as of yet.

As an initial phase for transitioning to the second stage of its nuclear power development, India is building its first Prototype Fast Breeder Reactor at Madras Atomic Power Station in Kalpakkam, Tamil Nadu, a 500 MWe sodium-cooled fast reactor. The project has been facing delays since 2010 and as of today, the reactor might go critical only in December 2021. According to industry experts, the absence of fissile material in India is the single most important factor impeding nuclear progress in the country in terms of increasing nuclear capacity. Global trade of Pu could potentially increase fissile material stock but diplomatic issues related to non-proliferation present challenges for international cooperation in this area.

Conclusion

Nuclear power is a carbon-free energy source that has massive potential for clean energy production in the XXI century and beyond. A number of countries have undertaken ambitious projects to transform their national energy mix with a larger share of nuclear power. Some are pursing nuclear development strategies with fast reactor deployment due to limited uranium resources and a desire to eliminate nuclear waste related issues. Another approach is developing advanced small modular reactors in the effort to lower capital costs and expand nuclear application to new markets (heat, hydrogen, water desalination). These strategies offer a variety of options for developing secure and sustainable nuclear energy systems with a wide range of reactor technologies. It seems that for large-scale application the most popular Generation IV type reactor under development is the liquid metal cooled reactor. Globally, there are numerous projects pursuing other types of reactors, including molten salt and high-temperature gas cooled reactor technologies. These reactors could also be used in concert with more «traditional» FRs for niche applications, including hydrogen production, MA burning or supplying energy to isolated areas. It is true that some nuclear programmes have encountered difficulties in expanding NPP capacity to larger scale systems due to a number of factors, including fierce competition from alternative energy sources, political and social opposition, resource related issues and economics. If the industry manages to overcome these difficulties, nuclear power could play a more significant, if not deciding role in mitigating climate change and developing sustainable solutions to key global energy issues.

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Supplementary material 1

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