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Nuclear Innovation and Newly Emerging Disruptive Technologies: Recent Initiatives by Industry, Research Laboratories and Governments

This report's preparation was led by Emma Wong

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Nuclear Innovation and Newly Emerging Disruptive Technologies

Recent Initiatives by Industry, Research Laboratories and Governments

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Foreword

From its inception as a scientific discovery to its evolution into a key component of global energy infrastructure, nuclear energy has benefited from breakthroughs in physics, engineering and materials science. The sector now faces critical challenges that demand technological advancements and shifts in strategic thinking. Embracing next-generation reactor designs, leveraging digital technologies and fostering a culture of creativity and collaboration can unlock new applications for nuclear-generated industrial heat for, *inter alia*, energy-intensive industries, hydrogen production, petrochemical operations and district heating. This compilation of articles focused on nuclear innovation and newly emerging technologies gathers insights and perspectives from government, industry and research organisation stakeholders. It presents a snapshot of initiatives for disruptive innovation in nuclear energy technologies across the industrial economy.

The story of nuclear energy and disruptive innovation begins with Henri Becquerel's discovery of radioactivity in 1896 and the subsequent work of Marie and Pierre Curie. These early innovative findings laid the groundwork for understanding atomic energy. Enrico Fermi's groundbreaking discovery of nuclear fission followed in the 1930s, and his subsequent development of Chicago Pile-1 (CP-1) was a monumental milestone in the history of nuclear science. On 20 December 1951, Experimental Breeder Reactor I (EBR-I) successfully produced electricity by lighting four 200-watt light bulbs at the Argonne-West National Laboratory, proving that nuclear energy could be harnessed to generate power. By the mid-20th century, breakthroughs such as the Manhattan Project's advances in nuclear fission and the development of nuclear reactors for energy generation laid the groundwork for the significant expansion of nuclear power in the 1970s and 1980s internationally.

Since these early beginnings, the nuclear sector has maintained a steady yet largely incremental approach to innovation, even as the Internet of Things (IoT) and digitisation continue to revolutionise the global economy. For nearly 70 years, the Nuclear Energy Agency (NEA) has spearheaded numerous initiatives and projects that have significantly advanced nuclear technology and safety. Some notable examples of this work are the European Company for the Chemical Processing of Irradiated Fuels (Eurochemic), Halden Reactor Project, and FIDES (Framework for Irradiation Damage Evaluation and Simulation) - I & II. Furthermore, the NEA has served for over 25 years as the Technical Secretariat of research co-operation under the Generation IV International Forum's international framework on sustainability, safety, reliability, proliferation resistance, physical protection and cost-effectiveness for a next generation of nuclear reactor technologies.

As the world looks for technology solutions to meet international energy security and net zero demands, innovation will be required to transform the nuclear energy sector to accelerate deployment while ensuring safety and security consistent with public trust. Accelerating the time to market for the current suite of innovative nuclear technologies in terms of cost and speed will determine the role of nuclear power in the future energy mix. Challenges include new supply chain needs and building confidence among utilities to take on the risks associated with deploying first-of-a-kind (FOAK) technologies. Furthermore, governments and the private sector will benefit from workforce preparedness and the presence of coherent regulatory frameworks for licensing new innovative reactor designs, advanced materials and new accident-tolerant fuels.

Through innovation and the advancement of enabling frameworks, countries can:

- Make nuclear energy easier to deploy. Effective mass production and deployment strategies enabled by technological advancement in areas like advanced manufacturing can help small

and microreactors (SMRs and MMRs) offer simpler, less costly options to bring nuclear energy capacity to market and operate with more efficient management and increased levels of safety and security.
- Use nuclear energy to power, heat and cool buildings and transport. In addition to the larger markets of traditional-sized reactors, SMRs can decarbonise the electricity supply as these communities strive to electrify transportation, homes and public and commercial spaces.
- Advance nuclear designs for uses beyond on-grid electricity production. SMRs can directly provide behind-the-metre energy to industrial customers. This includes hard-to-abate sectors like resource extraction and processing and data centres.
- Reduce costs and improve efficiencies of long-term operations. Innovative technologies can strengthen the effectiveness and efficiency of existing nuclear energy assets to ensure performance excellence, longevity and more straightforward, cost-effective operations.
- Accelerate testing and research. The nuclear sector's recent wave of innovation in materials science, fuel development, and technologies such as SMRs will likely mean competition for existing testing facilities and research expertise to verify and validate nuclear fuels and materials (F&M).
- Nurture international government-to-government, public-private, and business-to-business co-operation. This will help lay the groundwork for core-enabling conditions such as licensing readiness, financing, supply chain, workforce development and fuel availability.

Opportunities for disruptive innovation in nuclear energy are abundant, despite the complexities involved. While the nuclear sector operates within a highly controlled and regulated framework, disruptive innovation, known for its potential to deliver high value and significant benefits, offers transformative possibilities. Integrating innovation at scale within the nuclear sector, and within the necessary timescales, presents an exciting challenge that calls for adaptability and forward-thinking strategies while adhering to critical safety and controls standards.

This compilation of articles from professionals in government, research and industry highlights the power for disruptive innovation across the nuclear energy lifecycle, everywhere from the design, licensing and delivery processes to more straightforward, cost-effective waste management and operations.

Among the innovations reviewed:

- Improved finance, business and regulatory models through digitalisation, strengthening decision making and forecast scenarios (p.175 - Disruptive Business and Markets Models).
- Strengthened talent pipeline from biotechnologies and human enhancement, enabling adaptive training (see p.55 - Biotechnologies and human enhancement).
- Distributed ledger technology, enabling training standardisation and promoting qualification and certification for mutual recognition between entities (p.73 - Distributed ledger technology) and deter counterfeit or suspect parts.
- Enhanced materials and advanced manufacturing techniques to enable complex parts and supply chain readiness (p.79 - Novel materials and manufacturing).
- Bolstered enabling frameworks through automated data collection, analysis, reporting and adherence to standards (p.95 - Automation and p.188 - Regulatory Implications).

This NEA Working Paper is not intended as a complete survey of disruptive innovation. Instead, the articles, submitted in 2023-24, provide an overview of innovation to better understand its transformative potential in the nuclear sector.

This compilation would not have been possible without the dedication and effort of the named authors, as well as the countless other contributors whose hard work and insights have enriched these articles. Their commitment to advancing the discourse on nuclear innovation is commendable, and the NEA extends its gratitude to everyone who contributed to bringing this publication to fruition.

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Canadian Nuclear Laboratories - Clean energy and health through nuclear research

Abstract

Canadian Nuclear Laboratories (CNL), under the oversight and in collaboration with the federal crown corporation, Atomic Energy of Canada Limited (AECL), is working to respond to the science and technology challenges of the nuclear sector in Canada and abroad.

As a private site operator, CNL leverages AECL-owned facilities and equipment, as well as its 800 scientists, engineers, and technicians, to drive innovation across multiple sectors, including energy, health, environment, safety, and security.

CNL plays a critical role, as Canada's national nuclear laboratory, in advancing nuclear technologies up the technology readiness level (TRL) ladder, mobilising the nuclear ecosystem around shared priorities, and training the next generation workforce. Partnership is at the heart of CNL's successes. Recognising that it cannot do everything for everyone, CNL has focused its capabilities around niche areas of strength that support the development of technology solutions for ecosystem partners. In recent years, CNL has also broadened its capacity to provide innovation services and deploy disruptive technologies, such as artificial intelligence/machine learning, 3-D printing, etc., both in response to internal needs as well as those of partners.

This portfolio is anchored in an overarching innovation strategy that sets out an institutional framework built on innovation management tools and systems to support organisation-wide objectives.

Introduction

As a federal Crown corporation, AECL, receives funding from the Government of Canada with the vision of leveraging the full potential of Canada's expertise in nuclear technology to achieve a better future for Canada and the world.

Since 2015, AECL has delivered this mandate through a government-owned, contractor-operated model (GoCo), which means that a private sector organisation, CNL, is responsible for managing and operating AECL's sites. Under the GoCo model, AECL owns the sites, facilities, assets, intellectual property, and responsibility for environmental remediation and waste management. CNL is responsible for the day-to-day operations of the sites, is the employer of the workforce and responsible for all licences and permits.

For 75 years, CNL/AECL has been at the forefront of nuclear innovation in energy, health, the environment, and safety and security. AECL scientists invented the CANDU reactor, which has been deployed in two Canadian provinces and six countries and were pioneers in nuclear medicine and the global effort to fight cancer. CNL driven innovation in material science has enabled success in industrial sectors from aerospace to mineral extraction.

Today, CNL is working on new targeted radiopharmaceuticals that kill cancer at the source without exposing patients to chemotherapy. It is making progress in clean energy technologies, bringing Canada closer to its net-zero targets. CNL is also safely addressing the industry's early environmental legacy and building a more sustainable path for the future.

CNL occupies a distinctly unique niche in Canada's innovation ecosystem. As Canada's national nuclear laboratory, CNL offers an extensive range of capabilities that provide value to partners in their research and commercialisation pursuits. CNL's value can be characterised as follows:

1. As an innovation incubator moving R&D across the TRL ladder, towards commercial application.
2. As an innovation convener leveraging an expansive base of S&T partners to respond to the R&D needs of industry.
3. As an innovation integrator using a wide range of specialised expertise to lead collaborative projects.
4. As a receptor for talent and a location for training and talent development.

The above characterisation of CNL's unique value is underpinned by leading-edge infrastructure and equipment, research data, knowledge base, talent as well as industrial and international networks.

Innovation portfolio

CNL's role in both the Canadian and international ecosystems is to provide solutions to problems through innovation across multiple S&T areas. Successes in this role is rooted firmly in CNL's range of leading-edge capabilities, which are deployed to generate new products and services for ecosystem partners across industry, federal and provincial governments, and academia. Key capabilities driving innovation at CNL include:

- **Tritium processing, handling, and storage**: Detritiation of heavy water is a proven method to process waste heavy water from CANDU reactors. It yields clean heavy water which can be sold for nuclear and non-nuclear applications as well as clean tritium which is essential in fusion research. CNL's detritiation facility and existing supply of tritiated heavy water is being developed to provide both clean tritium and heavy water for revenue generation and reuse in commercial applications.
- **Hydrogen safety:** Hydrogen is one of the most promising energy storage and carrier materials. However, extensive safety standards need to be developed and implemented to support the growth of a hydrogen economy infrastructure. CNL has extensive expertise and experimental tools in its Hydrogen Research Facility. The Canadian Hydrogen Safety Centre has been founded by CNL to assemble a community of practice for hydrogen safety that can collaboratively address hydrogen safety technical challenges and develop best practices for the Canadian ecosystem.
- **Small modular reactor (SMR) deployment:** SMRs are an emerging technology that aim to provide clean and reliable power to remote locations and to support local needs of the electricity grid. SMRs can strengthen accessibility to nuclear energy. They offer lower capital costs and passive safety systems that require less active management compared with traditional-scale nuclear power plants.
- **R&D expertise and support:** CNL provides SMR vendors and future owners with expertise and support in research and development as well as siting of SMRs. CNL's CEDIR initiative provides SMR vendors and related industries with a controlled environment to test and demonstrate the grid integration of SMRs and their siting in future locations.

- **National security and critical infrastructure:** CNL's Cybersecurity Centre supports the development of robust and effective protection strategies for critical infrastructure (i.e. ten Canadian sectors, including energy and utilities, water, transportation, government, and manufacturing) as well as training opportunities for operators of existing infrastructure. Additionally, CNL's nuclear forensics and detection capabilities support law enforcement and national security agencies with essential data collection and early threat detection tools.
- **Cancer treatment*:*** In the health sector, one of the most efficient tools to cure all forms of cancer in patients has been radiotherapy and chemotherapy. Both methods have historically had side effects affecting the quality of life of patients. CNL is helping advance the development of novel targeted alpha radiotherapy methods (alpha radiotherapeutics) using rare isotopes that have shown great promise to reduce side effects and revolutionise the way cancer is being treated.
- **Environmental remediation:** CNL's Environmental Remediation Management mission has leveraged internally developed innovation to improve safety, reduce environmental risk and generate cost efficiencies associate with decommissioning and waste management.

Applications of innovation

CNL's innovation portfolio is activated through the development of technology solutions for ecosystem partners, and innovation services and disruptive technology deployment (AI/ML, 3-D printing), which provide solutions to clients by leveraging unique capabilities, including enabling technologies. These include artificial intelligence (AI), machine learning, 3-D printing, and digital twins. This portfolio is anchored in an overarching innovation strategy that sets an institutional framework built on innovation management tools and systems to support organisation-wide science and technology (S&T) and commercial objectives.

CNL is generating impact through innovation across multiple sectors. CNL plays an important role in spearheading Canada's shift to clean energy with key projects that merge nuclear with renewables for net-zero targets. Through partnerships and research, CNL addresses SMR deployment challenges, making strides in practical demonstrations and informing policy decisions. CNL is also contributing key capabilities for advancing fusion fuel cycle technologies, to support the future deployment of fusion reactors.

CNL supports the innovation challenges of the existing CANDU fleet, including projects to strengthen efficiencies and safety. For example, CNL has worked with partners to deploy new technologies for corrosion monitoring that has reduced processes to two days, versus a typical duration of five to eight days (approximately CAD 3-CAD 6M in savings). CNL has also successfully deployed decontamination S&T to support management of power-reactor components and inform long-term operations.

In the health sector, CNL's Actinium-225 production capabilities will be greatly extended to provide a reliable and steady supply to the global market. CNL has partnered with ITM Isotope Technologies Munich SE to spin-out Actineer, a new joint venture in the global production of Actinium-225.

In the national security and critical infrastructure sector, CNL is exploring using additive manufacturing to advance radiological and nuclear detector development to support national security requirements, such as border security, disarmament verification, and nuclear safeguards.

Leveraging nuclear expertise, CNL collaborates with partners to develop nuclear-powered solutions for space exploration. Our work addresses the unique energy needs of spacecraft and extra-terrestrial bases, positioning Canada at the forefront of nuclear space technology.

Environmental remediation uses innovative technologies, including custom tools, like quadruped (four-legged) robots with scanners, to reduce worker exposure and enable remote operations. Another example is the development of a portable, modular, high-precision manipulator that brings the functionality of a hot cell to the field.

Conclusion

As Canada and the world continue to embrace nuclear to tackle some of society's greatest challenges, CNL is here to play a role in achieving success by underpinning the provision of clean energy for today and tomorrow, restoring and protecting our environment, and improving people's health. Under the guidance of AECL, CNL will continue to invest in its own innovation and internal capabilities to remain a trusted partner to the international community.

Commissariat à l'énergie atomique - CEA's innovation practices and work

Abstract

The Commissariat à l'énergie atomique (CEA) is a French public research and technology (R&T) organisation. For more than 75 years CEA has led the way in numerous domains of the nuclear industry to push forward innovative technologies and concepts. The activities of the CEA range from dismantling legacy installations, long-term operation (LTO) of the existing nuclear fleet, development of the new SMR and advanced modular reactor (AMR) concepts, and the future deployment of advanced Gen4 nuclear power plants, together with activities on nuclear fuels.

The CEA is promoting innovation both regarding the technologies used in the nuclear field, but also innovation in the uses of nuclear energy to fully decarbonise our societies. To reach this target CEA has shifted its research domains from a focus on nuclear power to an integrated low-carbon energy approach. This includes production for electricity, heat, and low-carbon hydrogen (H_2); transport systems for these energy vectors; and a circular economy approach for critical materials and carbon dioxide (CO_2).

Introduction

The CEA is a French public research and technology organisation (RTO), like Fraunhofer institutes in Germany, with a specific mission to transfer its technologies to industry, in support of its competitiveness and in response to major societal challenges. This explains why innovation is at the heart of the organisation's priorities, with a leading position both in Europe and internationally.

The CEA is the leading patent-registering research organisation in France and Europe, with around 650 priority patents registered in France each year.

For 12 years, the CEA has been included in the Clarivate's ranking of the world's 100 most innovative companies. In 2024, it is even ranked as the world's most innovative research organisation.

Historically, the CEA has structured its activities and operations to meet this innovation imperative and ensure a close link between its research, applications and the market.

Technology transfer at CEA is organised around two axes:

- Most technology transfer is carried out with existing industrial partners. The CEA works with over 700 industrial partners to develop innovations that meet their needs, then transfers them for industrialisation and marketing.
- In a complementary way, CEA has also developed a long-standing business start-up capability. This activity is particularly important for breakthrough innovations and emerging markets, where no existing player is willing to take up a position due to the risk involved and the distance from its business model. This is why the CEA has set up its own systems to help companies emerge and promote -their innovations. Since the early 1970s, the CEA has been involved in the creation of over 250 technology companies, including such well-known players as Cogema, ST microelectronics, SOITEC and, more recently, GENVIA.

In support of these technology transfer activities, the CEA has developed in-house skills in business development, marketing, prototyping and design. It has also set up technological platforms of excellence, enabling the companies to go as far as industrial pre-series.

Innovation portfolio

Active in the field of nuclear technologies for more than 75 years, CEA has led the way in numerous domains of the nuclear industry to push forward innovative technologies and concepts. The activities of the CEA cover the dismantling of legacy installations, the LTO of the existing nuclear fleet, development of the new SMR/AMR concepts, future deployment of advanced Gen4 nuclear power plants, and activities on nuclear fuels.

CEA has been one of the first entities to promote an integrated low-carbon energy approach encompassing both production means for electricity, heat and low-carbon hydrogen; transport systems for these energy vectors; a circular economy approach for critical materials and CO_2. This represents a significant shift from the former perspective focused on nuclear power and helped open new research domains in cross-cutting fields.

For technical innovations, CEA is working from the basic science field by:

- Developing novel types of simulation methods and codes (for example, using AI to take advantage of meta-modelling of the finest scale of fluid mechanics in larger domains, or GPU-type cluster architectures to tackle very large calculations).
- Using innovative numerical methods and fabrication processes (such as additive manufacturing) to design tailored materials and their qualification under representative environments with one recent example being accident tolerant fuels concepts for pressurised water reactors (PWRs).
- Designing new systems and processes both for the current PWR technology (with the development of new passive systems and their integration in PWRs, new energy conversion systems for advanced concepts, the development of processes to help dismantle/decontaminate nuclear facilities (laser cutting under water, robot-assisted operations).
- Working on new reactor designs to tackle other uses of nuclear energy (such as a low pressure PWR dedicated to heat production or optimised Gen4 concepts using the extensive sodium fast reactor [SFR] technology expertise of the CEA).

Beyond innovation in the technical field, CEA has also pushed for new ways of using nuclear heat generated from nuclear power plants to alleviate some of the constraints related to standard configurations, optimise the energy efficiency, or optimise the output of combined heat and power on a given design.

Possible applications of innovation

The CEA is promoting innovation regarding the technologies used in the nuclear field, be it for new materials, systems or simulation capacities, and innovation in the uses of nuclear energy to fully decarbonise our societies. That is made possible by the range of CEA activities, which go far beyond nuclear and allow innovative cross-research activities to be conducted, for example on the coupling of nuclear reactors with hydrogen production processes, and of e-fuels, with optimal efficiency.

E-fuels, and in particular sustainable aviation fuels, are a major issue to be tackled to achieve significant aviation industry CO_2 emission reductions. They produce massive amounts of low-carbon energy, to produce and combine hydrogen and carbon from biogenic sources, be it biomass or CO_2 from the air for carbon, and water for H_2 through electrolysis. Designing systems which take advantage of the capacity of nuclear units to supply, in a dispatchable way, both heat and electricity opens a whole new field for nuclear power.

In this field, one of the key innovations the CEA has been pushing is the integration of these technologies (nuclear power, H_2 production through high-temperature steam electrolysis, carbon capture, and chemical processes related to organic molecules production) to produce e-molecules in the most energy-effective way. That leads to configurations which are very different from the standard operation of a nuclear unit, providing the possibility to recover heat at the different stages and use it to maximise the quantity of e-molecules produced. That also implies new business and industrial models for the nuclear industry.

Conclusions, further plans and recommendations

The CEA is promoting innovation over the full scope of nuclear activities, from the installed power plants to future ones, and from large ones to the SMRs and AMRs to come, including the associated fuel cycles. To fully decarbonise our societies, CEA has extended its research field to other domains such as H_2 production and chemical processes to advance e-molecules (such as e-fuels) in association with carbon capture. This is made possible thanks to innovative cross-research activities involving the diverse teams across CEA.

Electric Power Research Institute – Innovation at EPRI

EPRI or the Electric Power Research Institute was founded in 1972 as an independent, non-profit energy research and development organisation for the benefit of the public. Its mission is to advance safe, reliable, affordable, and clean energy for society through global collaboration, science and technology innovation, and applied research.

EPRI brings together scientists, engineers, government, and experts from academia and industry to shape and drive innovative global research and development (R&D).

Innovation at EPRI

EPRI fosters collaborative research, technology transfer, customised solutions, and application services to improve and address current public, government, and utility needs in power generation (nuclear, renewables, etc.), transmission & distribution infrastructure, integrated grid and energy systems, electrification, and sustainable energy strategies. EPRI drives thought leadership and R&D advances to gain a deeper understanding of potential solutions to support an integrated and decarbonised energy network in areas such as:

- advanced power generation (small modular reactors, fusion, advanced solar and wind, etc.)
- energy storage technologies
- grid modernisation and developing the energy system of the future
- digital technologies (digital transformation, AI, cybersecurity, and quantum technologies).

EPRI brings together over 1 000 experienced research professionals to perform collaborative R&D across the energy sector around the world.

Euratom - Nuclear innovation and newly emerging disruptive technologies in the Euratom research and training programme of the European Commission

Abstract

The EU-funded Euratom research and training (R&T) programme has the general objective to develop technological leadership and promote excellence in nuclear research and innovation, ensuring the highest standards of safety, security, safeguards, radiological protection, safe spent fuel, radioactive waste management and decommissioning in the nuclear field. The Euratom programme is periodically evaluated on its coherence, relevance and effectiveness, monitoring its innovation impact and added value to the EU. In this framework, the funded research projects develop and apply several innovative technologies or facilitate the deployment of disruptive industries. Key enabling technologies in the programme are artificial intelligence (AI) and digital twins. The revolutionary application of AI in the fusion research field and in material science will improve respectively simulation capabilities and effectiveness of nuclear safety inspections. The use of digital twins in radioactive waste management allows scientists to have an overview of nuclear facility decommissioning. Examples of disruptive industries supported by the programme are hydrogen and process heat production, and space exploration. The latter could support the development of a supply-chain in Europe to produce radioisotope power systems (RPS), also improving their design.

Introduction

The European Commission's Directorate General for Research and Innovation (DG RTD) manages the Euratom R&T programme, a complementary funding programme to Horizon Europe[1] which covers nuclear research and innovation.

The programme is a crucial part of the Union's efforts to further develop technological leadership and promote excellence in nuclear research and innovation, ensuring the highest standards of nuclear safety.

The Euratom programme's indirect actions provide research grants through competitive calls for proposals and to named beneficiaries. In this framework, the European Commission supports the most relevant, innovative and disruptive research project proposals, to maintain strong competences in nuclear research and innovation in both fission and fusion. The programme contributes to the development of technologies, like small modular reactors[2], which have been classified as 'net-zero' in the European Net-Zero Industry Act.

Innovation is fostered by rewarding excellence in nuclear research via the SOFT[3] and the Nuclear

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[1] The EU's key funding programme for research and innovation with a budget of EUR 95.5 billion.

[2] The European Commission has recently launched the European Industrial Alliance on Small Modular Reactors ("the Alliance"), aiming to facilitate and coordinate stakeholders' co-operation at EU level for the development, demonstration and deployment of Small Modular Reactors (SMRs) as a viable and competitive technological solution to decarbonise the European energy system in the next years.

[3] The SOFT Innovation prize, named after the biennial Symposium on Fusion Technology (SOFT) during which the recipients of the prize are presented, supports rewards excellence in Fusion research.

Innovation prizes[4], promoting the mobility of young researchers in Europe via Euratom sponsored Marie Skłodowska-Curie grants[5] and ensuring the best education to the new generations via the European Nuclear Education Network (ENEN) and the European Fusion Education Network (Fusenet). Finally, the programme also contributes to the evolution of new competences and skills in the sector, through the work of the Euratom co-funded partnerships EUROfusion[6], EURAD[7] and Pianoforte[8].

Programmatically, the R&T is organised in seven-year time frames, split in five plus two years[9], following the long-term EU budget cycles, known as the Multi-annual Financial Framework of seven years. In this context, the programme is subject to an interim evaluation, capturing its design, implementation and first results achieved. The interim evaluation also addresses the programme's relevance, coherence, effectiveness and EU value added, giving input to the ex-ante assessment of the programme extension. The latter identifies and analyses the issues to be addressed by the Programme to ensure its continued relevance.

This evaluation cycle serves to monitor the innovative potential of the research carried out in the framework of the programme and to identify the most disruptive technologies employed and discovered. The evaluations also give the opportunity to effectively design the following Euratom R&T programme, making sure that promising innovation paths receive long-term support and are given the chance to properly develop.

Innovation portfolio

The Euratom R&T programme has a broad portfolio of research activities employing several advanced technologies and supporting the development of disruptive industries.

The most relevant innovative technologies playing a key role in the programme are:

- The use of AI, in particular machine learning, in fusion research, diagnostic applications of ionising radiation, material flaws detection in nuclear installations, severe accidents simulation, radioactive waste management and non-power applications.
- The use of digital twins in radioactive waste management.
- Gyrokinetic modelling of turbulent fusion plasmas.

Regarding research into innovative industries, the most notable examples are:

- Hydrogen production: Evaluation of the potential for developing large scale, low-carbon, hydrogen production facilities linked to nuclear power plants.

[4] The Nuclear Innovation Prize allow (young) researchers to be rewarded for the most innovative ideas in the fields of reactor safety, waste management and radiation protection.

[5] The Marie Skłodowska-Curie Actions are the European Union's reference programme for doctoral education and postdoctoral training.

[6] EUROfusion is the European Consortium for the Development of Fusion Energy.

[7] EURAD is the European Joint Programme on Radioactive Waste Management (RWM).

[8] Pianoforte is the European co-funded partnership for radiation protection.

[9] This is a specificity of the Euratom Programme, stemming from a requirement of the Euratom Treaty of having research funding programmes with five years cycles. The programme is now managed in five + two years programmes to align with Horizon Europe and the Multiannual Financial Framework.

- Process heat: Provide a global solution for the competitive and safe decarbonisation of industrial activities with high-temperature reactors.
- Space exploration: Develop the technology and the capabilities in Europe to produce Pu-238 to fuel radioisotope power systems (RPS) and subsequently significantly increase the efficiency of the RPS thanks to an advanced Stirling engine.

Possible applications of innovation

The Euratom research and training programme features several truly innovative projects, employing innovative technologies like AI and digital twins or supporting the development and possibly deployment of innovative industries, like nuclear-powered space exploration. In this section we describe a few, extremely relevant, examples of the possible applications of these technologies.

Artificial intelligence

The use of AI is widespread around the Euratom programme, and it is not a goal as such. There are no projects carrying out fundamental research on AI. AI in the Euratom programme is an enabling tool to reach the project's objectives.

The El-peacetolero project, co-ordinated by the Sorbonne University, has the objective of designing a hand-held, low power, embedded optoelectronic system that can deploy AI for in situ real-time measurement, identification and diagnosis of the material state of ageing polymers in an industrial environment, particularly in the nuclear sector at technology readiness level 7 (preindustrial prototype). This tool, when pointed at the polymer, uses a machine learning trained algorithm to assess in real time if degradation has occurred.

Another relevant example is the study carried out by a group of researchers, working for EUROfusion, in the field of diagnostics and control of plasma instabilities in tokamaks[10]. A diagnostic and control system usually monitors known phenomena. However, in the field of plasma physics, there are only so many plasma instabilities which are known. This considerably complicates reliably controlling a plasma. Researchers are training a machine with data sets regarding known instabilities and with this knowledge the machine can control other (unknown) scenarios.

Digital twins

The use of digital twins in radioactive waste management is also an interesting case of innovative technology use. One of the key goals of the EU-funded PLEIADES project is to develop a digital-twin inspired from the Building Information Modelling (BIM)[11] concept, which enables all the information related to the construction of a new building to be managed in a single 3D model. Adapted to the dismantling of a nuclear installation, the digital twin developed within PLEIADES will gather all the relevant data for describing the nuclear facility and radiation status.

The digital twin allows to plan the dismantling & decommissioning (D&D) process but also to continuously adapt the process based on field feedback and to update the project status during the whole decommissioning activity.

[10] A tokamak is a device which uses a powerful magnetic field to confine plasma in the shape of a torus. The tokamak is one of several types of magnetic confinement devices being developed to produce controlled thermonuclear fusion power.

[11] Building information modelling (BIM) is a process involving the generation and management of digital representations of the physical and functional characteristics of places.

The data constituting the digital twin depends on each D&D project, but the whole methodology, the platform and connected simulation tools and the best practices are common and can be shared between projects and actors around Europe.

Space exploration

Current nuclear batteries, Radioisotope Thermoelectric Generators (RTGs), are Pu-238[12] fuelled and have low conversion efficiencies. This means that substantial amounts of fuel and large RTGs are needed to power space missions, which increases the weight to be launched by the space rocket, adversely affecting rocket payload capability.

Neither Pu-238 nor Radioisotope Power Systems (RPS), of which RTGs are a subsystem, are currently manufactured on European soil. The EU-funded PULSAR project aims to further develop technology and capabilities in Europe to produce Pu-238 to fuel radioisotope power systems (RPS). Its second objective is to significantly increase the efficiency of the RPS thanks to an advanced Stirling engine. PULSAR is a step forward for Europe to become an autonomous global leader in space exploration.

Conclusions, further plans and recommendations

Innovation is a cornerstone of the Euratom research and training (R&T) programme, which supports the application of innovative technologies and the development of disruptive industries. The effectiveness of the programme in reaching its objectives and therefore also its capability to foster innovation, are regularly evaluated by means of tools like interim programme evaluations.

Currently, artificial intelligence and digital twins are among the most innovative technologies employed in the Euratom funded projects, particularly in the fields of fusion research, material science and radioactive waste management. The Euratom R&T programme also funds research promoting the evolution of industries which could possibly revolutionise the use of nuclear heat and energy, like hydrogen production, process heat production and space exploration.

Supporting innovation in nuclear research is crucial for advancing clean energy solutions and addressing global challenges such as climate change and energy security. The Euratom R&T programme is a key contributor to the pursue of this objective in Europe.

[12] Plutonium-238 is a radioactive isotope of plutonium. Plutonium-238 is a very powerful alpha emitter and it is suitable for usage in radioisotope thermoelectric generators (RTGs).

Japan Atomic Energy Agency – Innovation at JAEA

Abstract

The Japan Atomic Energy Agency (JAEA) mission is to contribute to the welfare and prosperity of human society through nuclear science and technology. To achieve it, our research and development is based on three core pillars, through which nuclear energy and renewable energy coexist most effectively. The pillars are nuclear-renewable synergy, sustainable nuclear energy, and ubiquitous nuclear technology. For the mission, we aim to return value to society through innovations including improved safety of light water reactors, development of advanced reactors such as fast reactors and high-temperature gas reactors, reduction of the volume and toxicity of high-level radioactive waste, the closed cycle, medical isotope production, and uranium storage battery development.

Introduction

JAEA's research and development (R&D) activities are based on our three core pillars: making nuclear energy sustainable, pursuing nuclear-renewable synergy, and making nuclear technology ubiquitous.

Making nuclear energy sustainable: Some say that although nuclear power is carbon-free, it is not green because of radioactive waste. To be accepted as a sustainable source of energy, we must reduce the amount of radioactive waste and its toxicity to a reasonably acceptable level. Also, ensuring the safety and security of nuclear facilities is the key to gain the trust of the public.

Pursuing nuclear-renewable synergy*:* Safety and cost effectiveness are prerequisite. We need to grasp the overall picture of the energy market towards net-zero emissions and optimise the role of nuclear energy when used with other energy sources, mainly variable renewable energies.

Making nuclear technology ubiquitous: We will widen the potential of the technology so that the application can be maximised in a wide range of fields other than energy.

We believe that our R&D in these pillars will lead to innovation.

Innovation portfolio

JAEA's innovation portfolios are made up of R&D activities for the pillars. The activities include those for:

- acceptance of nuclear technology as a sustainable energy source by ensuring safety and security
- the synergy by efficiently coexisting nuclear with renewables
- ubiquitous nuclear technology by maximising its potential.

We have been developing the Generation IV (Gen-IV) reactors, namely sodium-cooled fast reactors (SFRs) and high-temperature gas-cooled reactors (HTGRs) that provide S+3Es[13]. These and other activities will pave the way for the third pillar, which we regard as disruptive innovation.

Our disruptive innovations below can transform the conventional energy market other than the nuclear field. These include:

- reduction of the volume and toxicity of high-level radioactive waste using a fast reactor;

[13] S: Safety, 3Es: Energy security, economic efficiency, and environment.

- small modular reactors (SMRs) or advanced modular reactors (AMRs), equipped with cutting-edge seismic isolation technology, which will dramatically expand siting flexibility close to a populated area with high electricity demand;
- additive manufacturing (3D printing technology) of ceramic and oxide fuel, which will solve human resource challenges;
- development of ARKADIA[14];
- uranium-based redox flow (URF) storage battery with recycled depleted uranium;
- separation of useful chemical elements from spent fuel;
- power generation using heat from radio isotopes (RIs);
- radioisotopes (RI) production for medical use;
- hydrogen production using nuclear heat.

Possible applications of innovation

We believe our disruptive innovations with possible applications below will create a new era for the nuclear industry.

Reduction of the volume and toxicity of high-level radioactive waste using a fast reactor

One of the public's concerns is the management of radioactive waste. With its cycle technology, fast reactors can reduce the volume and toxicity of high-level radioactive waste by separating and recovering long-lived nuclides and transmuting them into short-lived ones. The process uses reprocessing technology for recovering plutonium and uranium from spent fuel as well as fuel fabrication technology for MOX. Achieving this technology will gain the acceptance from the public.

SMRs or AMRs that can be located close to a populated area

Japan's floating seismic isolation system (FSIS) uses air cavities arranged in rows for reducing seismic response and associated orifices for dissipating seismic energy. These are installed in the structural platform paired with the base of an SMR plant that floats in a water pool. The FSIS is a passive system with design adaptable to a broad range of site seismic conditions and capable of reducing the seismic response of the paired SMR in the horizontal and vertical directions.

The technology is potentially deployable with reactors of any type and with a plant containing single or multiple reactor units. In co-operation with domestic research and industrial partners, JAEA has recently concluded a series of large-scale demonstration tests for the innovative FSIS system intended for pairing with SMRs to enable siting feasibility, including in areas of high seismicity. JAEA and its industry partners have begun pre-application engagement with the US Nuclear Regulatory Commission for the FSIS paired to an SMR design.

Additive manufacturing (3D printing technology) of ceramic and oxide fuel to solve human resource challenges

Our innovative ceramic stereolithography laser technology, in development, will be applied to 3D-printing fabrication of ceramic and oxide fuels typically used in advanced reactors such as SFRs and HTGRs. JAEA has been focusing on a multi-scale and multi-physics simulation technology that models

[14] ARKADIA: Advanced reactor knowledge and AI-aided design integration approach through the whole plant lifecycle.

the entire physical phenomena that govern the additive manufacturing processes ranging from fuel material slurry preparation to laser printing and then to sintering steps.

JAEA has recently concluded the test validation of the elemental models of the simulation system intended as a design and analysis tool to assist throughout fuel design, development, and manufacturing processes. This simulation technology will accelerate the development of new, high-performing fuels for advanced reactors and promote the high-quality design and fabrication of the fuels. We believe this will help address the human resource challenges.

Development of ARKADIA

ARKADIA is an AI-powered database that consists of three systems: the Virtual Plant Life System (VLS), the Enhanced and AI-aided optimisation System (EAS), and the Knowledge Management System (KMS). It will enable designers to design a reactor efficiently by providing AI-based insight into optimised design and safety evaluation combined. This will drastically improve and accelerate design work and support private sectors that examine a wide range of reactor design concepts.

So far, we have developed the tools for basic design optimisation and safety evaluation. We will improve and integrate the tools and advance the AI technology to optimise design work of plant systems including the plant life cycle safety, economic efficiency, and maintenance. The development effort taken for ARKADIA benefits advanced reactor technology from the perspectives of maintenance and improvement of nuclear technology and development of human resources.

URF battery with recycled depleted uranium

Japan has a large amount of depleted uranium that is made by separating fissile uranium-235 from natural uranium. To reuse the depleted uranium as a resource, JAEA is developing URF batteries that use the redox reaction of uranium. The URF batteries can store excess electricity generated by renewable energy sources, reducing the burden on thermal power generation and providing stable electricity supply. JAEA will build a small-scale storage battery using uranium as an active material in 2024 and aim to store MWh-scale electricity generated by nuclear and renewable energies in 2035.

Separation of useful chemical elements from spent fuel

Spent fuel contains a variety of valuable resources such as RIs, platinum, and rare-earth elements. At present, the separation of these useful elements from spent fuel has not yet fully established. JAEA is working on it using the solvent extraction method, which is also under development, and on a highly element-selective separation technology using a laser-assisted method based on a photo-induced reaction. JAEA’s current target is to separate a small amount of Americium in 2024 and a few kilogrammes of useful elements from actual waste in 2035.

Power generation using heat from radioisotopes

In general, thermoelectric materials are semiconductor-based and vulnerable to radiation. However, if they are made resistant to radiation, various RIs can be used as heat sources for nuclear batteries. Converting heat from radioactive waste and radioisotopes into electricity could provide a semi-permanent, maintenance-free power source in severe environments that are not easily accessible to humans. JAEA is focusing on spintronics, a hybrid technology of electricity and magnetism, and is developing a new technology based on the radiation-resistant thermoelectric elements. Our aim is to demonstrate power generation using radioisotopes in 2024 and W-scale power generation at nuclear facilities in 2028.

Conclusions, further plans and recommendations

JAEA has developed the innovation strategies described above and invested resources in them, aiming at advancing nuclear science and technology. These disruptive innovation strategies will function as a dynamic roadmap in parallel with our development strategies and can be a driving force for Japan's nuclear industry rather than mere plans. Currently, Japan is pursuing the advanced reactors JAEA is developing under the "green transformation" investment. It is important that sufficient resources are allocated to R&D, technology infrastructure, and human resources. JAEA believes that the S+3E should be achieved and improved through international co-operation while ensuring the core competencies of each organisation, so that these strategies will be efficiently deployed in the world.

Korea Atomic Energy Research Institute - Exploration for functions of international co-operation: focusing on the co-operation with the KAERI's collaboration with the NEA

Youngjune Kim, Head, International Co-operation Team

Abstract

This article aims to showcase the significance of international collaboration as one of key factors in nuclear innovation, focusing on KAERI's collaboration with the NEA as a case study.

As Korea's sole comprehensive nuclear research institute, KAERI maintains a broad network of international collaborations, notably with the NEA, engaging numerous researchers across various NEA sub-entities and international research projects. The collaboration between KAERI and the NEA has notably enhanced KAERI's R&D productivity, facilitated the identification of novel innovative technologies, and contributed to shaping essential policy agendas to enhance national capacity on nuclear technology innovation. The article underscores the necessity of expanding international collaboration to address future challenges in the nuclear energy sector and suggests fostering networking among international collaboration coordinators.

Introduction

International co-operation in the nuclear sector is imperative for fostering innovation in nuclear technology. Nuclear technology has been developed with public resources due to special characteristics - the long time frames, expense and high risk of failure. Its integration into the system is influenced by government policies, regulations, and societal environments beyond the confines of the research laboratories. International collaboration in this context has been an option to maximise effectiveness of research and development (R&D).

Concerns regarding dual-use capabilities have spurred the establishment of international regimes aimed at preventing the uncontrolled proliferation of nuclear technology and materials. Consequently, international co-operation in nuclear energy is driven by various factors, including the cost-effectiveness of R&D, risk mitigation, adherence to standards and regulations that consider proliferation risks from initial technology development to global supply chains, as well as international support for peaceful applications. In essence, nuclear technology is international.

Nuclear international co-operation is expected to gain more attention in the 21st century. With nuclear technology assuming greater importance as a crucial energy source in the era of carbon neutrality and for its versatility across various applications, responding to shifts in market dynamics necessitates innovative approaches to enhance safety, affordability, and accessibility. Against this backdrop, international co-operation emerges as a pivotal factor in effectively addressing the rapidly evolving nuclear technology landscape and facilitating the development of advanced technologies.

This article explores how international co-operation can be leveraged within the evolving nuclear R&D landscape, using the case of the Korea Atomic Energy Research Institute (KAERI) participation in multilateral co-operation focusing on the Nuclear Energy Agency (NEA) as a reference point. While KAERI's multilateral collaboration primarily pertains to nuclear power development within Korea, insights gained offer implications for the evolution of nuclear international co-operation.

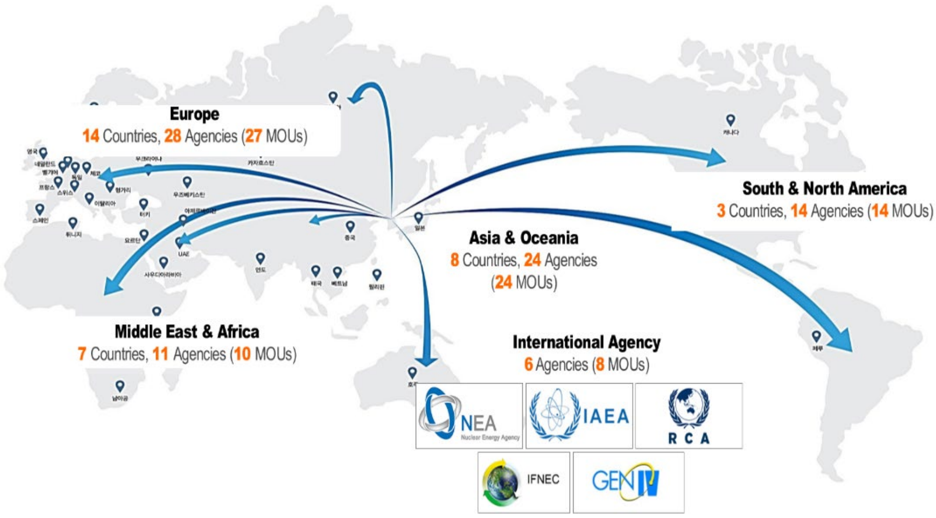
Overview on KAERI international co-operation

As a government-funded research organisation, KAERI endeavours to bolster national energy security through the pursuit of safe and sustainable nuclear energy for a carbon-neutral future.

To achieve this goal, KAERI conducts diverse research and development activities in basic and applied science and technology, undertakes institutional and policy studies, and fosters the training and development of specialised human resources to drive national capacity for nuclear technology innovation. In this context, the nature of international co-operation is geared towards advancing the knowledge necessary for fulfilling the institute’s mission.

With over 60 years of experience in international co-operation, KAERI currently maintains 83 bilateral co-operation agreements with 77 organisations across 32 countries.

Figure 1.1 Map of the KAERI’s global network

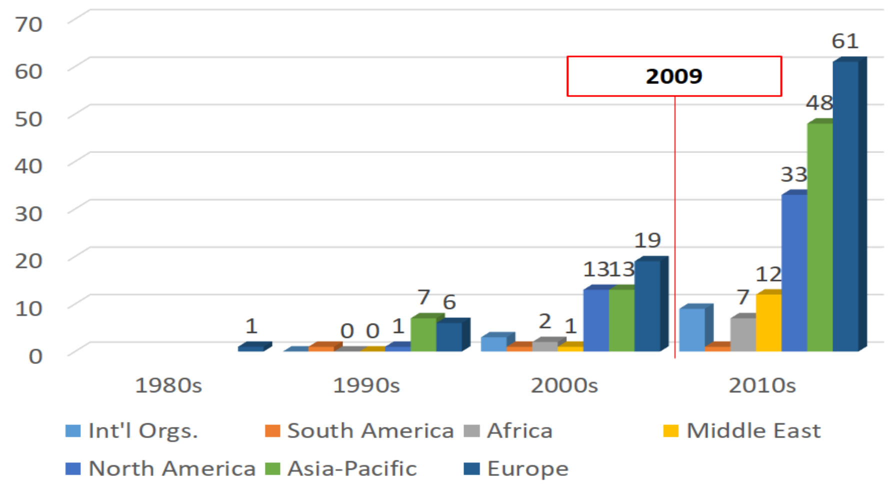


Source: KAERI

KAERI participates in multilateral co-operation with international organisations and entities, including the Nuclear Energy Agency (NEA), the International Atomic Energy Agency (IAEA), the Generation IV International Forum (GIF), International Framework for Nuclear Energy Co-operation (IFNEC), the Regional Co-operation Agreement for research, development, training related to nuclear science and technology for Asia and the Pacific (RCA), and others.

It is noteworthy that the KAERI global network has expanded since 2009, marked by initiating major overseas nuclear construction projects, such as the construction of nuclear power plants in the United Arab Emirates in 2009 and a research and training reactor in Jordan. Multilateral co-operation activities are also expanding both qualitatively and quantitatively, with 83 KAERI experts actively participating as a representative for each of 75 subsidiary bodies (e.g. working groups, standing committees, task forces, and others) of international organisations.

Figure 1.2 Trends in MOUs between KAERI and international partners (1980s-present)



Source: KAERI

Specific cases of KAERI activities for enhancing nuclear technology innovation

KAERI's participation in NEA activities is driven by multiple factors, encompassing research endeavours, identification of emerging challenges, and addressing global issues for future innovation.

First and foremost, the primary motivation for international co-operation in science and technology is the advancement of scientific knowledge. Participating in the NEA enables KAERI to enhance research productivity efficiently and effectively. KAERI nominates 48 staff to participate in NEA activities and engages in multiple research frameworks, including joint research projects, such as Fire Risk Assessment through Innovative Research project (FAIR), PSI, Switzerland, (PANDA), Rod Bundle Heat Transfer (RBHT) project and the KAERI-led, Advanced Thermal-hydraulic Test Loop for Accident Simulation project (ATLAS).

Among the various motivations for participating in NEA-driven joint research frameworks, the most important driving force is cost-sharing, facilitated by access to both hard infrastructures, such as advanced research facilities in member states, and soft infrastructures, including experimental data.

The NEA has garnered acclaim within international societies for its high-quality research frameworks, providing access to state-of-the-art research facilities and facilitating peer reviews among experts from distinguished institutes nominated by each member state government. The project using the Halden Reactor in Norway, which shut down in 2018, had been a hub for testing fuel and reactor components that led each members including KAERI to enhance technology development within the NEA framework. Sharing soft infrastructure such as experimental data also allows the member states to conduct technology development efficiently.

Nowadays, KAERI is preparing to join more NEA research programmes, including the Framework for Irradiation Experiments project (FIDES)-II and the newly initiated Waste Integration for Small and Advanced Reactor Designs project (WISARD), as an accelerator for developing advanced nuclear systems and waste management technology.

Secondly, international co-operation helps set a policy agenda for new technological innovation. Under the OECD umbrella, the NEA wields influence within policy communities, including policymakers, industry stakeholders, academia, and research organisations, shaping nuclear policy discourse on emerging challenges. It serves as a platform for introducing innovative technologies crucial for ensuring the sustainable operation of nuclear power, particularly in areas such as nuclear safety and waste management. The International Workshop on Disruptive Technologies for Nuclear Safety Applications, co-hosted by NEA, KAERI, and the Korean Nuclear Society in May 2023, underscored how the information and communications technology (ICT) can bolster nuclear safety, heightening national awareness of the transformative potential of converging technologies in Korea.

Finally, while one of the core roles of international organisations is to address global issues, it is also important for members to prioritise issues and define strategies to embrace and disseminate future innovative technologies. In September 2023, the Joint Communique, developed by 20 member states with NEA support, acknowledged the pivotal role of nuclear energy in de-carbonisation and delineated a nine-point agenda encompassing nuclear financing, policy and regulation, R&D, supply chains, fuel supply, skills development, public engagement, energy systems and innovation, and international co-operation. International organisations' role as agenda-setters can streamline decision-making processes, fostering policy evolution by shaping perceptions across diverse stakeholder groups.

The Korea Atomic Energy Commission recently announced the policy direction to expand support for advanced nuclear technology programmes within the framework of Public and Private Partnership (PPP) and international collaboration. This virtuous circle of progress, where issues raised through international organisation are reflected in domestic policies, is an important example of why international co-operation is crucial for future preparedness.

Conclusion

This article underscores the utility of international co-operation as an innovation catalyst through KAERI's collaboration within the NEA framework. In summary, international co-operation in nuclear technology has the function of improving R&D productivity as well as promoting innovation in nuclear technology by providing policy agendas and directions. There is no disputing that the safe and sustainable use of nuclear technology requires more innovative approaches than conventional methods. From this perspective, collaboration with the NEA allow KAERI to help create an environment in which R&D can be managed efficiently and effectively through international co-operation.

Further exploration will be essential for advancing future international co-operation programmes to create more innovation opportunities. Establishing a network of international co-operation among member states warrants consideration. A networking approach among international co-operation coordinators can facilitate knowledge sharing through comparative research, enabling a comprehensive review of successes and failures in various international collaborations. Such endeavours can underscore the importance of international co-operation and inspire creative approaches to promote more international joint research initiatives, further enhancing the efficacy of international collaboration within the NEA.

NRG Pallas - Driving innovation in nuclear energy through advanced technologies and cross-sector collaboration

Abstract

Six decades of funded research have resulted in a nuclear ecosystem in the Netherlands with benefits and many breakthroughs for the worldwide nuclear community covering both the medical as well as the energy domain. NRG|PALLAS and the High Flux Reactor (HFR) have played a key role in the advancement of medical isotopes and the progress made within the field of advanced fuel and material qualification. Research programmes in collaboration with international partners in the field of nuclear safety, long term operation, decommissioning, radioactive waste management and radiological protection continuously guarantee a state-of-the-art level of expertise securing safe operation of nuclear facilities. The construction of the PALLAS reactor – the successor of the HFR – and the plans for the new build of two GENIII power plants are attended with budgets to reinforce the knowledge infrastructure and to stimulate new industrial activities to give a major impetus on the development of innovative technologies within the field of energy and health. An example is the recently opened FIELD-LAB, a state-of-the-art processing facility to produce medical isotopes for clinical trials facilitating research and development of promising isotopes and new products for the treatment of cancer.

The Dutch nuclear landscape

The foundations of the Dutch nuclear infrastructure were laid in the1950s and 1960s. The ambition to benefit from the promise of nuclear energy led to large investments in experimental facilities and R&D programmes. This and the close co-operation between government, research institutes and Dutch industry resulted in a flourishing landscape with activities that encompass large parts of the nuclear value chain, from the enrichment plants for uranium and stable isotopes to nuclear power plants to an advanced facility for the long-term storage of radioactive waste. Whereas interest in nuclear energy showed a decline in the 1980s and 1990s, the Netherlands caught up with the advances within the field of medical isotopes, eventually becoming the most important supplier of medical isotopes in the world.

Recent developments have moved the Netherlands on the brink of a new nuclear era. Two years ago, the Dutch government announced plans for the new build of two GENIII+ reactors and intention to prolong the operation of the current Borssele power plant beyond 60 years. In addition, the government allocated budget for the PALLAS reactor, the successor of the High Flux Reactor (HFR) in Petten, securing the production of medical isotopes and nuclear R&D beyond 2030.

Clearly, these developments have – and will continue to have - a major impact on the Dutch nuclear landscape. New budgets to reinforce the knowledge infrastructure and to stimulate new industrial activities give a major impetus on the development of innovative technologies within the field of energy and health. This document gives an account on some of the recent technological advances within the domain of nuclear energy and medical isotopes including the expansion of the nuclear R&D infrastructure.

A new generation of nuclear infrastructure

NRG|PALLAS, the operator of the HFR, is focusing on both isotope production and R&D, for energy and health applications. Each day, the HFR provides isotopes for 30 000 patient doses, adding up to more than 10-million patient doses per year. For many decades the HFR has also played a pivotal role in worldwide research and qualification of a wide range of fuels and reactor materials.

The HFR is one of the largest Mo-99 producers in the world. Diagnostic isotopes, notably Mo-99, are required for a larger part of the nuclear medicine procedures worldwide. Increasing prosperity in larger parts of the world, increasing life expectancy and ever better diagnostics for an ageing population contribute to a growing demand for nuclear medicine; the increased use of therapeutic isotopes reinforces this growth.

The HFR started operation in 1961. The continuation of the important production function of the HFR will be taken over by the PALLAS reactor in the future. In 2023, the Dutch government decided for full-financing of the PALLAS-reactor. The building preparations for the PALLAS-reactor are ongoing; the target is to have it operational around 2030.

The PALLAS-reactor will produce medical isotopes for therapy and diagnosis, facilitate the innovation for new nuclear medicines, and hosts provisions for irradiation experiments for the worldwide nuclear energy community. NRG|PALLAS currently focuses on identifying the questions and needs of the global nuclear energy community like the NEA FIDES-II programme. That input will help determine the scope, design and capabilities of the various irradiation facilities.

A key element in the medical innovation strategy of NRG|PALLAS is the ***FIELD-LAB***. This state-of-the-art production facility was opened in December 2023 together with customers and partners, the province of North Holland, and the Dutch government. The FIELD-LAB is a processing facility to produce batches of medical isotopes for clinical trials. The FIELD-LAB enables and facilitates research and development of promising medical isotopes and new products for the treatment of cancer, together with FIELD-LAB partners. This innovation infrastructure will further enlarge the health impact of the HFR and PALLAS.

Innovations with the energy domain

NRG Pallas' R&D programme PIONEER (Program for Innovation and cOmpetence development for NuclEar infrastructurE and Research), commissioned by the Ministry of Economic Affairs and Climate Policy, is one of the key elements of the national nuclear knowledge infrastructure. The objectives of the programme are:

- Maintain and develop the level of nuclear knowledge to secure safe operation of nuclear facilities in line with the policy goals in the field of nuclear safety, radioactive waste and radiological protection.
- Develop new technologies and innovations to advance the role of nuclear technology in the energy mix (Figure 1.3).

Below, key developments within each of the seven themes of the programme, that cover the life cycle of nuclear infrastructure, are highlighted (see also Figure 1.4).

Long-term operation
Innovations are related to modelling and simulation of phenomena which play an important role in a long-term operation (LTO) assessment, such as the time-limited ageing analyses (TLAA), including for phenomena like concrete ageing, fatigue (thermal and environmental), fracture mechanics, and irradiation assisted stress corrosion cracking fatigue. On the experimental side, focus is on the development of an experimental ecosystem for in-depth study on the effects of embrittlement of reactor pressure vessel materials using advanced techniques like mini coupon testing and reconstitution of sample fragments. For this research both surveillance samples from nuclear power plants as well as samples irradiated in the High Flux Reactor in Petten are used.

Nuclear modelling and simulation
Innovative work is related to reactor physics, turbulence and heat transfer modelling, simulation of fluid-structure interaction, hydrogen distribution and combustion modelling using 3D simulation

methods, molten core (corium) modelling, and the development of multi-phase (e.g. to analyse behaviour of water-steam mixtures), multi-scale (e.g. combing 1D and 3D methods), and multi-physics (e.g. coupling reactor physics to thermal hydraulics and thermal mechanics methods) numerical solvers leading to a nuclear numerical toolkit.

Nuclear safety and compliance
The theme of nuclear safety and compliance puts emphasis on deterministic as well as probabilistic safety analysis methods and facilitating methods for their application, like development of uncertainty quantification methods and application of these in so-called Best Estimate Plus Uncertainty approaches. The innovation within the field of probabilistic safety analyses considers ageing aspects, dynamic aspects, combined safety and security aspects, reliability of mobile equipment, and radiological impact analyses for which the Netherlands is a forerunner from a regulatory point of view.

Fuels and materials
Since NRG Pallas operates the High Flux Reactor, a material test reactor in operations since the 1960s, and PALLAS is constructing the new PALLAS reactor for medical isotope production and fuel and material research, which is an important theme. Within this theme, innovations in the field of in-core instrumentation for irradiation experiments is an important topic. With respect to fuels, emphasis is on enhanced performance fuels while with respect to materials emphasis is on creep and behaviour of additive manufactured materials. To this end NRG|PALLAS and JRC are currently designing a new irradiation facility to establish the effects of prolonged exposure of neutron irradiation on the mechanical properties of advanced candidate-materials for application in future water-cooled SMR and advanced (non-water cooled) reactors.

Radioactive waste management
Radioactive waste management mainly focuses on characterisation and decommissioning. The revived interest in nuclear energy and the surge in the demand of medical isotopes require development of technologies capable of processing new waste streams to durable, stabilised forms. The programme anticipates these developments with studies into the use of 3D-printed materials in a radiating environment, radiochemical analysis techniques for difficult to measure nuclides, thermodynamic modelling of waste packages including the use of digital twins, shielding simulations, dose reduction within decommissioning.

Radiation protection
The innovation programme in the theme Radiation Protection has three focus areas: biosphere, dosimetry, and naturally occurring radioactive materials (NORM). Within the biosphere area, topics include aquatic and terrestrial modelling, environmental monitoring, and advanced dispersion modelling. Dosimetry focuses on the topics macro-, micro- and nano dosimetry including the development of biokinetic models to gain insight into distribution of nuclides (medical isotopes) in the human body. Finally, the NORM area deals with recycling NORM streams and concrete waste handling.

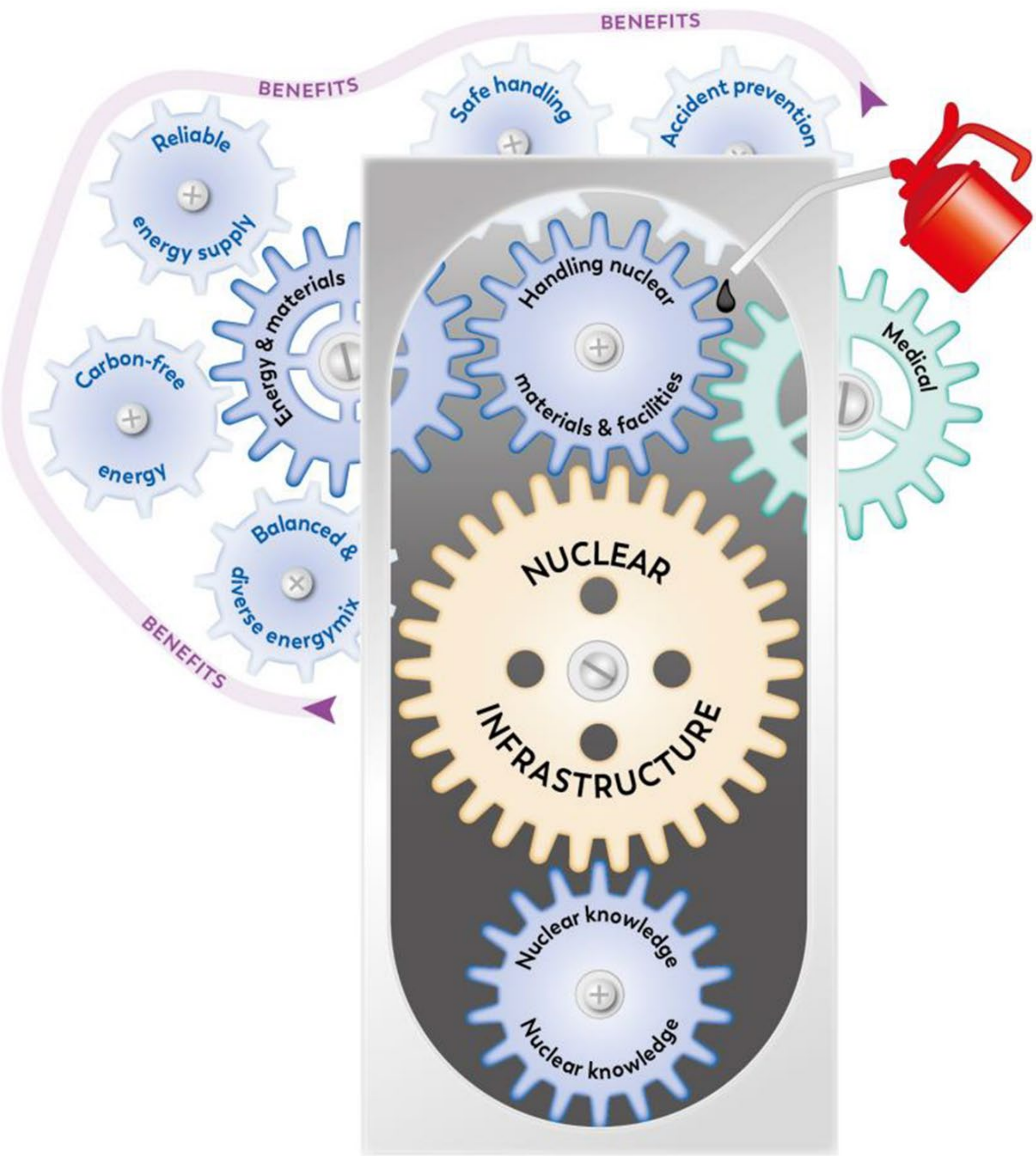
Innovative nuclear systems
Within the theme of Innovative Nuclear Systems, developments on small modular reactors (SMRs), high-temperature, gas-cooled reactors (HTGRs), liquid metal fast reactors (LMFRs), and molten salt reactors (MSRs) are being considered. Both experimental irradiations using the high flux reactor (HFR) and post-irradiation facilities are being used, as well as simulation techniques to support design and safety assessments of such reactors. One of the most prominent examples of groundbreaking experiments concerned a two-year irradiation of Th-bearing salts, the first fuelled salt experiment since the experiments at Oak Ridge in the 1960s. This instrumented capsule-based experiment was designed to acquire practical knowledge on handling of irradiated, fuelled salts and to gain insight in the behaviour of the salts, the fuel and the fission products during irradiation.

Innovations within the health domain

Projections of the number of new patients suffering from cardiovascular diseases and cancer show a significant increase. Nuclear medicine is foreseen to play an increasingly important role in patient treatment. Traditionally the role was mainly played by Mo-99, the workhorse of nuclear medicine. The advance of Mo-99, and other medical isotopes for diagnostic applications, is also referred to as the first wave of nuclear medicine. Currently we're on the brink of the second wave with a strong increase of beta-emitting therapeutic isotopes, such as Lu-177. And one can already register the advent of the third wave with alfa-emitting isotopes. Projections of the number of future treatments with therapeutic isotopes in Europe indicate a fivefold increase from 2020 to 2040.

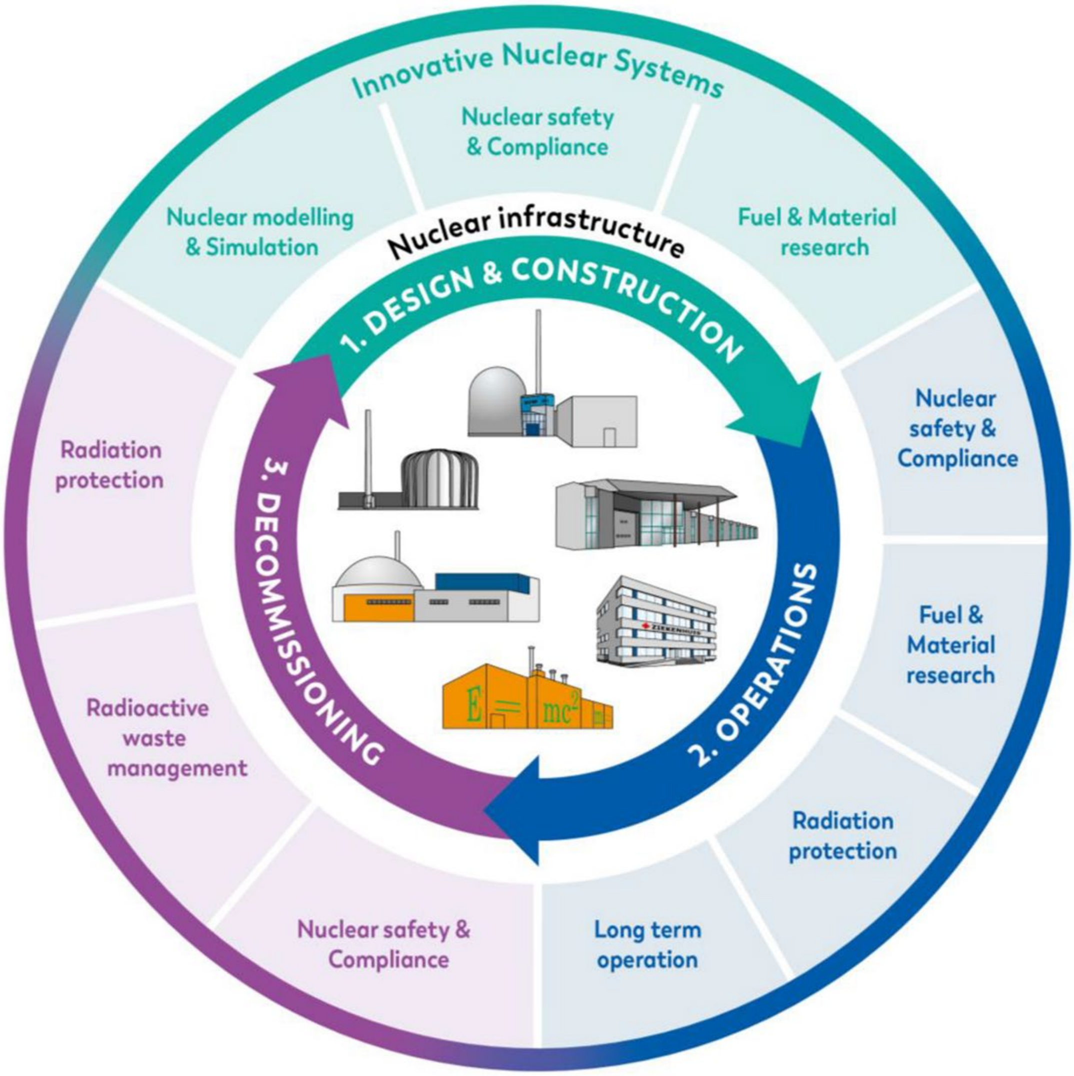
With the developments in FIELD-LAB, promising medical isotopes are becoming available and new end products for the treatment of cancer are being developed together with FIELD-LAB partners. At the end of 2023, the FIELD-LAB production facilities were realised. Good progress has been made with the development of the production processes of Lu-177 and Pb-212 in line with the expected implementation in the FIELD-LAB facilities, planned to be delivered by the end of 2024. Then, NRG|PALLAS will supply batches of material to academic and industrial partners for clinical trials. Another major milestone worth mentioning: six lung cancer patients were included in the human pilot study in 2023 with radioactive [195mPt] Cisplatin, a product developed by NRG|PALLAS with partners. The product could be used to determine whether standard chemotherapy will help the patient. Other important results achieved with partners of the FIELD-LAB consortium are the promising results of pre-clinical studies with innovative end products based on Pb-212.

Figure 1.3 Nuclear infrastructure and knowledge as a gearbox



Source: NRG Pallas
Note: The combination of nuclear knowledge and infrastructure with research (budget; the oil) ensures a working engine with innovations for the domains of Energy & Materials, managing and safe handling of nuclear materials and facilities, and medical Isotopes.

Figure 1.4 The life cycle of nuclear infrastructure with the relevant research and innovation themes of the nuclear R&D programme PIONEER of NRG|PALLAS for each of the three phases



Source: NRG Pallas

United Kingdom National Nuclear Laboratory - Advancing the Nuclear Sector Through Innovation, Collaboration, and Next-Generation Technologies

The United Kingdom's National Nuclear Laboratory (NNL) for fission operates nationally and undertakes research across the entire fuel cycle. As a science and technology organisation one of its key facets is the translation of science and engineering into sector-benefitting innovations. Government owned and operating on a commercial basis, it provides services and technologies for many of the key players in the nuclear sector. This operating model enables NNL to focus on delivering tangible, value-add products and services to support its customers and the UK Government's missions; in particular, net zero by 2050.

Through a variety of mechanisms, it delivers innovation across its Focus Areas and actively engages internally and externally to maximise opportunities. Partnership and collaboration with innovators, customers and suppliers, are core tenets of the innovation programme.

With a broad agenda, NNL serves to deliver on the immediate needs of its customers while conducting R&D in next generation technologies, such as advanced fuels and alternative uses of nuclear energy and heat within integrated energy systems.

The NNL for fission operates across nine sites and undertakes research across the entire fuel cycle. It is the custodian of ~£1.5Bn of nationally important infrastructure that encompasses active and non-active testing and experimental facilities. As a science and technology organisation its purpose is *nuclear science to benefit society*. To enable NNL to maximise its operations and deliver benefit to society and the sector as a whole; it develops capability through its Science & Technology Agenda[15] which is delivered through its four Focus Areas[16]:

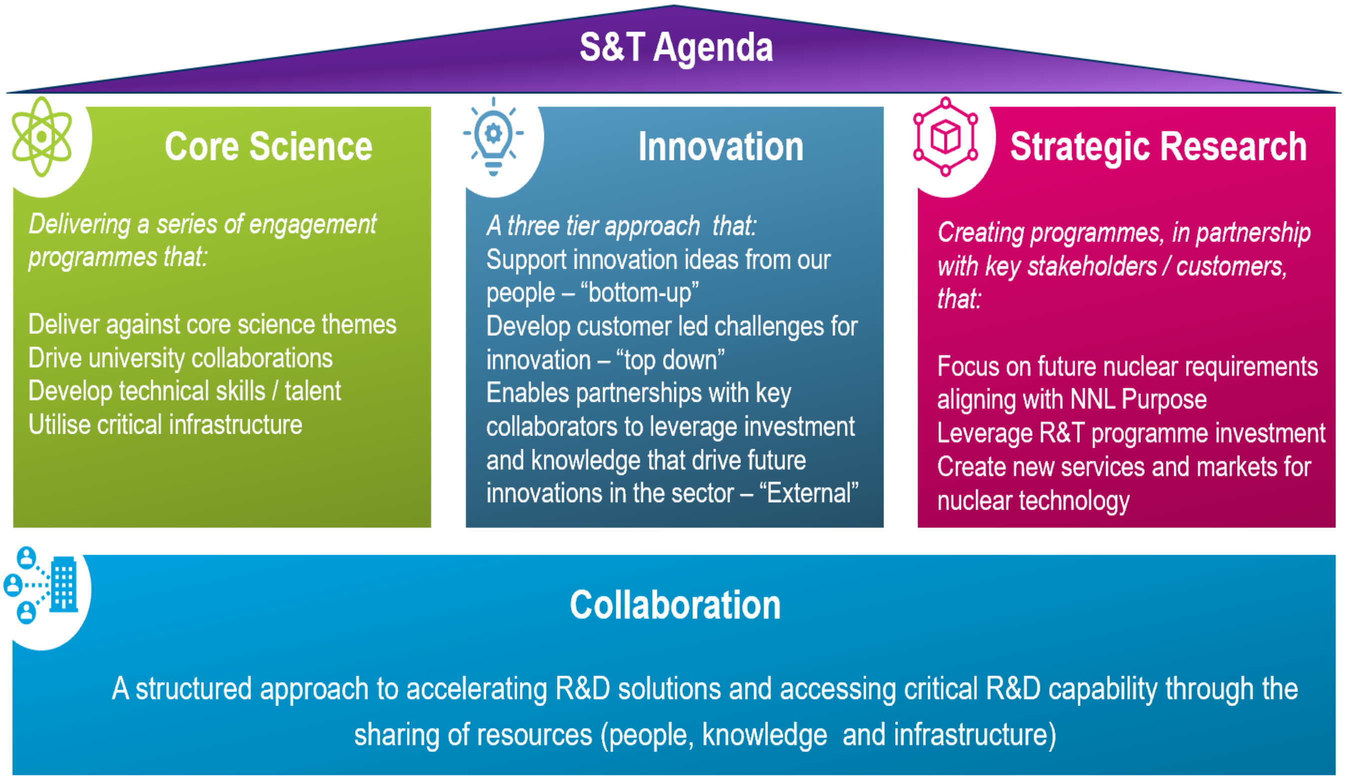
- **Clean Energy**: Securing the UK's place as a global leader in the clean energies of the future by developing advanced nuclear technologies and leading their deployment.
- **Environmental Restoration:** Driving a step change in the way legacy and future wastes are processed by applying innovative science and breakthrough technologies.
- **Health & Nuclear Medicine**: Establishing an Indigenous UK supply of vital medical radioisotopes.
- **Security & Non-Proliferation:** Facilitating the global deployment of new nuclear technologies by ensuring security and non-proliferation.

As NNL evolves and sets its sights firmly on the international agenda of net zero by 2050, the role of innovation in nuclear is critical to address the challenges we face. The Science & Technology Agenda enables NNL to deliver innovation as one of its core pillars (Figure 1.5)) alongside its core science and strategic research programmes. All programmes within the Science & Technology Agenda are funded by NNL's earnings to reinvest, where a portion of its profits are re-invested to advance NNL's capability.

[15] https://nnl.foleon.com/nnl-st-agenda/our-science-and-technology-agenda/cover/

[16] https://www.nnl.co.uk/focus-areas/

Figure 1.5 Three core pillars of NNL's Science & Technology Agenda



NNL deliver innovation through three key mechanisms:

- **Internally derived**: supporting ideas from colleagues across the organisation, open to anyone and everyone. Colleagues can apply for funding to develop ideas where they see an internal need, either technological or process-derived, or where a customer need has been identified and they feel they have a solution.
- **Top-down challenge led**: challenges are identified by colleagues and stratified by the Innovation Team to determine the most efficient innovation intervention. This may include an internally disseminated challenge, against which colleagues can submit ideas for potential solutions. It may include the Innovation Team running an innovation sprint or a Tiger Team with a select group of end-users and stakeholders, to develop a workable solution. Alternatively, the challenge may be disseminated externally, via NNL's open innovation platform, Open Nuclear[17].
- **Open innovation**: aimed at opening up NNL's challenges to an external, innovator audience. The challenges are visible to anyone in the world and actively marketed to technology organisations and academic institutions. Once a challenge is identified, NNL's proprietary Challenge Statement Sprint is undertaken to develop a clear, accurate and easily understood portrayal of the challenge. These are posted on the Open Nuclear platform; a webinar is held with the challenge holders and potential applicants before submissions are received. NNL welcomes divergent thinking and approaches to challenges from outside of the sector to help address its challenges.

[17] https://opennuclear.nnlinnovation.wazoku.com/home-page.

NNL has a wide-ranging portfolio that purposefully blends low to high-risk projects across its business activities. These can range from internally applied innovations to customer facing, critical support activities. Innovations from across both technical and process oriented innovations are welcome and supported. Given the nature of the business and its legacy operations, there tends to be a dominance of technical innovation ideas submitted, with a leaning towards environmental restoration applications. However, with the launch of NNL's Focus Areas a couple of years ago, the team are seeing a growth in idea submissions from a wider range of technical disciplines. It is anticipated that this trend will continue to grow, both in idea submissions and challenges identified.

The Focus Area of Health & Nuclear Medicine (H&NM) offers great potential for NNL to establish fruitful partnerships with players in non-traditional nuclear sectors, which can benefit from NNL's expertise, facilities and operations alongside complementing their own. The H&NM team are working on taking legacy material from the industry's previous operations and extracting medically relevant isotopes that can be used as targeted alpha therapies in the treatment of cancer. To support this nationally important work, NNL has invested in developing a Radiopharmaceutical Development Lab in its facility in Preston. This is a dedicated lab to exploit and expand the availability of radioisotopes for medical use and is a step change in the way NNL operates.

NNL supports both internally derived ideas and those that are developed with partners from inside and outside of the sector. To generate ideas and address challenges the Innovation Team delivers innovation sprints and Tiger Teams to take a small group of stakeholders through the innovation process and develop minimal viable products. This type of iterative innovation practice ensures teams are developing fit-for-purpose solutions that are deployable and meet the requirements of the end user. Naturally, many of NNL's innovations arise from our customer-intimate approach, where we understand the challenge, the value proposition and end-user requirement.

A colleague in our endoscopy team identified a need to digitise their current working practice of manually recording survey inspection data on fuel pins stored in cooling ponds. This was historically done using pen and paper, which can become contaminated. This process requires manual transfer of data from one format to another to enable statistical reporting. To improve this process a digital system was proposed. Through collaboration with a small-to-medium enterprise app developer, the NNL team has co-developed an app to be used on a tablet, pond side, that allows data from inspections to be recorded and then transferred to our network and automatically processed, ready to be reported to our customer.

At the other end of the fuel cycle, as customers move towards post-operational clean out and decontamination, we've developed a technology that utilises electro pickling to clean contamination-ingrained metallic surfaces. This can effectively reclassify metallic items to either low level or free release material. This has a huge cost saving on the eventual storage of contaminated items and may enable reuse of materials within the industry.

On more of a future, global scale the team at NNL's Preston facility is working on next generation fuels for advanced reactors. This is part of the UK Government's investment in the sector, supporting their ambitions to provide 25% of the UK's electricity from nuclear generation by 2050, putting NNL at the forefront of this exciting and globally important research area.

These are just snippets of a broad range of innovation opportunities that NNL is involved with; it's an exciting place to be.

As a national lab, NNL is mandated to deliver on the government's ambitions for clean energy. Through NNL's activities, it is ensuring the best technologies are deployed, which add a tangible benefit to the UK's energy sector. Through the development and adoption of innovative technologies, the industry has a fantastic opportunity to provide low carbon electricity and heat to decarbonise industries, power homes and deliver on net zero. With the onset of small modular reactors and advanced modular reactors to bolster energy systems, it is vital that the global sector adopts with passion new ways of working and technologies.

NNL is taking a systems approach to understanding where future nuclear plays its part, beyond electricity generation. Whether that's through providing heat to co-located industries that currently require enormous amounts of energy to generate heat, or direct electricity to produce hydrogen. There are many opportunities for nuclear to support such divergent use cases, but we need to deliver on our ambitions and provide solutions at a cost-effective price point. We need to innovate at pace if we are going to hit our growth ambitions and effectively contribute and deliver on net zero 2050. This is exactly what NNL is delivering on through their purpose of *nuclear science to benefit society*.

2. Disruptive Technologies

Artificial intelligence

Electric Power Research Institute - Transforming the Energy Sector with Artificial Intelligence: Current Trends and Future Horizons

Abstract

Artificial intelligence (AI) has emerged as one of the most impactful and transformative technologies of the last few years and is reshaping how business is done around the world. This brief provides a high-level overview of the development, current state, and future path for AI with a focus on the energy sector and associated impacts, including several high-value use cases. This report will also cover an overview of adoption across the energy industry as well as potential future development paths for AI in the energy sector.

Introduction of the technology

Artificial intelligence is a term that refers to the ability of computers or other machines to mimic the performance of or accomplish duties normally requiring human intelligence, logic, and reasoning to execute. The concepts for AI have been around since the mid-1950s, shortly after the introduction of computers. The Dartmouth Summer Research Project on Artificial Intelligence in 1956 has been credited as the founding event for the field of AI (McCarthy et al., 1955). Some of the original workshop participants believed that a major advancement in the nascent field could be accomplished over two months that summer with the ten-person team (McCarthy et al., 1955).

Unfortunately, AI development and progress proved significantly more challenging and complex than originally imagined. Over the course of the last seven decades, the field of AI has gone through several cycles of optimism as well as "AI winters" where investments and excitement declined, and development slowed as well. It has only been in the past 15 years that the convergence of big data alongside modern deep-learning architectures and significantly enhanced processing capabilities have provided the necessary combination to spark dramatic progress in the field of AI.

Most recently, generative AI models, such as large language models (LLMs) like ChatGPT, have witnesses significant progress and are poised to lead AI development into the future with additional capabilities offered by AI to generate accurate text, audio, image, video, and other forms of data.

Advantages and disadvantages

Due to its many potential applications and value (EPRI, 2019, 2023; USECGS, 2023), it is natural that there is excitement around AI, however, AI is not a cure-all for any application. Like other technologies, AI has numerous advantages and disadvantages related to its use (EPRI, 2023; USECGS, 2023). Several of these are discussed below:

Advantages of AI

- Automating complex or repetitive tasks to streamline a range of burdensome tasks from workers.

- Performing tasks that are dirty, dull, or dangerous for humans. AI models don't get tired or bored or distracted from performing a task. This can also help to improve reliability and repeatability.
- Processing vast quantities of data to identify underlying or hidden trends.
- Generating data in the form of text, audio, video, images, etc.
- The use of AI can help to optimise energy usage in homes, buildings, and in energy generation, transmission, and distribution, helping to reduce emissions and positively impacting climate change.

Disadvantages of AI

- AI models typically need large volumes of training data to be useful. Compare this to humans who typically only need one or a few examples of an action or activity to intuit broadly from that instruction.
- AI models, and LLMs in particular, currently require large amounts of energy to train and operate. It is anticipated that continued development of enhanced chips, more efficient models, and other advances (such as quantum computing) will help to reduce the high energy needs of AI over time.
- AI models often cannot extrapolate (or extrapolate poorly) outside of the parameters they were trained on.
- AI models rely on the quality and accuracy of the data they are trained on. If a model is trained on inaccurate, false, or biased data it is likely that the model will produce inaccurate, false, or biased results. In fact, it can enhance and reinforce these errors and issues.
- Most AI models are not currently able to explain to a user why they produced the result that they did and are seen as a black box. This is an actively studied field called explainable AI. While the field is still nascent, it is progressing rapidly and anticipated that progress in this area will facilitate additional and more detailed explainable AI models in the future.
- Data privacy and security is a major concern. AI models are often trained on very large sets of data that may contain personally identifiable information (PII) or other forms of sensitive data that should not be made publicly available. For this reason, model training data need to be maintained confidential from accidental exposure or malicious attempts to obtain the training data.

Possible applications

AI has myriad use cases across essentially every industry in existence today. Hundreds of potential use cases across industries can be achieved from protein folding and drug discovery in healthcare to tailored ads and products in advertising. These benefits are not confined to a single industry or use case (EPRI, 2019) and range from healthcare and advertising to finance, material discovery, energy, and more.

For energy, a wide range of potential use cases have been identified with many either in operation today or under development. Several of these use cases include:

- online health monitoring and diagnostics (in use)

- automated wildfire detection (in use)
- AI-assisted inspections in T&D infrastructure (in use)
- AI-augmented inspections in nuclear power plants (in use)
- enhanced energy storage applications (in development)
- AI-enhanced cybersecurity (applications both in use and in development)
- analysing satellite data for vegetation management, storm recovery, wildfire risk evaluation, etc. (in various stages of development)
- grid management solutions: This covers a wide range of potential technologies such as control centre alarm data, distributed energy resource management systems (DERMS) automation, and up to full-scale grid optimisation (in various stages of development).

Recently, with the introduction of ChatGPT and other LLMs, generative AI tools have become mainstream and in widespread use around the world. Such tools can ingest large volumes of data and provide answers to questions/prompts; however, such tools sometimes suffer from hallucination, or the AI model provides an incorrect response, or one not based on its training data. These tools provide text, audio, image, and video generation capabilities, enabling new and different use cases, such as:

- virtual assistants
- autonomous vehicles (or grids)
- generating data for training AI models
- optimising predictive maintenance.

These are just a few of the potential use cases for generative AI in the energy sector, though many more exist.

Continued development and path forward

While AI R&D has made remarkable progress in the last 15 years, the next 15 years could be equally transformative with new models being developed, additional data becoming available, increased computational capabilities coming online, and significant investments from large technology companies, governments, startups, and other organisations. A wide range of initiatives seek to democratise AI for broader use across the globe to help develop AI technologies in an ethical and responsible manner.

Conclusions

As progress continues forward, AI will continue to extend into everyday life in both home and work settings. This continued development shows no signs of stopping or slowing down and with an ever-increasing impact on society. As organisations collaborate and compete to develop more capable models; improve hardware and software tools; share and utilise larger, more robust data sets; and responsibly develop ethical AI models, progress will continue forward with additional capabilities being developed each year.

In conclusion, AI development will continue to advance as interest, investment, available data, and computational capabilities grow and new models are developed. While the path for future development will be impossible to predict, it is anticipated that many new advancements are on the horizon and will be built out in the coming years.

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Idaho National Laboratory - AI and big data opportunities for nuclear power plants

Christopher Ritter, Vivek Agarwal, Ashley Shields, Ryan Stewart, and Emerald Ryan

Abstract

Nuclear energy represents one of the largest contributors of clean, resilient energy to communities, globally. To meet net-zero targets, McKinsey & Company estimates that up to 800 GW of new nuclear may be needed. This represents an unprecedented opportunity to deploy new efficiencies across the design, deployment, and operations life cycle of a nuclear power plant, potentially saving hundreds of billions (USD) in new capital investment. One significant opportunity to reduce nuclear power plant construction time and overall operating costs is to leverage disruptive innovations that artificial intelligence (AI) and big data presents. AI can partially automate the creation of computer-aided design files, analysis reports, process diagrams, and documentation needed during the design and licensing stages of a new nuclear power plant; thereby minimising the inefficiencies in these processes. Additionally, nuclear power plant reliability is a trademark advantage of investing in nuclear power. Risk-informed predicative maintenance promises to both increase nuclear power plant reliability and provide new layers of safety for one of the world's safest power generation technologies. Nuclear power plants can be integrated across a system of digital twins to dynamically meet grid operations needs through the continued integration of renewables and hydrogen production technologies. AI holds a key to accelerate the deployment of clean energy to meet the world's energy needs.

Introduction

The international monetary fund estimates that artificial intelligence (AI) will affect up to 40% of jobs globally (Georgieva, 2024). At the same time, global power demands are increasing, partially due to computational facilities needed to train the latest AI models, such as large language models (LLMs). AI needs alone could consume 85 TW of energy globally (Aldrete, Ward, Pandise, 2024), which will need to be offset with clean energy sources.

McKinsey estimates that up to 800 GW of new nuclear capacity may be needed worldwide to meet climate goals (Cramer et al., 2023), falling short of what is needed to support the future of AI. This demand suggests that an integrated energy solution, including an expansion of nuclear energy, is required to meet climate goals as AI potential is increasing. Despite those energy requirements, AI has the potential to be a transformational technology that can reshape the entire life cycle of a nuclear power plant from design, licensing, deployment, and operation.

Today, nuclear power plants are designed through a hands-on process with design requirements, computer-aided design (CAD) models, analysis models, and safety analysis reports all generated by hundreds of humans. While this process has proven successful historically, it is both costly, labour-intense, time-consuming, and can cascade schedule risk throughout the reactor design. The integration of AI with the design process, digital twin (DT) architectures, and automation processes provides the opportunity to save ~21% (Ritter and Rhoades, 2023) of the design and deployment process, representing ~60% of nuclear power plant total cost (OECD, 2000). Furthermore, these technologies could be integrated with cyber-informed engineering principles to reduce cyber threats early and to support the autonomy of operations for new advanced reactors.

AI cannot automate all aspects of new nuclear power plant design. Therefore, linked data technologies combined with AI are needed to bridge both worlds. Digital engineering is an integrated, model-based approach which connects proven digital tools such as building information management (BIM) and systems engineering software tools into a cohesive capability. Using an authoritative source of truth for new NPPs can reduce the probability of cascading risks (Ritter et al., 2022a). This information can highlight risks of change and ensure that every change to a nuclear power plant's design is properly addressed. Many nuclear power plant projects are using digital paper-based processes with a few advanced reactor developers in the early stages of building their own digital engineering systems (Vilim, R., Ibarra, L., 2022).

For perspective, NuScale Power spent approximately $500 million preparing a licensing package for the Nuclear Regulatory Commission (NRC) (Neutron Bytes, 2020) on a plant forecast to cost ~$4.2 billion (Cho, 2020). In the United States, licensing policies for new nuclear power plants and hydropower plants significantly changed in the 1970s with the establishment of the NRC and Federal Energy Regulatory Commission. Since this time, the cost to deploy these technologies has effectively doubled (Ritter and Rhoades, 2023). To help reduce the cost, AI can automate input decks into different analyses, check constraints within digital models, prepare licensing reports, and highlight important areas of change to aid in the licensing process. Over time, these tools could be utilised by both the licensee and the regulator at regular intervals to ensure a safe design matures predictably.

Another area that could benefit from the use of AI is the design, development, and deployment of microreactors. Microreactors, manufactured on the scale of commercial airplanes, could save significant cost using AI and autonomy technologies. Further detail on the opportunities and current research state on autonomy for nuclear power plants is available in the complimentary paper "Autonomy in the Operation of Advanced Reactors."

Nuclear power's reliability is a hallmark of international success. Predictive maintenance can monitor and, using AI, detect faults in nuclear equipment before a failure occurs. Perceptions of cost and regulatory challenges have prevented large-scale adoption of predictive maintenance technologies. However, new applications of AI technology are making continued progress and ongoing research capitalising on the latest AI innovations (Walker et al., 2023).

As DTs are developed and matured for specific applications, the concept of bringing these DTs together to achieve a holistic system of systems (SoS) perspective needs to be explored. This concept is relevant to energy domains such as the nuclear fuel cycle or integrated energy systems where many individual facilities contribute to the common goal of reliable and adaptable grid penetration strategies for clean energy sources. Approached from a systems engineering perspective, each energy asset is a complex system that must perform as part of a single collective system. A DT that integrates information from multiple DTs to optimise operations and perform system wide state of health analysis could strengthen system reliability.

Consider a system that includes individual DTs of a nuclear power plant, a hydropower plant, a solar plant, and a wind plant, each separately monitoring performance. An SoS DT can be developed to look at all four of these plants from a grid perspective and interact with each respective DT to compensate for changes in power demands. For example, the SoS DT can monitor the current need for electricity. If electricity demand drops, the SoS DT informs the nuclear power plant and hydropower plant to limit electricity output; this might involve transitioning the nuclear power plant to additional hydrogen generation. If there is an increased need for water resources, the SoS DT can demand a higher power from the nuclear power plant. Lastly, the SoS DT can send adjustments to the nuclear power plant and hydropower plant based on the solar and wind electricity production at a given time. This hypothetical scenario shows the potential benefit of a SoS DT which can examine the entire system and balance multiple objectives.

INL innovations in AI and big data

To develop the technologies needed to semi-autonomously design a nuclear power plant, INL has developed automated meshing capabilities and enhancements to the Multiphysics Object-Oriented Simulation Environment (MOOSE). The Versatile Test Reactor programme developed automation for converting BIM models to pipe stress models needed for analysis. Additionally, INL is currently developing automation from BIM tools to common structural analysis tools used during the nuclear power plant design process. The Stochastic Tools Module of MOOSE harnesses AI techniques through dimensionality reduction, Bayesian learning algorithms, and neural network models. It natively leverages MOOSE-based simulations with active learning strategies for training surrogate models, accelerating the uncertainty quantification and sensitivity analysis of physical systems, and the integration of advanced neural network architectures (German, Yushu, 2023).

INL has developed and deployed several data adapters through Deep Lynx to leverage the application programming interfaces of commercial software tools, enabling the reuse of data throughout the engineering lifecycle. Typically, engineering software is deployed across geographically disparate teams that manually transfer point-in-time information back and forth using legacy formats such as PDF and Excel. This leads to tedious data re-entry, complicates configuration control between multiple instances of the same data, and often leads to human error.

Back-end software adapters facilitate real-time automatic data transfers to guarantee all project members have seamless access to the most up-to-date information from the approved source. In advanced applications, the properties of objects can be reused to reduce the time needed to perform validating analyses. For instance, the geometric and material attributes of a building developed using CAD can be used to generate the corresponding finite-element model for seismic analysis with limited human interaction (Idaho National Laboratory, n.d.).

Over the years, the nuclear fleet has relied on labour-intensive, time-consuming preventive maintenance programmes, driving up operation and maintenance costs to achieve high-capacity factors. A well-constructed risk-informed predictive maintenance approach for an identified plant asset was developed in this research, taking advantage of advancements in data analytics, AI, physics-informed modelling, and visualisation (Agarwal, V. et al., 2021). In fact, INL and Idaho State University demonstrated the first real-time DT of a nuclear reactor using AI and cloud technologies to predict plant anomalies. DTs, combined with AI technologies, can lead to new innovations in process-monitoring detection including event classification, real-time notification, and data tampering.

When combining AI with physics-based simulations, a deeper understanding of the AI decision-making process can be explained to ensure predictions match reality. It represents a technological leap in evaluation and detection capability to safeguard any nuclear facility (Ritter, C.et al., 2022b).

Conclusion

AI presents a significant opportunity to transform the nuclear design, deployment, and operations landscape. INL is currently developing digital engineering tools to automate error-prone and high-cost aspects of the nuclear design process. Furthermore, INL is researching methods to increase the level of automation available for developing a licence submittal to a regulator. INL has developed AI technologies which can be deployed both to existing reactors and transitioned to advanced reactors. These technologies can predict plant maintenance activities, automate inspections, and increase plant reliability.

Many recent AI innovations are dependent upon big data to train models, which magnifies the importance of big data technologies. INL has developed two technologies to expand collection and linkage of nuclear data for AI.

The Nuclear Research Data System (NRDS) is a public website which allows transfer of public datasets and includes integrated AI to enhance data uploaded to NRDS (Idaho National Laboratory, n.d.). INL has also developed Deep Lynx, a multi-model data technology, designed for near real-time connection to operating facilities with petabyte-scale time series capabilities and for designing new nuclear power plants. The opportunities for AI and big data across the nuclear life cycle are vast and provide an opportunity to accelerate the deployment of clean energy.

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Korea Atomic Energy Research Institute – Review of AI history, applications, benefits and drawbacks

Abstract

Artificial intelligence (AI), a rapidly evolving field in computer science, aims to build machines for tasks requiring human intelligence. Its growth is fuelled by vast data, increased computational power, and advances in deep learning and large language models (LLMs). AI's broad applications, particularly in the nuclear sector, promise to enhance reactor design, operation, safety, analysis, radiation detection, and waste management. Despite its potential, AI faces challenges like opaqueness, uncertainties, misinformation, reliability, and workforce resistance. This review outlines AI's history, current applications, benefits, and drawbacks.

Introduction of the technology

AI technology is highlighted in the nuclear sector due to its potential to enhance safety, efficiency, and reliability in nuclear power plant operations. AI algorithms can predict equipment failures, optimise reactor fuel management, simulate emergency scenarios, and improve the accuracy of radiation monitoring, thus reducing the risk of accidents and leading to more informed strategies and reduced human error. Moreover, AI-driven analytics can process vast amounts of data from nuclear plant operations to identify inefficiencies and recommend improvements, leading to cost savings and increased energy production.

Disruption factors

AI is recognised as a disruptive technology, as it can significantly change how businesses, societies, and various industry sectors operate, introducing innovative solutions that can alter traditional practices and create new industries or transform existing ones. Specially, within the nuclear sector, AI has potential to enhance safety, optimise operations, and accelerate problem solving. It shifts from manual monitoring to real-time analysis, predicting failures and boosting process optimisation. This change demands updated regulations and new skills, leading to greater safety and efficiency. AI's role in advancing nuclear technologies, such as small modular reactors and next-generation fuels, highlights its potential to revolutionise nuclear energy management.

Technology history

AI's history dates to ancient myths of artificial beings, but its modern phase started in the mid-20th century with digital computers. John McCarthy coined "artificial intelligence" in 1956, leading the first AI conference at Dartmouth College. Early pioneers like Alan Turing and Marvin Minsky explored machine intelligence. Initially, AI tackled specific tasks using symbolic logic. However, the 1970s brought challenges, such as representing common sense, leading to the first "AI winter" due to a progress slowdown. A second "AI winter" occurred in the late 1980s due to unmet expectations.

The revival of AI came with the emergence of new paradigms and techniques, such as neural networks, genetic algorithms, fuzzy logic, and probabilistic reasoning. These methods enabled AI systems to deal with uncertainty, complexity, and ambiguity, and to learn from data and experience. The availability of large amounts of data, the increase of computational power, and the collaborative spirit of the open-source community and platforms also contributed to the growth and innovation of AI.

One of the most influential and recent developments in AI is the emergence of large language models (LLMs), such as ChatGPT and its successors. These models are a subset of deep learning, characterised by their use of the transformer architecture and their training on massive amounts of text data through self-supervised learning. With 10 to 100 billion parameters, LLMs have significantly advanced natural language processing capabilities. Deep learning, a key area of machine learning, involves the use of neural networks with multiple layers to learn hierarchical representations of data. It enables machines to learn and make decisions autonomously, using data rather than explicit programming.

Status

Technology readiness level (TRL) of AI technology varies widely depending on the specific application or domain it is being applied to. Considering the diverse nature of AI's application, it is not an easy task to universally define its TRL.

AI technology has progressed through three waves: Handcrafted Knowledge, Statistical Learning, and the current wave, contextual AI, epitomised by foundation models like ChatGPT. These models are versatile, designed for multiple tasks, and can be fine-tuned with minimal adjustments. They offer superior performance across various fields and provide APIs for customisation, making AI technology more accessible and user-friendly.

Future AI R&D focuses on development of trustworthy AI, emphasising ethical AI, enhancing explainability, and reducing biases. Policies are gearing towards ensuring privacy, security, and fostering innovation while addressing job displacement concerns. Initiatives aim at global collaboration, standardising AI practices, and supporting sustainable development goals. The global view on AI is optimistic yet cautious, recognising its transformative potential across industries while emphasising the need for robust frameworks to manage ethical and societal implications. Emphasis is on balancing rapid technological advancements with safeguarding human rights and promoting inclusive growth.

Possible applications

AI technology can be used to improve numerical analysis in the nuclear field, particularly in solving PDEs (Partial Differential Equations) or speeding up analyses with surrogate modelling. Techniques like PINN (Physics Informed Neural Network), which incorporate physical laws into neural networks, are under active research. These methodologies enable fast, accurate simulation of complex multi-physics phenomena in reactor design, optimise reactor performance, and facilitate real-time monitoring and accident response simulation.

AI enhances decision-making in specific contexts, like nuclear reactor management, focusing on "recognition" through pattern identification and "planning" via scenario prediction. For example, in autonomous driving, AI uses varied data for navigation. The "digital twin" concept simulates future scenarios, improving predictions. This technology anticipates reactor accidents, allowing quick evaluation of strategies for safe responses, thus boosting decision accuracy by simulating future conditions and outcomes.

Another potential application is a chatbot that comprehends internal regulations and responds to complex queries via language foundation models. LLMs, understanding the nuanced meanings of information, can deeply grasp and specifically answer user questions. Furthermore, an AI model capable of document creation, query response, and searching, specifically for the nuclear sector, is being developed using a dedicated language model for nuclear documents.

LLMs, extended to handle not only language but also various sensor data, and combined with digital twin technology, can improve reactor safety and efficiency by quickly understanding complex procedures. They forecast future scenarios through digital twins, guiding operators' decisions. As pivotal AI assistants, LLMs will advance reactor technology by predicting and proactively responding to abnormalities without reactor shutdown.

Advantages and disadvantages

AI in the nuclear sector enhances safety, operational efficiency, and accuracy in monitoring and response. By processing complex data, AI helps overcome the challenges of nuclear operations. Predictive maintenance algorithms predict equipment failures, optimising reactor operation and fuel assembly design. Machine learning models rapidly detect radiation levels and leaks, improving hazard response times. However, relying solely on AI for nuclear decisions has limitations, underscoring the need for human oversight.

A major limitation of current AI technology is its reliance on data. AI algorithms need vast amounts of high-quality data, with its accuracy impacting results. Biased or erroneous data can lead to incorrect AI judgements. In the nuclear field, securing detailed data on abnormal situations, like accidents, is challenging.

The 'black box' nature of AI complicates understanding its decision-making, as it can be too complex to trace. This is problematic in critical fields like nuclear power, where safety is paramount, and AI systems must reliably operate as intended under all conditions, beyond mere quantitative performance assessments.

Balancing AI's strengths and weaknesses is essential for safer, more effective use, focusing on technological advancements in key areas:

- **Explainable AI (XAI):** Developing XAI to improve AI decision transparency and reliability. For instance, when AI identifies a reactor anomaly and proposes a response, it must clearly justify its reasoning.
- **Uncertainty Estimation:** Implementing technology to predict AI judgement reliability, aiding operators in recognising AI uncertainty.
- **Synthetic Data:** Solving data scarcity with virtual data generation and digital twin technology for richer AI model training.
- **Human-AI Collaboration:** Creating a system for human review and approval of AI decisions to enable optimal human-AI collaboration without depending too much on AI.
- **Testing and Verification:** Ensuring AI systems for nuclear use are rigorously tested and verified before deployment, with established technical standards.

If R&D overcomes these limitations and establishes a strict verification system, AI technology could be safely and effectively applied in the critical nuclear field.

Conclusions, further plans and recommendations

AI is expected to revolutionise nuclear technology, significantly transforming the nuclear sector into digital-based industry, thanks to remarkable advancements like machine learning and LLMs. Despite lower TRLs in some application areas, its potential for significant safety and efficiency has gained glowing attention.

AI enhances safety in hazardous environments, improves operational efficiency, and reduces human exposure to radiation. AI promises improved reliability through predictive maintenance, simulations, and optimised resource allocation.

Key challenges include ensuring AI's regulatory reliability, overcoming uncertainties, increasing transparency with explainable AI, utilising synthetic data, fostering human-AI co-operation, rigorous testing to enhance AI's dependability and comprehension, and addressing institutional and workforce resistance. Recommendations for the nuclear sector include closely tracking technological advancements, investing in workforce development, and participating in shaping regulatory frameworks to ensure safe, effective adoption of autonomous operations.

It is critical to harmonise AI's advantages with its challenges for reliable nuclear applications. Plans should focus on advancing TRLs, fostering collaboration between regulatory bodies and industry stakeholders, and ensuring a smooth workforce transition.

Biotechnologies and human enhancement

Electric Power Research Institute - Extended Reality (XR) and Potential for Disruptive Training

Summary

In recent years, technological advancements have created an increased potential for enhancing training and workforce development across various industries. Among these innovations, Extended Reality (XR), which is comprised of augmented reality (AR), virtual reality (VR), and mixed reality (MR), may be utilised to transform how training programmes prepare individuals for tasks in their respective fields. The impact of these immersive technologies on training programmes potentially includes effectiveness, scalability, and cost efficiency.

- AR overlays digital information onto the real-world environment to enhance the user's perception and interaction. Potential applications of AR for training include contextual learning, on-the-job-training (OJT), and scalability.
- VR immerses users in computer-generated environments and may be used to promote experiential learning. Potential applications of VR for training include scenario-based (situational) learning, high-fidelity simulations, emotional engagement, and replication of high-cost or physically dangerous equipment or settings.
- MR merges real and virtual elements to create a hybrid learning environment. Training applications for MR could support situational simulation in a real-world setting, dynamic interactions and feedback, and adaptive training progression.

AR, VR, and MR have the potential to deliver realistic, scalable, and efficient workforce development solutions and fundamentally change training approaches. As organisations experience changes to the workforce, these technologies may support job performance through experiential learning, increased situational understanding, and higher worker engagement.

Introduction

Augmented reality (AR), virtual reality (VR), and mixed reality (MR) are examples of technologies that have a potential to change the way training programmes are structured and used to prepare workers in the performance of job duties. These technologies could be used to disrupt traditional training methods by introducing novel approaches that may innovate established training norms and methodologies with a potential to make training more effective, engaging, and accessible.

VR technologies have already been employed in fields that have low tolerances for errors such as healthcare, aviation, and military training and are being applied as a technology-readiness level (TRL) 9, "flight proven" technology, in some industries.

Typical VR applications consist of the user performing a self-paced exercise alone. Recent developments in technology have allowed EPRI to develop and begin to experiment with an ecosystem for VR that permits instructors and learners to be immersed in a virtual environment together. This "multi-player" functionality may enable geographically separated learners to engage in virtual classrooms, support virtual team training, and permit wider instructor and management participation in training. This can promote stronger organisational cultures and reinforce organisational expectations. In addition to the multi-player functionality, this ecosystem also supports full immersion through VR headsets or computer-based participation.

Within the EPRI VR ecosystem, a VR demonstration application has been developed with a goal to allow sites to customise a space to match their site configuration after which users can enter the virtual twin environment to support training needs. Another application allows the instructor and class to be miniaturised so they can observe cable degradation at a microscopic level.

Additionally, EPRI has developed AR applications to potentially support industrial needs from maintenance to engineering. One example is an overview of the Limitorque Valve Actuator that may be applied in classroom, training lab, or actual plant settings. This module is designed to display 3D models of all actuator parts and can be superimposed over a physical actuator to show how it is disassembled and reassembled.

Possible applications

- Training on equipment that is too expensive to have at a training centre.
- Training on equipment that would be hazardous to learners or in a hazardous location.
- Training on mission-critical equipment that is in use online.
- Training on equipment that has been traditionally a simulation or discussion only due to the above or other conditions.

Bloom's Taxonomy's Affective Domain related to worker behaviours has historically been the most difficult domain to effectively teach and instil in learners. In some applications, these technologies, particularly VR, have been shown to affect worker behaviours by tricking the brain into thinking the learner is doing the task and impacting their emotional engagement.

Advantages

While more research is required to understand the psychological impacts of these technologies to support training and development, some advantages for these technologies may include:

AR

Contextual Learning: AR technology can support real-time guidance and context-specific information during training exercises. For instance, maintenance technicians can visualise step-by-step repair procedures directly on equipment components.

On-the-Job Training: AR technology can enable hands-on learning without physical constraints. Trainees can practise tasks in their actual work environment, potentially improving retention and skill transfer.

Scalability: AR applications can be deployed on existing devices (e.g. smartphones, tablets, smart glasses), making widespread adoption feasible.

Portable Solutions: AR platforms, like EPRI's Scope AR platform, can offer flexibility and portability for training.

VR

High-Fidelity Simulations: VR technology can allow trainees to experience complex situations (e.g. emergency response, flight simulations) in a physically safe and controlled setting. Performance errors and mistakes may trigger the affective domain and create valuable learning opportunities without real-world ramifications.

Emotional Engagement: The sense of presence in VR enhances emotional engagement, leading to better memory retention and decision-making skills in the plant.

Cost-Effective Replication: VR may be applied to eliminate the need for physical props or specialised facilities, reducing training costs where these high-dollar items may be employed.

MR

Dynamic Interactions: MR systems can enable trainees to manipulate both physical and digital objects simultaneously. For example, assembling a complex machine using virtual components overlaid on real parts.

Adaptive Training: MR technologies can be used to adjusts scenarios based on trainee performance, tailoring challenges to individual needs.

The platforms that EPRI has developed for both AR and VR is being used to help explore the utilisation of these technologies for industrial and training applications. These projects aim to capture use data to support EPRI-member organisations implement MR platforms and solutions to meet organisational efficiency goals.

Disadvantages

Disadvantages of these technologies have historically been the cost of the hardware and software development, limiting functionality, and bulky hardware. As the technology continues to mature, hardware functionality and ergonomics are being improved, reducing the need for high dollar headsets, dedicated spaces with antennas or tethers, and gaming laptop computers for each headset. While hardware advances are being realised, the cost to develop the software applications remains high and may hinder adoption of this technology. Additionally, some trainees may initially be resistant to this form of training.

Conclusions, further plans and recommendations

These technologies have been employed in fields where there is an extremely low tolerance for errors. Development has reached a point where the industry would likely benefit from adoption of this technology for training and maintenance for several reasons:

- this technology may be attractive to the next generation workforce;
- it has been shown to potentially support training worker behaviours;
- the technology continues to mature bringing potential for improved functionality and cost effectiveness;
- training cost reductions and time savings may be realised by reducing the need for training equipment, mock-ups, and the capability of simultaneous trainee virtual-lab exercises;
- enables training in cases where the equipment or systems are unavailable or too dangerous for training;
- potential worker performance improvements due to increased familiarity, proficiency, and practice with tasks through virtual practice sessions.

In summary, these technologies have the potential to disrupt the status quo, redefine training, and empower learners with immersive, efficient, and personalised experiences.

Idaho Nuclear Laboratories - Extended reality opportunities for nuclear power plant

Christopher Ritter, Rajiv Khadka, and Kaleb Houck

Abstract

The global nuclear community is investing in new advanced reactor technologies that are less expensive to build, more fuel efficient, and offer passive safety capabilities. Along with technological investment in the nuclear island itself, the nuclear community can significantly benefit from new innovations in extended reality (XR) technologies that are evolving rapidly in commercial industry. Preliminary and critical design reviews are presently performed through hundreds of PowerPoint slides and Word documents. Design reviews of the future can be performed with XR technology, which in early testing, has proven to surface issues not easily discovered through digital documents. What if future reactor operators could be involved in the design process and learn the plant prior to development of a full-scale mock-up? XR offers new opportunities for operator and engineer training, both for new designs and existing designs. Lastly, AI promises to transform plant operators with new predictive and autonomy features available in future reactors. XR presents an opportunity to mix AI suggestions within the human's real-world environment, bridging the best insights from a human and AI team.

Introduction

The market for extended reality (XR) technologies is over USD100 billion in 2024 and expected to grow to over USD 400 billion by 2029 (Mordor Intelligence, n.d.). XR is an umbrella term that includes augmented reality, virtual reality (VR), and mixed reality (MR) technologies. AR overlays virtual assets into the real world through smart glasses or similar technologies. VR is a fully immersive XR technology that replaces the real world entirely with a virtual world. MR is an integration of both the immersive and real worlds with the ability to interact with objects from both worlds (Purdue University, n.d.).

XR's principles are over 100 years old with early flight simulators conceptualising the technology in the 1920s (XR Association, n.d.). Ivan Sutherland developed an early system where the user would "not be able to tell the difference between and real life" in the 1960s (Sutherland, 1968; Layzelle, 2021). VR systems continued to evolve for home use with early video games in the 1990s. Fast forward to the 2010s and a student, Palmer Luckey, had a vision for the future of VR. In his garage he would build the first prototypes of the oculus virtual reality (VR) headset. Facebook, now Meta, acquired this technology to build and design one of the first Metaverses (Dingman, 2021).

There are a few key opportunities to integrate XR technologies with nuclear energy technologies. The first is during the design phase of nuclear projects. Facilities and equipment inhabit the same three-dimensional space as their designers and operators. However, review of design is largely limited to two-dimensional mediums utilising documents such as Piping and Instrumentation Diagrams (P&ID), Computer-aided Design (CAD) or in Microsoft Office files, and mistakes not caught in this type of review cause project delays and cost increases.

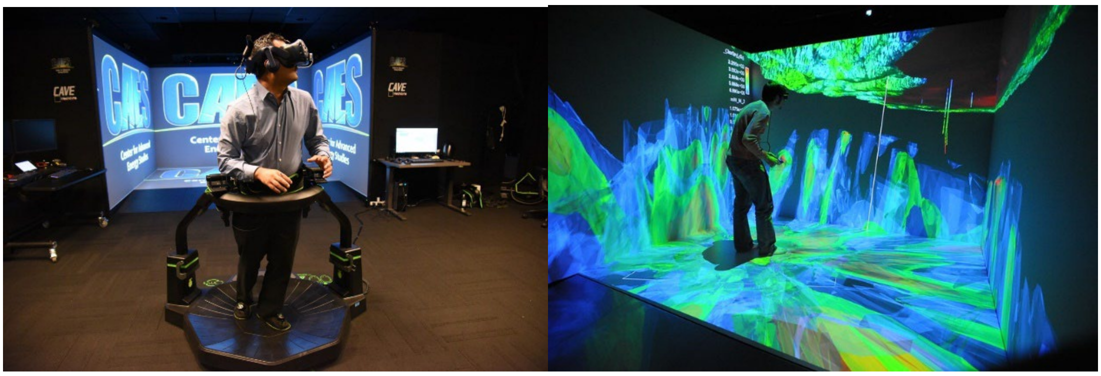
Mistakes caught during the design phase rather than in the operations phase cost around 1 500 times less to correct (Stecklein et al., 2004). With the cost of nuclear projects being in the billions of dollars, small investments to employ XR can save millions of dollars. Architecture, engineering, and construction (AEC) companies are already deploying these methods widely. According to a report produced by Engineering.com (Engineering.com, 2023), adoption rate can be as high as 82% in the case of plumbing, and though there exists adoption rates lows of around 28%, deploying XR for design is increasingly becoming an industry norm. Though XR is generally a high TRL for AEC, most adoption is using VR tools and methods.

VR requires building an entire ‘reality’ that replaces the physical one, which hinders adoption and provides limited utility during construction. MR tools and methods are lower TRL but offer greater potential of impact and ease of adoption. MR uses the physical world and merges digital elements into it meaningfully, and this removes the cost of creating an entire world. It also allows for the design to be overlaid onto the construction site. Extending the MR implementation used in design into construction provides further savings by ensuring the design is followed into the field and red lines are communicated back to engineering models like CAD or Building Information Models (BIM).

XR presents a promising avenue for enhancing the traditional approach to training. The evolution of XR training has been nothing short of remarkable, spanning from its beginning in the 1980s to its widespread adoption across various industries today (Kocian, 1977). XR training has undergone significant advancements, with the advent of mobile VR and AR headsets revolutionising the way training is conducted.

By offering interactive simulation and learning experiences and opportunities for remote collaboration, XR enhances training effectiveness while reducing costs and logistical constraints. The use of XR technology can help organisations reduce or eliminate expensive physical resources, such as training facilities, equipment, and materials. This level of accessibility democratises training, making it available to users across geographical locations. The use of training in XR is especially applicable to nuclear projects where as low as reasonably achievable (ALARA) and safety are critical issues. This method of training means that trainees and trainers can collaboratively train in a realistic situation without the cost of building a physical mock-up or the risk of learning on the job site.

Figure 2.1 A user of VR headset to interact during a training in a virtual nuclear power plant environment (Left) and VR environment to analyse sub-surface model data (Right)



Source: INL

Idaho National Laboratory Innovations in XR

INL has demonstrated the usefulness of employing MR across many of its engineering efforts. One of the first successes, during design reviews for Beartooth, occurred when the team brought members from the three core teams, including laboratory personnel and two contractors, and had them concurrently review a holographic true-to-scale representation of the engineering models. During these reviews many mistakes that had been missed on traditional reviews were discovered. These mistakes included the testbed fitting, which was in the intended location but unserviceable, and it was determined operating the testbed was ergonomically difficult for researchers. Employing this testing during design review required minor investment but produced substantial savings by accelerating discovery and remediation of errors in design.

Figure 2.2 Demonstration of MR interface of Beartooth (Left) and MAGNET digital twin(Right).

Source: INL

The Beartooth project is entering fabrication and there are efforts to accelerate schedule on the project. The MR implementation that was used for design reviews is being extended to provide familiarisation training for future operators and researchers that will perform work on the testbed. It requires either an expensive physical mock-up or the final system to be installed and ready for use.

The digital engineering team is bridging the gap between these two methods by using the digital twins (DT) and a MR system previously used for design to translate these traditional methods into interactive scenarios. The aim of the scenarios is to familiarise operators with this unique testbed in a way that allows for a quicker route to a readiness assessment.

Familiarisation is the process of training experienced operators on the specific form and functions of a new system. Beyond accelerating the schedule, this method will reduce project risk. The ability of DT to provide real-time analytics to operators in the field was demonstrated using a non-nuclear microreactor testbed (US DOE, 2022). The Microreactor AGile Non-nuclear Experimental Testbed (MAGNET) demonstration allowed laboratory personnel to see real-time information on the testbed, and what AI/ML and physics-based models (PBM) were predicting would occur on the testbed while enabling them to have their hands free to do experimental operations.

This type of technology could provide great value to nuclear plant operators by enabling maintenance personnel to have the latest information on an asset, and all relevant information on a work package without interrupting work. Additionally, the ability to work on an asset while being able to collaborate in a mixed reality environment with remote personnel enables resiliency.

Remote experts can add digital elements and cues onto the physical environment while seeing what the worker in the field is viewing. This ensures high certainty that remote collaboration is having the intended outcome without requiring experts to come on site.

Another example of INL's use of XR to develop a virtual prototype of the Mobile Hot Cell (MHC) not only revolutionised training methods for operators and engineers but also had profound implications across various aspects (Khadka et al., 2023).

By providing a comprehensive understanding of MHC setup and operations, the tool significantly enhanced safety protocols and decision-making processes in managing disused high-activity radioactive sources during end-of-life (EOL) procedures. The incorporation of radiation visualisation further supported risk management strategies, minimising potential hazards.

This innovative approach also yielded considerable cost savings by enabling design iterations and preliminary assessment in a virtual environment, reducing the need for physical prototypes and minimising operational downtime. Additionally, the tool facilitated faster training and upskilling of personnel, ensuring a proficient workforce capable of effectively managing EOL processes.

Overall, this work showcases the transformative potential of XR technology in the nuclear industry, delivering tangible value in terms of safety, cost efficiency, and workforce development. INL also has collaborated with College of Eastern Idaho to develop a virtual radiation safety and survey training. This simulation immerses operators and students in a pipe environment, providing guided instructions, real world scenarios, and interactive feedback. By leveraging 3D visualisation, students engage deeply, reducing costs and exposure risks associated with traditional training methods, while promoting virtual training for wider educational outreach.

Conclusion

Adoption of using XR in the design, construction, training, and operation of nuclear projects could substantially reduce cost and schedule risk with minimal investment. INL is developing a methodology and open-source capabilities to enable industry to utilise digital twin and XR throughout the life cycle of a project. INL has demonstrated and utilised these capabilities in design, training, and operations of complex engineering projects including a special nuclear material testbed (Beartooth), the MAGNET non-fissile microreactor testbed, and the Mobile Hot Cell. There exists great opportunity for large-scale nuclear projects to accelerate the deployment of clean energy around the world with the adoption of XR methodologies and tools.

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Digital Twins

Électricité de France - Digital twins in the Nuclear Industry

P. Morilhat, EDF R&D

Abstract

Like many other industrial sectors, the nuclear industry is deeply engaged in a digital transformation of its methods and processes. The objective is to simplify the design, operation and maintenance of installations, while maintaining a high level of safety. Significant innovations are brought about by the development of digital twins, i.e. digital models representing systems or components and powered by data flowing from the physical assets. Twinning a physical equipment with its digital model makes it possible to understand its behaviour, predict possible failures and optimise different operating modes. The concept of digital twins, initially devoted to elementary equipment (pumps, pipes), gradually extends to systems and installations (nuclear steam supply system, containment building) and even to organisations (outage planning, training and job preparation). Understanding the present, replaying the past and predicting the future is the main purpose of these twins. Their relevance is conditioned by their ability to adapt to the physical state of the constantly evolving installation. However, the development of digital twins still requires overcoming several scientific and technical challenges: data quality, representativeness of digital models, interoperability of solutions, reduction of computing times to reach real time, etc. Questions also remain about reducing high development costs and measuring gains, use cases prioritisation, qualification, cyber security and regulatory compliance.

Introduction of the technology

What is a digital twin?

The concept of a digital twin is based on a simple idea: bring together the physical equipment to be designed or monitored, with a digital model of it and, connecting the two, a data infrastructure to exchange information, feeding both the model and the real equipment. The data flows consist of operational and environmental data pertaining to the physical process introduced into the digital twin of the component to model its behaviour. In a predictive approach, the digital twin is used to test the expected behaviour of the real system in various operating cases.

A digital twin may address different levels of complexity: a component (pump, steam generator, turbine etc.), a system (reactor, etc.), a process (operation, outage management, etc.).

Figure 2.3 Examples of digital twins developed at different scales

Source**:** Varé, C., Morilhat, P., 2020.

Why is it considered disruptive?

Digitalisation is said to be one of the new frontiers of the nuclear industry, but the use of numerical models started in the 1980s for the design of the plants with mechanics and thermal-hydraulics, core calculations, electro-magnetism and others. However, until recently, a wider use of digital models often remained difficult for the industry due to limitations in the capabilities of digital technologies, access and volume of data to be processed, as well as the significant costs of implementation.

These obstacles have considerably reduced in recent years, with advances in Internet-of-things and high-performance computing capabilities, which opens the door to the systematic development of digital twins. Furthermore, advances in artificial intelligence and data science make it possible to adopt more agile, less expensive solutions that are less adhering to existing technologies. They facilitate the crossing of heterogeneous data, such as digital data provided by the process and textual data from maintenance reports.

What is the history of this technology?

The idea of digital twin dates to the National Aeronautics and Space Administration's (NASA's) Apollo programme in the 1960s. However, the concept, as we know it now, was first introduced in 2002. Articulating the nature of its model the name "digital twin" came into use in 2010 (Morilhat, 2022; EPRI, 2022). In the nuclear industry, the concept was used in many applications, even though it was not explicitly referred to as digital twins.

For example, in 1984, EDF designed the Operator Assistance System to help control neutron effects and their variation via the injection of boron and water. This involved coupling a neutron code in real time to provide the operator with decision support based on a what-if type simulation. This was in addition to the control-command system. The aim was to adapt its driving strategy, depending on the operating situation and fuel condition. In the 1990s, EDF developed and implemented a fatigue monitoring system for real-time evaluation of the usage factor of different points of the primary circuit, by coupling 3D thermos-mechanical finite element calculations and plant field data (Grieves, 2016). Based upon the same philosophy, so-called "e-monitoring" systems were then developed in the early 2000s and successfully deployed on many nuclear, thermal and hydraulic fleets around the world.

Status of the technology

The Technology Readiness Level (TRL) of digital twins' technology depends on the scale of complexity addressed. It ranges from TRL 7 to 9 for the component scale (most of the use cases today), TRL 6 to 7 at the system scale, and down to TRL 5 to 6 at the process level. Many industrial sectors have now experienced the development and use of digital twins for optimised design, predictive maintenance, process optimisation, among which manufacturing, automotive and transportation, energy and utilities, healthcare and medicine, retail, and smart cities are included.

Possible applications

Existing applications in the nuclear industry

The nuclear industry has already started to develop, implement and use digital twins for performance and efficiency improvement or operations and maintenance cost reduction.

A survey led by EPRI (EPRI, 2022) has identified potential benefits of these applications for the nuclear industry. These include faster deployment of new assets and systems, improved operational efficiency and reliability, enhanced simulation of potential scenarios and outcomes, optimised allocation of resources and labour, refined maintenance schedule, reduced design, construction, operation, maintenance, and decommissioning costs, improved integration of systems, better-informed decision-making, and reduced operator exposure to high-risk environments (such as high-radiation areas).

However, it is worth mentioning that compared to other industries, nuclear data is not "big data". For instance, the total volume of EDF plant digital process data, which are among the most digitalised plants in the world, amounts to some TBs equivalent to Twitter micro posts per year.

In terms of sensors, a typical plant has about 8 000 digital sensors, to be compared to 300 000 for a last generation Airbus aircraft, of which 24 000 are used for monitoring purposes. Therefore, the problem faced in nuclear plants is less volume, even though not negligible, than the diversity of data. Developing a sound, predictive-maintenance solution leads to mixed process data (numbers), results of non-destructive examinations (images), and maintenance reports (text or even written documents). The information used for diagnosis and prognosis must be extracted from various types of sources and formats and reconciled to provide the relevant information.

At EDF, the main applications are used to explore and validate a set of use cases that have been identified with a highest value and priority:

- predictive maintenance of components and systems (steam generator, alternator);
- long-term behaviour of the reactor building (evolution of tightness with time and optimisation of controls);
- fleet-level thermal performance optimisation (Metroscope™);
- chemistry monitoring and control;
- virtual plant simulator for operations training and rehearsal;
- virtual walkdown and inspection;
- 4D (planning + layout) preparation of construction sites;
- visualisation of interfaces between activities, location and resources to optimise the preparation of outage management;
- mobile access to digital configuration management information;
- value proposition.

Digital twins implementation should bring direct (revenue, increased generation, lower cost per kWh) or indirect benefits (environmental, safety, etc.). However, the business model, and value of digital twins, is not obvious, contrary to what may be stated. While information provides value, the journey from data to information is costly. Who bears the cost is fairly clear (usually the utility operator who must deploy and manage a data acquisition and management system). Who benefits is less clear, because it can be shared by many parties: the operator, the suppliers, the consulting companies selling data analysis services, and others. The literature review provides little information on the business case related to digital twins development and implementation.

Costs

Large investments are needed to set up digital twins. These include the initial costs for software, hardware, expert personnel as well as the ongoing costs to run, maintain and update the digital twins over the life cycle of the physical twins. As for other technologies, it is very likely that initial and ongoing costs should decrease in future, with standardisation of platforms and application.

Workforce implications

Since developing, using and maintaining digital twins can be complex, it is important to embark employees in relevant training programmes and to manage their concerns that digital twins could replace them. The advocacy for digital twin' benefits can be challenging with decision makers.

Challenges

Several challenges face the nuclear industry when implementing a digital twin.

High fidelity physic-based models, data harvesting and data quality
Digital twins need models which accurately represent multiple scales or multiple phenomena, plus data with sufficient volume, quality and completeness. Costs to access data might be challenging, since they need additional sensors or a more robust IT infrastructure. The quality of predictive and preventive decisions is based upon model training. AI and machine learning depends upon the volume and the quality of training data (garbage in, garbage out).

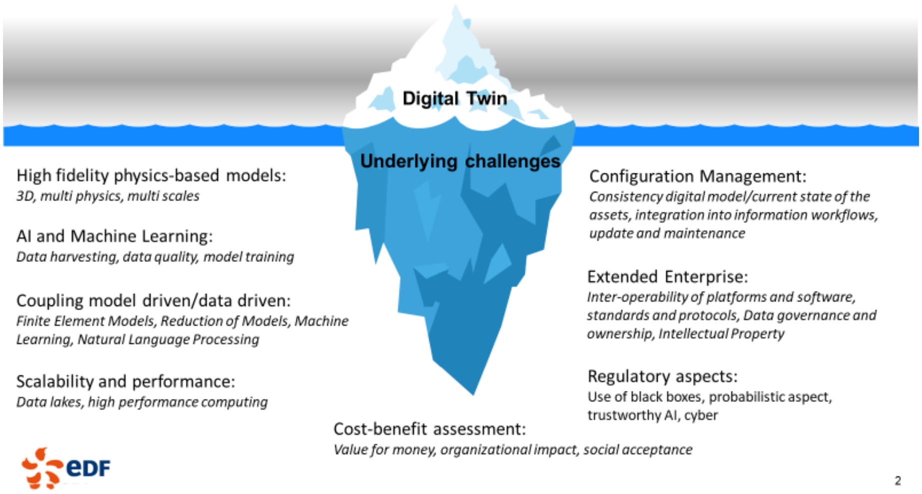
Scalability and performance
Digital twins require software and hardware capabilities that are strongly dependent on both scale and complexity of the problem: instrumentation network, data processing software, data storage capacities, physics-based and/or data-driven models. Increasing the scale will affect the performance of the digital twins' process: diversity of sensors and technologies (wired/wireless), data management and data lake volumes, high performance computing resources, etc. This leads to a strong need for limiting the use of digitals twins to a selected list of most critical and high value systems.

Configuration management
A digital twin is a living model. The physical twin will evolve during its life and any modification in design or behaviour should be reflected into its digital twin. Making sure the digital twin is updated might be challenging. Introducing the digital twin into the existing information workflow is also an issue in terms of costs, schedule constraints (too early or too late), already-implemented IT, software, workflows, norms, business practices, etc.

Extended enterprise
The operator's staff are not alone when using a digital twin. They are working in conjunction with suppliers, sub-contracting companies, and others. Interoperability between systems used or developed by different stakeholders for the same systems can be challenging when several platforms or data are connected or coming from different origins and formats.

Regulatory issues, trustworthy AI, cybersecurity
Verification and validation of the digital twin approach is important when it comes to maintenance but might be critical when deployed on safety-related equipment. Machine learning or AI algorithms are "black boxes" since they rely on artificial neural networks and deep-learning techniques that are probabilistic in nature. New verification and validation methods are required to build user confidence in these advanced technologies. Because the sensors and tools are connected and sometimes accessible in the cloud, cybersecurity concerns will grow as the technology progressively extends.

Figure 2.4 Underlying challenges of digital twins' development and implementation



Source: Varé, C., Morilhat, P., 2020.

Conclusions, further plans and recommendations

The use of digital twins for construction, operation and maintenance in the nuclear industry has a huge potential for simplification of operations, improved predictive maintenance, tests of modifications, and more.

However, the digital transformation raises a set of questions that are not well answered yet. Data governance must be made clear including, who owns the data, how to access the data repository or data lake, responsibilities regarding the data quality and the conclusions that data analytics may lead to. Verification and validation of data driven models (AI and machine learning) is not a process well established yet. The business model development is difficult to establish, due to the lack of shared experiences on digital twins across the industry.

Complexity of implementation cannot be under-estimated. Workers must be trained with skills through relevant training. A strong use-case must be established to assess, on a case-by-case basis, what and where the value is for each digital solution, and adjustments to be made in scale and complexity to achieve the value expected.

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University of Tokyo Institute of Technology – Digital twins

Abstract

The digital twin, a concept with immense potential, could potentially disrupt the nuclear energy industry and research. This paper delves into the status and the future that digital twins could bring to this field.

What is digital twin?

Digital twins are a technology that contributes to humankind's creative activities by linking the physical world with the virtual world and augmenting the physical world.

This technology could facilitate disruptive innovation in the physical world. Many physical-world technologies have grown through hypothesis testing and, sometimes, serendipity.

However, obtaining knowledge through experiments, calculations, and installation takes time, especially in advanced technology fields. This is due to costs, social acceptance, physical constraints, and lack of human resources. Therefore, it is possible to accelerate the process of hypothesis testing by accurately replicating them in a virtual environment, simulating them, and analysing the data. Furthermore, digital twins have attracted attention in recent years as a technological concept contributing to the efficiency of design and decision-making processes.

The digital twin has been developed through technological innovations such as precise monitoring technology-using sensors, simulation technology for physical phenomena, artificial intelligence (AI) and its data analysis technology, expansion of computing resources including cloud computing, quantum computing technology, and devices that expand cognitive functions, such as VR goggles. The technological innovations in devices are expanding the range of adaptability to a wider variety of phenomena and systems. Particularly in industry, it has become possible to trial and analyse any pattern or scenario in a virtual environment. Here it is free from physical constraints in the product and service planning, R&D, design, testing, and operation phases.

Recent advances in AI-enabling computational technologies and algorithms have facilitated optimising design and operational parameters. Furthermore, the digital twin has dramatically improved the effectiveness of training and education of workers and engineers by improving product performance and usability in line with user needs and creating a more realistic simulation environment.

The nuclear power industry has various constraints due to cost, risk, safety management, and complex operational processes when handling radioactive materials. Still, constructing a virtual environment and sophisticated analysis, visualisation, and simulation of data obtained in the physical world is expected to improve efficiency and accelerate the process. Thus, the use and operation of the digital twin has the potential to be a disruptive innovation that will generate significant breakthroughs not only in research and development but also in social implementation and demonstration.

Digital twin case study

Digital twins are being used and developed in the nuclear field to improve reactor safety, operation, and design. The US regulator, the NRC, in co-operation with the Idaho National Laboratory (INL), conducted a research project to assess the regulatory viability of digital twins in nuclear power plants. The project summarised current advanced digital twin initiatives in the nuclear sector, regulatory challenges, gaps in implementing digital twins, and potential use opportunities.

Many reactor developers, such as Kairos Power, GE, and Framatome, are developing digital twin technologies for predictive maintenance. This involves the advanced prediction and detection of equipment failures in nuclear facilities and appropriate maintenance, autonomous operation during load following, power fluctuations, and abnormal interlocks, ageing prediction, and reactor maintenance management.

It is expected to improve operational efficiency by monitoring equipment operation and the performance of the entire reactor system during operation, preventing unexpected equipment failures through more flexible simulation using AI and mathematical statistics, and improving preventive maintenance efficiency.

Digital twins are already widely used in the nuclear field, including operator training and equipment testing using plant simulators. Almost all nuclear reactors currently in operation have simulators tailored to the characteristics of individual reactors. By combining this simulator with actual central control room equipment, high-quality training is conducted to ensure that operators can respond effectively during normal, transient, and accident conditions. In addition, the operation simulator can be used with AI to test the system's and equipment's feasibility in a virtual environment when installing additional equipment in a plant efficiently.

We are also working on some projects to promote advanced digital twin in the nuclear field at the Tokyo Institute of Technology (Tokyo Tech). The first one is NEUChain, a digital twin project of the nuclear fuel cycle (NFC). In this project, various quantities of materials (raw materials, nuclear fuels, radioactive wastes, etc.) flowing from the front end to the back end of the NFC are simulated. This is shared among stakeholders with high reliability and security while maintaining their traceability. The aim is to develop a scheme that enables efficient operation of NFC facilities, strategic R&D policy decisions, and optimisation of the nuclear policy decision-making process.

Usually, data on various quantities in the NFC are highly confidential from nuclear security and commercial confidentiality viewpoints, and such data is not always used effectively. Therefore, this project is developing a data platform to manage various quantities of the NFC using distributed ledger technology (blockchain) and an NFC simulator, NMB 4.0 (developed by Tokyo Tech and JAEA).

The NMB code can provide a detailed evaluation of nuclear energy utilisation scenarios for each facility, operator, and country. The simulator was released globally in March 2022 to gain more attention to the importance of the NFC simulation and scenario studies in nuclear development. It will improve the efficiency of nuclear energy policy, facility operation, and R&D. Furthermore, evaluating the traceability of the various quantities is possible for anybody.

Improvement of the traceability of the assessments by combining NMB and blockchain technology can widen the applicable area of the digital twin in the nuclear field, such as knowledge management of radioactive waste disposal, strengthening safeguards, and nuclear security, which will lead to disruptive innovations.

Another example is the acceleration of actinide chemistry research by combining NEUChain technology with some machine learning (ML) schemes. In the field of actinide chemistry, experiments with actual radioisotopes are needed. Hence, the experiments are costly, and obtaining data with decreased waste generation is essential.

The experimental effort can be reduced as a digital twin technology. This provides a transfer-learning scheme, which can make extrapolative predictions by creating regression models of target substance data in combination with simulated substance data. Also, ML is applied to actinide chemistry, such as when you want to find good extractants to separate trivalent minor actinide (MA) and lanthanide (Ln) in advanced nuclear reprocessing. Increasing the data of actual MA is sometimes challenging. In such a case, human-in-the-loop (HITL) ML may be effective. When we create the regression model, we sometimes find low-probable data from the viewpoint of the experimentalist's experience. In such a case, the experimentalist can omit the data based on the experience, add new features or data, and remake the model. Such an interruption of humans to ML sometimes speeds up the experimental work. Therefore, applying digital twins to actinide chemistry or any activities with radioisotopes can accelerate the experimental activities, potentially triggering disruptive innovation in the basic science field of nuclear.

Digital twin implementation

Undoubtedly, the digital twin approach to solving problems promises to increase the sustainability of nuclear power generation by improving safety, reducing risks, improving operational efficiency, reducing the volume of radioactive waste, and accelerating basic research. However, the introduction of digital twin technology to the existing nuclear field is slow.

This can be attributed to issues such as the widespread use of analogue-type measurement and control equipment, costs associated with installation changes, information security, and high regulatory hurdles. In addition, there may be psychological anxiety challenges in introducing digital technology in the nuclear field, which requires extremely high safety and security. Introducing a new digital twin technology into an existing process requires a different workflow, which may require much effort from the on-site workers, psychologically. Appropriate assessment of the effects of introducing digital twin technology along with its technological development and embracing innovation will strengthen the competitiveness of the nuclear sector.

Conclusion

Digital twin technology integrates the physical and virtual worlds to enhance human creative activities and drive disruptive innovation, particularly by improving hypothesis testing and decision-making processes. This technology relies on advancements in sensor technology, AI, cloud and quantum computing, and VR devices, expanding its adaptability across various phenomena and industries. In the nuclear sector, digital twins are used for safety enhancements, operational improvements, and predictive maintenance, including operator training and system testing through simulators. Projects like the NEUChain at the Tokyo Institute of Technology employ digital twins to simulate the nuclear fuel cycle efficiently, incorporating blockchain for enhanced traceability and security. Despite its potential, adopting digital twin technology in nuclear power is slow due to legacy equipment, cost, security concerns, and regulatory challenges. However, its implementation could significantly enhance the sustainability and safety of nuclear power generation.

Distributed ledger technology

Electric Power Research Institute - Leveraging Distributed Ledger Technologies for Secure Data Management in the Nuclear Fuel Cycle

Dan Moneghan and Colton Smith

Abstract

Distributed ledger technologies (DLT) have grown in efficiency and market penetration rapidly over the past decades. These technologies provide a method of securely storing and transferring data between participants. One common DLT is the blockchain, the network of blocks and connections that is used to log, track, and transfer the cryptocurrency Bitcoin between participants of the network. To remove trust from the process of transferring data and assets, like currency, a DLT uses a type of consensus protocol, where various participants in the network solve computing problems to validate the movement of information on the ledger. There are various schemes by which this can be implemented, with trade-offs between them. These technologies may provide a novel means of storing and transferring data about the inventory of radioactive materials between various supply chain participants in the nuclear fuel cycle, while offering the potential to reduce the burden on verification of such information.

Introduction

Distributed ledger technologies were first developed to provide a secure, auditable, and immutable record of transactions that does not rely on a single, centralised database. Possibly the most well-known form of distributed ledger technology is the blockchain used to transact Bitcoin (₿) exchanges. A commonality between various DLTs is the need for proving the accuracy of the ledger itself, which differing technologies solve in different ways. The two most widespread methods for this are known as proof of work, and proof of stake.

In brief, proof of work provides validation for the ledger by solving cryptographic problems that would requires more computing power than half of the entire network to falsify. This contrasts to proof of stake where the ledger is updated by an algorithmically selected user based on their stake in the ledger, the falsification of which would require owning more than 51% of the stake in the ledger.

While controlling either 51% of the stake in a ledger or 51% of the total computing power contributing to a ledger might seem like sufficient protection, it is not unachievable for a co-ordinated group, especially one with state backing. This vulnerability has been exploited before, when the Ethereum Classic cryptocurrency ledger was attacked three times in August 2020 by a group with 51% of the computing power of the ledger. While DLT is most discussed as it applies to the numerous cryptocurrencies, there are many other uses for the technology.

Considerable effort has been taken to shift the Ethereum ledger from a proof of work to a proof of stake approach, in part due to concerns about the energy consumption. Proof or work requires a considerably higher compute power to function, which leads to a large energy footprint. In both cases, these technologies are effectively at TRL 9 with multiple independent variants and commercial implementations.

Possible applications

EPRI has previously explored how DLT can help solve the problem of properly managing distributed energy resources (DER), and other behind-the-metre generation assets through the distributed system operator (DSO) utility business model. These operators could leverage the power of a fast-operating

DLT, such as Hyperledger to balance supply and demand of energy in a transactional way between the traditional grid generation provided through an independent system operator (ISO) and the DER of residents within the DSO's operating territory. DLT would also contribute to the tracking and management of asset registration, especially of the DER as they exist in a very decentralised manner.

Proposed in EPRI research, but also explored in government funded projects and by university labs, are more specific use cases for DLT in the nuclear industry. They consider the use of ledgers to provide a storage location for data relating to nuclear signatures for nuclear forensics, as well as to serve in a material control function for the nuclear fuel cycle radioisotopes. Nuclear material control and accountability needs data storage that is accessible for both read and write activities by a variety of organisations and would benefit from tamper-proof storage. This concept is not unique in nuclear ledger research. Researchers at Tokyo Tech in the Nakase Lab have kicked off a research programme on this topic, titled NEUChain, with the intent to build a demonstration using operating low-level waste disposal facilities and the waste generated from the Fukushima Daiichi nuclear power plant.

What these applications share is the ability to leverage a unique aspect of ledgers not present in other databases: the smart contract. Complex software can be embedded into a ledger, so that it executes as data moves from one location to another. This can represent anything from the radioactive decay of isotopes within a waste form to the payment of dividends to an author when their work changes hands. The automatic execution of these pieces of code creates additional opportunity that does not exist with other technologies.

Advantages and disadvantages

Distributed ledger technology is fairly mature. Many commercial ledgers act as the backbone of cryptocurrencies, but many private ledgers function for industry users across multiple sectors of the economy. These technologies have grown rapidly in research and adoption in the last several years. There are many potential benefits from transitioning from a database for storage to a ledger with immutability, but similar challenges remain in implementation.

Connectivity of your real-world asset, such as a spectroscopic measurement system used to identify the radionuclides in each medium, to a ledger where the data can be stored and transferred still represent a weakness in the system. Even if the ledger is immutable, a device can be tampered with to create false signals. The verification method for ensuring that the data on the ledger is truly accurate is an area where further research is needed to ensure that this potentially disruptive technology could be adopted.

Conclusion

Identifying opportunities to demonstrate the connectivity between a ledger and various storage media for nuclear materials is what groups like the Nakase Lab seek to do. The first steps are to show how DLT can be implemented for this use case, with future opportunities to show impact leveraging the smart contract technologies to expand the complexity of materials tracking.

High fidelity computing

Electric Power Research Institute - Harnessing High-Performance Computing: Transforming Industries and Pioneering Innovations in the Nuclear Sector

In the past 50 years, the cost of computing hardware has come down by 11 orders of magnitude. As a result, industries across the globe have made high-performance computing (HPC) an integral part of industry activities ranging research and design to operations and deployment. In fact, the US Department of Energy is wrapping up a USD 25 billion Exascale Computing Program in 2024 which targeted rapid knowledge growth and information sharing with industry from oil and gas to aerospace and nuclear. The programme's goal is to accelerate the ability of those industries to take advantage of HPC and demonstrate the significant return on investment available.

High-performance computing is disruptive for two reasons: it is costly to adapt it to an existing business operation (less so for new business ventures), and it can completely change the way one operates daily. For example, most nuclear codes have their roots in old Fortran software developed over 50 years ago, when the programming paradigm was much different. Restructuring those codes to take advantage of HPC (or writing new ones) incurs costs measured in the millions of dollars range. Furthermore, as HPC systems focus more on GPUs than CPUs, even the HPC codes of the early 2000s are needing to undergo massive infrastructure overhauls to take advantage of modern petascale and exascale machines, especially as more CPU-focused supercomputers are getting retired and replaced with supercomputers with less CPU power. The significant investment required before one can start seeing a return on investment is the largest barrier to utilisation of HPC.

For an example of the disruptive nature of HPC related to how it changes daily operations, consider generative artificial intelligence (AI). The concept of generative AI and the algorithms involved have been around for decades. However, it wasn't until there was enough computing power available to train the models that they became reality.

Another example is the ability to replace expensive experimentation with modelling and simulation; a concept which has been demonstrated in applications ranging from aircraft engines to medicine, saving anywhere from millions to billions of dollars. HPC has enabled us to do impossible experiments, such as the radiation dispersal for a 1 MT bomb dropped in Times Square. Another experiment application is making predictions under tight deadline, such as identifying the abnormal left turn for Hurricane Sandy and thus the need to prepare New York City for a never-before-seen weather event.

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Idaho National Lab - Modular high-fidelity high-performance modelling and simulation

J. Cody

Abstract

The MOOSE (Multiphysics Object-Oriented Simulation Environment) framework empowers researchers and engineers with a versatile platform for developing complex multi-physics simulations, enabling the simulation of various physical phenomena and governing equations in a modular and scalable manner.

One of the disruptive features of the framework, which has significantly improved the ability to couple physics, are the Multiapps and Transfers systems within the framework. For the past several years, analysts have used these systems to routinely simulate complex physical systems such as whole nuclear reactor cores including neutronics, thermo-mechanics, thermal fluids, chemistry, and balance of plant, within a single simulation. The flexibility of the approach enables rapid design iteration of complex multi-physics systems such as passive physics-based safety systems and other critical components of advanced reactors.

Over the last decade, groundbreaking technologies for high-performance computing were developed by the DOE Exascale Compute Project (ECP) to achieve high scalability and efficient use of large, distributed computing clusters.

New research into using these state-of-the-art software libraries with capabilities found in MOOSE can enable the deployment of the MOOSE-based high-fidelity tools through large-scale advanced reactor design studies, full-device optimisation studies and distributed uncertainty quantification calculations. The deployment of these tools can enable the design of more efficient reactor systems.

are helping to realise even more rapid prototyping, design analysis, and safety basis analysis using higher fidelity tools that can reduce uncertainty and will produce even more efficient reactor designs in the future.

Introduction

The MOOSE framework is a modular open-source modelling and simulation platform capable of simulating a wide variety of physical phenomena, with numerous equation discretisations from various forms of finite elements to characteristics-based methods, to cell-centred finite volume discretisations.

It leverages a hybrid distributed and shared memory parallelism architecture to optimise performance on available parallel computing environments, such as modern high-performance computing clusters. MOOSE has been applied to a wide range of physics problems including subsurface fluid flows, rock mechanics, materials science, biological systems, along with nearly every aspect of the simulation of nuclear reactors and nuclear plants. The popularity of MOOSE for advanced reactor simulation has dramatically increased in recent years due to sponsorship within the Department of Energy, Nuclear Energy (DOE-NE) and the adoption of MOOSE-based tools by the United States Nuclear Regulatory Commission (US NRC) Office of Nuclear Regulatory Research. One key feature that helped launch this adoption and growth was the MOOSE Multiapp system.

The MOOSE Multiapp system allows multiple models to be readily coupled together through straightforward input file syntax. Furthermore, analysts have shown that several models can all be coupled together in a single simulation in a relatively robust way for building up models for complex systems.

This powerful capability has made the platform popular for modelling the wide variety of similar, yet somewhat unique reactor designs currently in development throughout the rapidly growing advanced reactor industry. The ability to use a single tool in such a flexible manner has been one of the primary reasons that the US NRC has adopted the tool for use as part of the confirmatory analysis process.

Beyond the ability to readily couple applications together, the Multiapp system can also be leveraged by both legacy tools and separately developed tools which may have longer verification and validation histories once a small set of APIs have been implemented. This allows comparisons of the results of both new tools to existing tools or combinations of those tools.

MOOSE has long supported both message passing interface (MPI) and threading for parallelism, but historically has not adopted technologies for utilising hardware accelerators such as graphical processing unit (GPUs), which are commonly found in high-performance computing systems. New funding, however, is starting to bridge this gap. With several high-quality software libraries produced through the DOE-NE Exascale Computing Project (ECP), the path to leveraging accelerators for MOOSE is more technically achievable and economically feasible than it has been in even the recent past. Multiple concurrent efforts are underway to investigate the use of Kokkos, MFEM, and libCEED in the MOOSE framework with the goal of minimising impact to both developers and users. Preliminary investigations are already yielding possible adoption paths and substantial acceleration of the linear solves. These tools can be coupled with an already successful Multiapps coupling formula and are setting the stage for further disruption in the multiphysics modelling and simulation space.

Several other promising technologies are currently in development within MOOSE and will be deployed and combined with ECP-based technology. These include the integration with state-of-the-art artificial intelligence and machine learning AI/ML libraries, physics-based reduced order modelling (ROM), Isogeometric Analysis (IGA), and built-in stochastic analysis tools. Each of these capabilities alone or in concert with the orchestrated technologies covered in this brief promise next-generation modelling and simulation capabilities for current and future problems of interest. Several ongoing research projects, including several dissertations, are all feeding into the MOOSE ecosystem improving state-of-the-art high-fidelity analysis.

In summary, the MOOSE platform has been instrumental in creating an ecosystem of modern modelling and simulation tools to support aggressive planning and deployment schedules of advanced nuclear reactors in the United States. The capabilities developed in this framework, integrated with products from other high-performance computing science initiatives, are paving the way for disruptive applications of computational science to nuclear applications. Furthermore, the open-science mindset of INL’s researchers in this space are making these technologies more impactful, creating lasting national and international collaborations in these areas.

Next generation communications networks

Electric Power Research Institute - Advancing Energy Systems with Next-Generation Communications: The Role of 5G and Beyond

In a decentralised, geographically distributed energy system, real-time situational awareness of the end-to-end system is critical to ensure system safety, reliability, and cost-effectiveness. In other words, reliable, resilient, cost-effective communications to establish real-time situational awareness for operation and maintenance of such systems is key. Historically, communications networks in large energy systems, such as the North American electrical grid, have relied on optical fibre as the communication medium of choice, because of its high reliability and despite its high cost. However, as energy sources become smaller in size, and distributed across large geographic areas, the communications flows required to protect, control, and co-ordinate such a system can no longer be enabled via optical fibre due to its high cost. Lower cost yet reliable point-to-multipoint wireless communications technologies, such as 5G, become more attractive.

5G technical specifications are developed by the 3rd Generation Partnership Project, a global body responsible for defining mobile communications standards. 5G defines a new class of Ultra Reliable Low Latency (URLLC) communications targeting latencies as low as one millisecond and network availability as high as 99.9999%. The 5G architecture provides connectivity to devices via the 5G Radio Access Network (most visualised as mobile/cell towers) and the 5G Core Network (typically hosted in a data centre). Devices access enterprise or other specialised services by routing traffic through the User Plane Function (UPF) typically extending from the cellular edge device to the end application (e.g. SCADA front end processors) via the radio network and the 5G Core.

5G has made ultra-reliable and low latency communications (URLLC) at the network edge a reality in the standards, but implementation has lagged. Now, momentum for development of standards beyond 5G towards 6G is pushing the boundaries and further enhancing the performance of URLLC based services in a holistic manner including the network edge and the network core.

This evolution of cellular technology to a state where it is fast becoming an attractive communications networking technology option for the distributed, decarbonised energy systems of the future, can be attributed to disruptive technologies such as software-defined networking (SDN) and network-function virtualisation (NFV).

In a legacy network, all devices within that network had to be individually configured and managed, with the data and control planes/functions present on every networking device. The SDN concept is about virtualising the control plane and moving it from all network devices to an SDN controller, i.e. a centralised control plane for the entire network. The data plane is streamlined, improving performance and reducing delays. This significantly improves the adaptability of the network to changes, such as link congestion or failure. SDN is expected to deliver a more efficient use of the network capacity and minimise costs by virtualising the actual network devices. Such virtualisation and control/data plane separation techniques have significantly improved wireless network efficiency to an extent where these networks can now meet the reliability and latency requirements of energy systems.

Novel materials and manufacturing

Argonne National Laboratory - Nuclear innovation and newly emerging disruptive technologies

Meimei Li

Abstract

This technology review outlines the transformative potential of advanced materials and manufacturing technologies in the nuclear energy sector, highlighting their role in enhancing reactor performance, safety, and cost-effectiveness. Advanced materials offer improved performance, such as high-temperature strength, radiation tolerance, and corrosion resistance, which are crucial for designing next-generation advanced reactors and extending the lifetimes of existing nuclear power plants. Advanced manufacturing, such as additive manufacturing, enables the production of complex components with optimised designs, previously unachievable through conventional methods, which could reduce costs and dependencies on supply chains. These technological advancements foster innovations in nuclear energy technologies and redefine traditional manufacturing concepts, contributing to economic, environmental, and societal impacts. However, adopting these innovations poses challenges such as significant upfront investment, regulatory barriers, and the need for a skilled workforce. Strategic investments in research and development, updated regulatory frameworks, workforce development, and international collaboration are crucial to unlocking the full potential of these technologies for a sustainable and economical nuclear energy future.

Introduction

Advanced materials offer superior properties and performance in nuclear environments over conventional materials, e.g. enhanced high-temperature strength, improved radiation tolerance, and better corrosion resistance. Their ability to endure harsh nuclear conditions over long lifetimes is crucial for designing next-generation advanced reactors and extending the operating lifetimes of current nuclear power plants. Advanced manufacturing techniques, such as additive manufacturing (also called 3D printing), allow the production of components with complex geometries and optimised designs unachievable by traditional methods. They also offer new ways to create novel materials with properties tailored for specific applications. These technological advancements lead to innovations in nuclear energy technologies, potential cost reductions, and decreased supply chain dependencies for reactor components, which are vital for ensuring nuclear power's safety, reliability, and economy.

Advanced materials and manufacturing technologies have evolved from ancient natural resource utilisation to the Industrial Revolution and the modern era of smart manufacturing (so-called Industry 4.0). This progression underscores the continuous human innovation that drives societal progress and economic growth. These technologies continue to evolve today, with an emphasis on sustainability, efficiency, and customisation. The readiness level of these innovations varies widely, with some advanced alloys and manufacturing techniques being ready for commercial applications while others, particularly new materials and processes, remain in the development stage. This variation highlights the dynamic nature of technological advancement and the critical role of ongoing research and development (R&D).

Advanced materials and manufacturing have fundamentally changed the landscape of product design, fabrication, and utilisation, profoundly impacting the nuclear industry and the global economy. The introduction of advanced materials enhances the performance of reactor structural components through increased strength and durability in nuclear environments, while advanced manufacturing processes, such as 3D printing, are allowing unprecedented customisation and optimisation. The rapid prototyping capabilities of advanced manufacturing accelerate the innovation process, enabling new products to reach the market faster than ever. This paradigm shift in manufacturing not only represents a technological advancement but also a fundamental change in product creation and use, with significant economic, environmental, and societal benefits. It opens new pathways for developing innovative reactor technologies and contributes to the broader goal of achieving a sustainable, reliable, and clean energy mix.

Possible applications

The nuclear industry is at the forefront of adopting advanced materials and manufacturing techniques to address key challenges in the safety, reliability, and economics of nuclear power. For example, advanced high-performance steels provide superior mechanical strength in reactor components exposed to extreme conditions, potentially increasing reactor design lives and reducing maintenance needs (Was et al., 2019). Advanced nickel alloys are being developed for their corrosion resistance in molten salt environments for use in molten salt reactors (Guo et al., 2018). The use of oxide-dispersion-strengthened alloys that can resist radiation to high doses leads to improved nuclear fuel performance (Jayakumar, Mathew, and Laha, 2013). Accident-tolerant fuels have improved performance under accident conditions, enhancing the safety of nuclear reactors (Zinkle et al., 2014).

Manufacturing innovations like 3D printing allow for the fabrication of complex components, e.g. upper tie plate grids in fuel assembly, channel fasteners, potentially reducing costs and improving the functionality and performance of nuclear reactors (IAEA Bulletin, 2023). Embedded sensing enabled by advanced manufacturing allows for enhanced system control, health monitoring, and autonomy (Petrie et al., 2021). These applications demonstrate the transformative potential of advanced materials and manufacturing technologies in the nuclear sector, pushing towards safer, more economical, and sustainable nuclear power.

The development of advanced materials involves manipulating matter at the atomic level to discover and create materials with novel properties through an integrated approach involving advanced experimental and computational methods. Integrating advanced manufacturing with digital technologies like artificial intelligence promises to revolutionise manufacturing with enhanced efficiency, flexibility, and customisation. Early R&D investment is crucial for exploring the full potential of these technologies, driving economic growth, creating high-value jobs, and fostering innovation across various industries. Despite the risks and challenges involved, the potential rewards of economic growth and societal benefits make these investments worthwhile, highlighting the need to support innovation and development in these critical areas.

Many countries are investing in advanced materials and manufacturing R&D in recognition of the importance of nuclear energy to achieving climate goals. Significant international collaboration is being done through organisations such as the International Atomic Energy Agency (IAEA) and the Generation IV International Forum (GIF). Introductions of new materials and manufacturing technologies in the nuclear sector are often slowed by regulatory processes. Harmonising international standards and codes and streamlining qualification and certification processes without compromising safety are vital steps for their commercialisation.

The applications of advanced materials and manufacturing technologies in the nuclear industry bring a range of workforce implications, e.g. shifts in skill requirements, changes in job roles, and the necessity for continuous training and education. The development and implementation of advanced materials and manufacturing technologies involve a wide range of disciplines, such as materials science, nuclear engineering, mechanical engineering, and computer science, making for a workforce that is capable of interdisciplinary collaboration and communication. The rapid pace of technological advancement also requires the workforce to be adaptable and ever willing to learn and adopt new technologies. To address these requirements, stakeholders, including governments, educational institutions, and private companies, must work together to develop strategic plans for workforce development. These include investing in STEM education, creating specialised training programmes, and fostering partnerships between industry and academia to ensure that the workforce is prepared for future challenges and opportunities.

Advantages and disadvantages

Advanced materials and manufacturing technologies hold enormous promise for the nuclear energy sector.

Advanced materials can withstand higher temperatures and radiation levels and more corrosive environments. The longevity and reliability of advanced materials also can decrease maintenance and operational costs.

The ability to custom-design components and systems enabled by advanced manufacturing opens possibilities for innovative reactor designs, and rapid prototyping and customisation can accelerate research and development cycles. These innovations can lead to improvements in reactor performance, safety, cost-effectiveness, and sustainability.

However, research, development, and implementation of these technologies require significant upfront investment as some advanced materials and manufacturing technologies remain in developmental stages and may be unproven on an industrial scale for some time.

Upgrading existing facilities and infrastructure or building anew can be costly. New materials and manufacturing technologies must undergo rigorous testing and qualification processes to ensure safety and reliability, which are time-consuming and expensive.

Regulatory frameworks may need updates or revisions to accommodate new technologies, posing additional challenges. A skilled workforce is essential, requiring significant commitment to training and education. While advanced materials and manufacturing technologies offer revolutionary prospects for the nuclear industry, their successful implementation and integration require careful consideration of the associated costs, regulatory hurdles, and workforce needs.

Conclusions

To fully harness the potential of advanced materials and manufacturing technologies in the nuclear sector, a multifaceted approach is needed, including strategic investment in materials science R&D. This is necessary to develop high-performance materials, and in advanced manufacturing, such as additive manufacturing and automation, to improve production efficiency and reduce supply chain dependencies.

Equipping the workforce with necessary skills through strengthened STEM education, specialised training, and industry-academia collaboration is crucial. Regulatory frameworks also must be updated to accelerate the adoption of advanced materials and new manufacturing processes. International collaboration is essential to harmonising codes and standards and facilitating global co-operation. Encouraging public-private partnerships can further support innovation and expedite technology commercialisation.

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Idaho Nuclear Laboratory - Digital design and new material manufacturing

Allen Roach

Abstract

Nuclear, aerospace, medical, and homeland security missions are increasingly requiring materials to operate in a wide range of extreme environments: radiation, thermal, mechanical, extreme deformation, and corrosive. To meet these requirements, new innovations in materials design, development, and manufacturing must be prioritised to facilitate creation of the lightweight materials, nuclear fuels, and advanced survivability materials required for the extreme environments of next generation reactors. Fundamental understanding of multi-scale materials synthesis is needed to leverage advanced manufacturing techniques, including additive manufacturing or 3D printing, for material discovery and rapid fabrication of materials with the highly tuned and tightly controlled properties to achieve these advanced requirements. Predicting material attributes during manufacturing processes and throughout service life requires shifting from current iterative design-build-test to digital design and manufacturing. Emerging materials options include high entropy alloys, high temperature materials, metamaterials, damage tolerant and radiation-resistant alloys. New initiatives focused on growing new national capabilities to design, develop, test, characterise, and manufacture these needed materials must be initiated. Initiatives that make use of prior national lab investments are feasible and preferred. The main goal must be to develop capabilities for transformative materials design and advanced manufacturing for material functionality and durability in extreme environments.

Introduction

New materials that can perform in extreme environments, such as radiation, thermal, mechanical, extreme deformation, and corrosive are currently a limiting factor in commercialisation of advanced nuclear reactors.

Advanced manufacturing techniques are needed to develop many of these materials, but these techniques have not yet been applied broadly to materials for new nuclear fuels for advanced reactor designs, lightweight materials for extreme environments, or advanced survivability materials, or other applications.

In addition, the capabilities to design materials strategically and rapidly with predicted performance in extreme environments do not currently exist. This tremendous fundamental science challenge with real world impact presents an excellent opportunity for cross-discipline collaboration, leveraging the multi-discipline capabilities in the national labs and universities. By leveraging existing expertise in materials research and development for extreme environments coupled with innovation in advanced manufacturing, we can initiate a paradigm shift to digital design and manufacturing, away from the traditional and iterative design-build-test approach.

Advanced manufacturing allows simultaneous fabrication and process-monitoring and control and is perfectly suited to support the development and design of the new materials and novel material structures for advanced nuclear reactor designs.

Possible applications

Developing new materials and manufacturing approaches for next generation materials for extreme environments connects and advances nearly all the proposed and planned advanced nuclear reactor designs. The need to develop first principles understanding of the microstructural evolution and defect evolution of materials in advanced nuclear reactor service environments is a well-documented need for future reactor designs. Advanced material solutions directly support demonstration of innovative energy solutions and beyond and are imperative for materials performance in advanced reactor service environments, such as radiation, thermal, mechanical, extreme deformation, and corrosive.

The capabilities to design materials strategically and rapidly with predicted performance in these extreme environments are not readily available, and materials currently qualified for use in extreme environments are very limited.

Advantages and disadvantages

By leveraging existing expertise in the national lab system for materials R&D for extreme environments coupled with innovation in advanced manufacturing, the opportunity to initiate a paradigm shift to digital design and manufacturing away from the traditional design-build-test approach is within reach in a decade.

Advanced manufacturing is ideally suited to accelerate innovation in advanced materials and manufacturing for extreme environments by enabling these emerging capabilities: (1) developing advanced manufacturing process-informed material design; (2) expanding advanced manufacturing process development and innovation; (3) enabling rapid material characterisation and testing designed for advanced manufacturing; and (4) integrating comprehensive data analytic and modelling and simulation techniques.

These areas align strongly with the Department of Energy (DOE) BES Basic Research Needs for Future Nuclear Energy, Advanced Nuclear Systems, and Transformative Manufacturing, while also providing strong linkage with the DOE Advanced Materials and Manufacturing Technology Office and Industrial Efficiency and Decarbonization Office programmes and DOE-NE-5 Advanced Materials & Manufacturing Technologies programmes.

A fundamental understanding of multi-scale materials synthesis is needed to leverage advanced manufacturing techniques for material discovery and rapid fabrication of materials to achieve highly tuned and tightly controlled properties.

Coupling fundamental understanding and systems design techniques for rapid materials synthesis and processing enables fabrication and qualification of customised, high-performance materials. For example, a key component of material design capability is to predict phases and phase transformations for a system of interest allowing materials with specific microstructures and thus performance behaviour to be developed. Traditionally, developing phase diagrams and measuring phase transformations and other kinetics information required extensive experimental campaigns. The development of phase diagrams and transformation of new systems computationally will greatly reduce the cost and accelerate the speed of gathering this foundational information.

A high-throughput experimental infrastructure and the expanded use of advanced artificial intelligence (AI) techniques provides the ability to select and evaluate the broad array of material compositions that can be created via a digital design and manufacturing capability. Combining these high-throughput testing capabilities with advanced manufacturing and materials design will drive fundamental understanding and facilitate the efficient down-selection of methods that must be developed for evaluating materials performance. This will require strong integration with advanced manufacturing process development efforts and integrating comprehensive data analytics and modelling. One focus of these efforts is to facilitate strong integration between the experimentalist and modelling and simulation capability development to drive materials development efforts across national labs, industry, and universities.

Experimental, computational, AI, and data analytics approaches are all key capabilities to relate the advanced manufacturing process parameters to the material properties and to ultimately predict performance in their service environments. Advancements in algorithms that integrate multi-physics model(s) with the full range of manufacturing systems must be an area of focus. This advancement will close the loop between the experimental system and multi-physics models and provide a foundation for the next generation of digital twins where the twin is aware of its processing history. The resulting numerical tools and machine learning (ML) models are dependent upon trustworthy algorithms and verifiable data.

Conclusions

Digital design and manufacture of new materials is to operate in a wide range of extreme environments: radiation, thermal, mechanical, extreme deformation, and corrosive. Success in developing new materials for advanced reactor fuel designs will be a springboard for utilisation of these capabilities in industries with similar challenging materials requirements such as aerospace, medical, national defence, space, and nuclear deterrence.

Integrated experimental, computational, and data-driven design approaches will be available to link the advanced manufacturing process parameters to the material microstructure and ultimately predict their performance in service environments without onerous qualification campaigns. Emerging materials include, but are not limited to, high entropy alloys, high temperature materials, metamaterials, dissimilar materials, damage and penetration tolerant materials, and radiation-resistant alloys.

A design capability for new advanced materials with tailored/improved performance will significantly add value by accelerating development times while also reducing both technical and programmatic risks. In addition, the ability to verify and predict process stability and eventually materials assurance allows for science-based and trusted manufacturing and an increased confidence in lifetime performance.

Nuclear Advanced Manufacturing Research Centre - Advanced manufacturing in nuclear

Achieving net-zero targets will only be possible with a low-carbon, resilient and affordable energy supply, in which nuclear power is expected to play a crucial role. Recent developments in new generation reactor technologies have opened the opportunity to deploy advanced manufacturing techniques in a way that can revolutionise production for the nuclear sector.

Techniques such as electron beam welding (EBW) and powder metallurgy hot iso-static pressing (PM HIP) offer significant potential to reduce costs, lead times and carbon emissions, as well as the prospect of extending existing supply chains and increasing the productivity and skills of the nuclear workforce.

Application of modularisation and design for manufacturing principles to technologies such as small modular reactors (SMRs) will also increase the type and number of components that can be produced in factories. Factory production will allow greater use of industrial automation, which can be further supported by digital technologies such as artificial intelligence to enable disruptive change, by significantly reducing the time and effort required to qualify advanced manufacturing, new materials and alternate supply chains.

Electron Beam Welding

Electron beam welding (EBW) is a fusion welding technique that has been seen significant adoption in other industries. A good example is the manufacture of an offshore-wind turbine monopile. In the nuclear sector, the Nuclear AMRC and EPRI have demonstrated that advanced manufacturing techniques such as EBW can reduce the lead time of an SMR from two and a half years to less than one year, while reducing manufacturing emissions during fabrication by over 1 800 kg of CO_2 for each reactor pressure vessel (RPV).

EBW uses a beam of electrons that is focused by magnetic fields to achieve high power density levels and must be performed within a vacuum to prevent the electrons from colliding with gases and disrupting the electron beam. Due to the requirement of a vacuum for the EBW process, this has the potential to limit the size of components that can be welded. Research has been done to address this through the development of various methods, in particular local vacuum technology and modular in-chamber capability. As part of these efforts, Sheffield Forgemasters has successfully demonstrated the use of local vacuum technology with EBW to weld thick sections over 200 mm in a single pass effectively reducing welding time from several weeks to hours, widening the application of EBW.

Because EBW is an autogenous, single-pass, high energy density welding technique, process times for joining thick sections are significantly reduced by eliminating the need for machined joint profiles, filler material, pre-heating, hydrogen bake-out. This has the potential to reduce the circumferential weld of an SMR RPV by 80% and material requirements by approximately 325 kg (filler material and additional machined joint material). This also has significant workforce implications, as it has been identified that there is a shortage of welding skills in the nuclear sector, from operators to engineers, which spills over into other energy sectors, including offshore wind.

Although EBW has been adopted in other sectors and has some limited applications in the nuclear sector, there are several barriers to enable further adoption and realisation of the full benefits. The Nuclear AMRC is in collaboration with several key partners, primarily to codify EBW into American Society of Mechanical Engineers (ASME) Section III for nuclear components, but also to ensure that EBW operations are performed in accordance with other safety and quality standards as well, progress of which is critical to lift barriers for the nuclear supply chain.

Powder Metallurgy Hot Isostatic Pressing

PM HIP is a solid-state diffusion process that produces fully consolidated components from metal powders. In the nuclear sector, there has been a growing interest in PM HIP to produce large components, such as pumps and valves, as an alternate production route to traditional methods including forging and casting. Notably, ASME Section III has approved the use of Grade 316 stainless steel components manufactured via PM HIP.

The PM HIP process uses high-quality metal powders, usually produced to ASTM standards. The powder is first encapsulated in a can, which is then degassed, filled with inert gas and finally sealed. The can is then put under a constant pressure and heated typically up to 70%-80% of the metal powder's melting point. Under this high pressure and temperature, powder consolidates, and porosity is reduced through volumetric shrinkage. Understanding the powder consolidation process and the associated can deformation is critical to achieving a near-net shape right first time. For this reason, modelling and simulation techniques are widely used to optimise can size and design, reducing PM HIP costs and excess material usage.

The forging and casting supply chain for some of the high integrity components has been described as a 'pinch point' for the nuclear sector, facing increasing supply pressures from other sectors such as aerospace, renewable energy and defence. As one of the key advanced manufacturing techniques, PM HIP could form and provide an alternate supply chain for these components, reducing reliance on already limited forging and casting capacity worldwide and consequent cost and lead times. Notably, the Nuclear AMRC and EPRI have also been working in this area and have successfully demonstrated the use of PM HIP for the near net manufacturing of various SMR components that would traditionally be manufactured by forging.

Due to the high pressure and temperature required for the PM HIP process, the cost of building facilities capable of producing large components is high, with costs increasing exponentially with component size. There are only a few PM HIP facilities in the world capable of producing components in the 1m to 2m diameter range. Initiatives are underway to build a PM HIP facility capable of producing components over 3m in diameter, the most prominent of which is ATLAS.

There are also limited material grades approved for PM HIP by ASME Section III, which are currently limited to low temperature service applications. Codification of additional material grades will require the development of data packages for both powders and the PM HIP process. Moreover, additional testing will be required for high temperature applications that require time-dependent properties such as creep data. Collecting, analysing and presenting experimental data on this scale can take decades, so digital technologies are seen as instrumental to speeding up this process, a good example of which is the work done at Argonne National Laboratory to extrapolate creep data for ASME Section III Division 5.

Conclusion

Advanced manufacturing will be a key enabler for the global deployment of new generation nuclear technologies, such as SMRs, at the desired cost levels and production rates. However, accelerating the adoption of advanced manufacturing techniques in nuclear production will require continued close collaboration between technology providers, research institutions, the supply chain and regulators, with financial support for research and development, codes and standards development, and a clear forward demand for components to validate the business case for investment.

Quantum technologies

Electric Power Research Institute – Technical Brief on Quantum Technologies

Abstract

Quantum technologies represent a step change in computational and networking capabilities for a range of applications and could provide significant benefits for energy-system applications. Quantum technologies describe a family of related technologies built around real-world applications of quantum mechanics in real-world systems. This technical brief describes the current state of these technologies, advantages and limitations, potential use cases, and value that the technologies can bring to the nuclear industry.

Introduction of the technology

Quantum computing evolved out of the field of quantum mechanics when Richard Feynman, David Deutsch and other quantum pioneers realised the revolutionary potential for using quantum mechanical systems to perform computations (Feynman, 1982). While the concepts of quantum computing have been established for decades, it has only been in recent years when the requisite fields materials science, computer science, mechanical engineering, etc. have converged to provide the necessary advancements to enable new developments in the field of quantum computing, such as advanced materials, algorithm development and error correction, among others. A more extensive discussion of these technologies and underlying principles can be found in the references (EPRI, 2022c; Feynman, 1982; QED-C, 2022a).

Quantum technologies include three main technical areas. These are: quantum computing; quantum communications, networking, and cybersecurity; and quantum sensors. Each of these technologies is based around manipulation of quantum mechanics in physical systems.

These three modalities are described in more detail below:

Quantum computing

Quantum computing uses the fundamental properties of quantum particles to perform parallel calculations rapidly. The fundamental unit of quantum computing is a qubit, or quantum bit, analogous to a bit in standard computing. Quantum computing uses the combination of superposition and entanglement to provide polynomial to exponential speedups for completing certain types of computational tasks, such as optimisation problems, AI and machine learning, as well as factoring numbers and performing searches within a database. Quantum computing will not currently produce any speedups in various other tasks, so it is important to understand how and when to use this technology in computing applications. However, for problems that quantum computers do provide speedups, the potential speedups can be exponentially faster and more energy efficient on a quantum computer than on a standard computer. Additional details on quantum computing can be found in the references (EPRI, 2022a, 2022b, 2022c.; Feynman, 1982; QED-C, 2022a).

Quantum communications, networking, and cybersecurity

Quantum technologies can be used for a range of valuable and interesting capabilities. For example, to verify secure communication between a sender and receiver of information by detecting the presence of an attacker trying to intercept packets of information or using quantum teleportation to instantaneously and securely transmit information across vast distances. Similarly, quantum technologies can help to provide secure key exchange via quantum key distribution.

Quantum sensors
In contrast to traditional sensors that use bulk material properties to perform measurements, quantum sensors use a single quantum particle (such as photon, atom or ion) to perform very detailed measurements of a particular property. A range of quantum sensors is already available with one of the most well-known sensors being a quantum clock.

Possible applications

The possible applications for these three technologies are discussed below and organised into the three topical areas described above.

Quantum computing
Quantum computers have the innate capability to handle a wide range of parallel computing and/or optimisation type problems. The list of applications below covers several energy-related use cases (EPRI, 2022c) but is far from exhaustive and a more complete set of use cases can be found in (QED-C, 2022a).

- **Quantum-enhanced AI/ML application:** Such applications could train AI models faster with higher accuracy while consuming less energy than current practices.
- **Probabilistic Risk Assessment (PRA):** PRA models can have thousands of combinations of event trees and fault trees within an evaluation. Quantum computing algorithms could drastically speed up the analysis of PRA models to optimise the maintenance and usability of a model.
- **Capacity expansion planning**: As new energy generation sites are planned and sited, models involve vast amounts of spatial, temporal, and cost complexities with some models reaching over 1 billion parameters.
- **Materials discovery:** Quantum computing offers the potential to accelerate materials discovery and development for advanced materials with improved structural, thermal, shielding, and other properties, which could – in turn – accelerate the development of quantum computing.
- **Quantum communications, networking, and cybersecurity:**
    - Quantum networks offer the ability to provide virtually unhackable communications (QED-C, 2022b).
    - Quantum networking could help to support enhanced quantum computing to integrate the data from a network of quantum sensors as well as help to solve energy-related challenges, such as scheduling, dispatch, and help with reliability analysis.
- **Quantum sensors**: A range of quantum sensors have been developed for a broad suite of applications. Only a few of these use cases are covered below:
    - Grid health monitoring: Quantum sensors can be used to identify both temperature and stress/strain in transmission and distribution wires (QED-C, 2022b; US Department of Energy, n.d.), helping utilities to identify early onset of failure.
    - Nuclear isotope detection: An atom interferometric quantum sensor may be able to detect the presence of specific isotopes of interest with high sensitivity [8].
- **Quantum clocks:** Quantum clocks are ultra-accurate clocks that can operate without satellite or other external communications equipment and are accurate to within a second over a period of 1 billion years or more. Such accuracy reduces the dependency on GPS positioning systems and associated timing and helps to harden devices against denial-of-service attacks.
- **Other applications:** Quantum sensors can detect a wide range of parameters, including temperature, stress/strain, electric or magnetic fields, force, thermal conductivity, and more; as

such, quantum sensors could support a wide range of benefits to many different energy applications, as discussed in the references (QED-C, 2022b; US Department of Energy, n.d.).

These are just a few of the potential use cases for quantum technologies in the energy sector. As previously noted, this is just a small fraction of the total potential range of use cases that could be deployed in the future, depending on technology cost, reliability, availability, regulations, and other factors.

Advantages and disadvantages

Like other emerging technologies, quantum technologies offer a range of benefits over standard solutions, however, this does not mean that they are without their own disadvantages. For the most part, quantum technologies are still relatively immature technologies with quantum computing typically at a lower TRL level than quantum sensors, some of which are already commercialised and deployed into the field. These include nuclear magnetic resonance (NMR) machines which employ quantum sensing. The discussion below includes several advantages and disadvantages of quantum technologies:

Advantages of quantum technologies

- **Computation speed and scaling:** The main advantage of quantum computing is the exponential scaling that is obtained by adding more qubits. For example, each additional error-corrected qubit that is added has the potential to double the processing capability of the overall system, compared to a linear increase from standard bits. For a better example, if 10 bits are added to a 100-bit processor, it becomes 1.1X faster (10%). If 10 error-corrected qubits are added to an error corrected 100-qubit processor, it will receive up to a 1024X boost (or 102 400% faster) for certain mathematical operations – typically parallel processing type applications (while other computations, such as serial processing, will not experience a boost in productivity).
- **Secure communication:** Quantum networking offers the ability to increase communication security as well as identify the presence of a would-be hacker attempting to intercept a message.
- **Improved encryption:** Standard computers struggle to generate truly random numbers and while the numbers may seem random to humans, given the same set of inputs (the seed), a standard computer will always produce the same set of random numbers as an output. Quantum computers offer the ability to provide increased randomness in cryptography applications via quantum seeds via random number generation for improved cybersecurity.
- **Improved accuracy and precision:** Quantum sensors can make ultra-accurate and precise measurements of various physical parameters. This sometimes comes at the cost of measurement speed.

Disadvantages of quantum technologies

- **Error rates and reliability/repeatability:** One of the key disadvantages today with quantum computing is the error rates in qubits due to decoherence and a collapse of the quantum state due to interactions with the surrounding environment. Various means are in place to reduce the likelihood of decoherence from interactions with the environment as well as the impact of errors by using error correction methods. But the issue remains and is an active area of research today. A standard practice to improve accuracy is to perform calculations many times and average the results to identify the most likely solution.
- **Scaling issues:** Like the above challenge, the difficulty in maintaining qubit coherence and stability with increasing numbers of qubits, limits the ability of current quantum computers to

scale to the degree necessary for widespread adoption. However, qubit counts continue to increase each year and may soon reach a tipping point.

- **Cost:** While some quantum technologies are cost competitive with standard technologies today (such as quantum sensors), others are not. Quantum technologies require upfront investment as well as training to operate effectively. It is anticipated that with continued development, the costs for quantum technologies will continue to come down over time.
- **Complexity:** Quantum computing involves complex construction, and in-depth knowledge to operate, making their use limited to those with specialised knowledge and skills.
- **Speed:** Certain types of quantum sensors may take longer than their standard counterparts to perform measurements.
- **Cybersecurity risks:** The main threat from quantum technologies is related to the ability of Shor's algorithm to factor numbers exponentially faster than standard computers today, allowing a large-scale, fault-tolerant quantum computer to break essentially all encryption methods currently in place. However, this can only be performed on a large-scale, fault-tolerant quantum computer, which is well beyond anything available today or the near future. This means that once such a machine is available, individuals, organisations, and governments will need to have deployed post-quantum cryptography solutions to protect data at risk of decryption.

Conclusions

As progress continues, quantum technologies will begin to play an increasingly larger role in industry and especially for large-scale computing workloads, such as AI/ML, materials discovery, large-scale optimisation and simulation. Eventually, once large-scale, fault tolerant computers become available, risk will elevate across all industries due to the ability to use Shor's algorithm to break current encryption methods. However, quantum utility and quantum advantage will be available well in advance of this, providing time for individuals, companies, and governments to continue to develop quantum ready applications and tools.

In conclusion, quantum technology development will continue to advance as investment and interest continue to grow and value is obtained from early wins. While the path for future development will be difficult to predict for this broad family of technologies, it is anticipated that many new advancements are on the horizon and will be built out in the coming years.

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Idaho National Laboratory - Quantum technologies

Krzysztof Gofryk

Quantum technologies have emerged as a disruptive force with the potential to revolutionise various fields, including nuclear research and technology. These technologies leverage the principles of quantum mechanics to perform tasks that were previously thought to be impossible or impractical with standard approaches. From material science to nuclear security, fusion research, and beyond, the integration of disruptive quantum technologies into the nuclear domain holds promise to advance fundamental understanding and enhance safety, efficiency, and security across various facets of the nuclear industry.

One of the most promising applications of quantum technologies in nuclear research is in simulation and modelling. Quantum computing has the potential to revolutionise the simulation and modelling of processes, with its ability to handle complex calculations in parallel, offers the potential to simulate microscopic processes in nuclear materials with unprecedented accuracy and efficiency. Quantum algorithms can be used to model nuclear reactions and material properties enabling researchers to explore new designs, optimise fuel cycles, and understand related nuclear phenomena at a deeper level. By harnessing the power of quantum simulation, scientists could accelerate the development of advanced nuclear technologies while reducing reliance on costly and time-consuming experimental methods.

Using this approach, quantum technologies have the potential to revolutionise fundamental actinide research and various fields within nuclear physics, chemistry, and material science.

Quantum computing algorithms offer an unprecedented opportunity to conduct theoretical calculations for systems far larger and more complex than what can be achieved with even the most advanced supercomputing facilities available today. This is particularly significant for actinide elements, where many properties remain poorly understood and rely heavily on expensive empirical studies. Traditional computational methods, predominantly Density Functional Theory and Dynamical Mean-Field Theory, have faced persistent challenges in providing comprehensive insights into the intricate properties of actinide materials at an atomistic level, often yielding limited success.

Future fault-tolerant quantum algorithms hold the potential to simulate interactions and the bonding of 5f-electrons in actinide materials, especially within the strongly correlated regime, at speeds surpassing those achievable with conventional high-performance computing methods. Moreover, by simulating material behaviour at the quantum level, researchers can identify novel materials endowed with enhanced properties such as radiation resistance, thermal conductivity, and structural integrity.

Quantum computing expedites the discovery and design of materials crucial for fuel cladding, reactor components, and shielding, ultimately paving the way for safer and more efficient nuclear systems. Additionally, in the domain of plasma physics, particularly within the warm-dense regime, quantum-enhanced diagnostics and control systems facilitate real-time monitoring and optimisation of fusion experiments. This enhances the efficiency and reliability of fusion energy systems, propelling us closer to realising the potential of fusion as a clean and sustainable energy source.

Quantum sensing technologies and metrology might offer unprecedented capabilities for detecting and imaging nuclear materials and radiation. Quantum sensors, based on principles such as quantum entanglement and superposition, can achieve ultra-high sensitivity and resolution, enabling the detection of trace amounts of radioactive isotopes and the mapping of radiation fields with exquisite precision. Experiments, using quantum sensors and quantum information processing, could shed light on nuclear interactions, symmetries, and fundamental constants, advancing our understanding of the atomic nucleus and its properties. Also, quantum metrology techniques, such as atomic clocks and precision measurements, provide precise tools for studying nuclear phenomena and testing fundamental theories. By pushing the boundaries of precision measurement and control, quantum technologies will enable new insights into nuclear physics and pave the way for future discoveries in the field.

A last and important point, quantum encryption and cryptography offer robust solutions for securing nuclear data, communications, and infrastructure. Quantum key distribution (QKD) protocols provide provably secure communication channels, protecting sensitive information related to nuclear materials, facilities, and operations from cyber threats and espionage.

Quantum cryptography ensures the confidentiality, integrity, and authenticity of nuclear data, mitigating the risks of data breaches, sabotage, and unauthorised access. By integrating quantum security solutions into nuclear systems, governments and organisations can enhance the resilience and trustworthiness of their nuclear infrastructure.

In summary, disruptive quantum technologies hold immense promise for advancing fundamental and applied nuclear research and technology across various domains. From simulation and modelling to material science, security, and fusion research, quantum technologies offer transformative capabilities that enable breakthroughs in understanding, innovation, and application. By embracing these technologies and leveraging their unique properties, the nuclear community can address long standing challenges, accelerate progress, and unlock new opportunities for sustainable and secure nuclear energy.

As quantum technologies continue to evolve and mature, their impact on nuclear research and technology is expected to grow, shaping the future of nuclear science and engineering for generations to come. To support such initiatives and foster innovation and collaboration in this rapidly evolving field, in 2021, INL established a Centre for Quantum Actinide Science and Technology (https://inl.gov/c-qast/).

3. Crosscutting areas

Automation

Electric Power Research Institute - Technology review: autonomous operations

Bruce Greer, Joshua Bell, and Dan Moneghan

There is a sequence in Kurt Vonnegut's classic novel, *Player Piano,* where the invention of the barber machine is described. This task was considered impossible to automate because it was too complicated; required too much skill, training, and human intervention to accomplish. Then, night after night, one barber would fall asleep and dream of exactly how to mechanically automate a single step in the hair cutting process. Process by process, dream by dream, step by step, this barber developed the entire barber machine that altered an industry forever.

Automation describes a system that performs an action based on an input without any additional human interaction required. One example of simple automation is an early alarm clock. This system used a candle made to melt at a known rate. People would then put a nail into the candle at a height that represented the amount of time till their desired alarm and light the candle. When the candle melted the nail would fall and land on metal plate, thus ringing the alarm.

Since then, we have automated many portions of our life with things like thermostats to turn on our air condition systems, motion sensors to open the doors of our most frequently entered buildings, or light sensors to appropriately engage a building's exterior illumination as needed.

As technology advances, automation solutions become more and more capable. Science fiction scenes like Tony Stark walking into his high-tech condo and having all his lights and devices come to life as he starts a conversation with his virtual assistant become much closer to the mundane and expected than the futuristic fantasies of eccentric billionaires. As this vision becomes reality, the power industry is facing a reality made possible by incorporating these capabilities to enable a level of automation that was previously thought impossible.

The nuclear industry finds itself facing the same reality as Vonnegut's fictional barber, originally thinking there is no way that something so complex could ever be automated, but now finding solutions to individual challenges one piece at a time. Through instrumentation, controls, and now robotics and AI, challenges that have been considered technologically insurmountable throughout the development of and deployment of nuclear power production seem closer to small hurdles on the path to automation. All it takes is a review of existing technologies and operational practices in other power plants (hydro, gas, wind, and others) to see just how close and attainable automated nuclear power production really is.

There are many examples of power production facilities which are currently applying effective automation solutions to improve safety and efficiency while reducing costs. One example of this possibility is Japan's T-Point 2 power plant. T-Point 2 is a combined cycle natural gas 566 MWe power plant considered to be one of the most digitally enabled power stations in the world. This station incorporates more than 4 300 data points to first enable remote monitoring systems and then to drive automated functions. For example, using data analytics and AI, combustion pressure can be autonomously maintained throughout changing environment and fuel composition conditions.

Another example of automation in power production is the deployment of ground quadruped robotics at Obervermuntwerk II, a hydroelectric power plant of illwerke vkw AG in the Austrian Alps. This hydroelectric station is already controlled entirely remotely but requires regular inspection to ensure safety standards. Facilitating theses inspections is challenging, especially in the winter due to the remote location and potentially hazardous road conditions. However, equipped with LIDAR, optical and thermal cameras, and programmed with autonomous inspection routines, this robot can gather and transmit the data needed to support this unmanned power production location.

Similarly, unmanned arial systems (or drones) are being autonomously deployed by Ontario Power Generation (OPG) for gird monitoring. These drones are remotely inspecting the McConnell Lake Control Dam more quickly and more frequently than current resources would allow and avoiding the safety risk of personnel climbing towers perform these inspections. The data facilitates insights about current facility condition to improve reliability and ensure operation conditions are maintained.

These are only a few examples of how the power industry is shifting towards autonomous operations with existing technologies today.

Even within the nuclear industry there are many examples of automated operations currently deployed among the fleet. The Vogtle 3 & 4 AP1000 incorporate a fully digital control room with integrated smart procedure processes for plant operation. These enhancements, along with the passive design of these stations, allow the design to potentially be operated by a minimal staff due to the integrated autonomous operation functionality. The value and potential of a digital control room and associated smart procedures are so widely recognised that many utilities across the industry have implemented or are planning to implement digital transformation projects as part of industry-wide modernisations efforts and operating licence extension enhancements.

Robotics have also begun to find their way into nuclear station operations. The Nuclear Energy Institute (NEI) 2023 Top Innovation Practice (TIP) Award, Best of the Best winner recognised Dominion Energy's project to deploy quadruped ground robotics equipped with a 3D radiation detector to remotely perform radiation surveys and produce a 3D visualisation of radiation conditions.

This combined system was deployed at Surry Power Station to evaluate newly installed shielding in containment while operators received minimal dose. The resulting never-before-seen visualisation of radiation validated the shielding's effectiveness. The same team also equipped their ground robotics system with traditional radiation detection devices and set the system to autonomously survey select locations within their radiation-controlled area.

Other nuclear operational areas are taking advantage of AI for enhanced operational efficiency. Xcel Energy also received a TIP award the same year for its implementation of artificial intelligence-assisted Corrective Action Program (CAP IA) software that streamlines the entry, tracking and sharing action items found while operating a nuclear reactor. This CAP IA software removes much of the previous burden, minimises human inconsistency and subjectivity, and leverages data to improves safety while reducing costs. Using AI helps identify performance trends and highlights small problems before they become significant.

While the advent of AI has become much more popular recently with the rise of ChatGPT and other large language models over the last year and a half, AI has been on the horizon in the nuclear industry in varying degrees for years. Many utilities have been developing monitoring and diagnostic centres using advanced pattern recognition software for early identify of diverging indications from monitored plant parameters since the mid-2010s. Utilities are also building out more complete and digital models of their stations for thermal performance monitoring, effectively creating a physics-based digital twin of their power plants. These systems are facilitating a fundamental shift in the thinking on maintenance cycles and planning.

These two systems on their own have the potential to shift the cost and operation of the existing fleet through a deeper understanding of the precursor indications of component failure and the expected time to failure following those indications. Incorporating these two data streams further enable the capabilities of these systems. Adding in systems like CAP IA to these models will provide a more complete data representation of a power plant than previously possible. Adding the data collection capabilities enabled by robotics and drones creates a unified system that is much closer to full station autonomous operation than is generally recognised. Many of the individual steps have been solved and only need to be brought together in a meaningful way. There are many challenges ahead in this final synthesis.

Nuclear infrastructure needs to be updated to take advantage of these technologies starting with fully enabling secure wireless communication. This enables data to be transferred across the network and allows in-field sensors to be connected to processing devices, driving automation. The capabilities enabled by lead utilities monitoring and diagnostic centres need to continue to be implemented across the industry. These models provide the initial processing of the existing data streams and deliver the indications of station conditions.

Robotic and drone applications, uses cases, and capabilities, also need to continue to develop. This allows for flexible and deployable resources that can access plant conditions in un-instrumented areas for more complete monitoring of the stations. These technologies provide the infrastructure and data streams that this autonomous operation future will rely on. This requires a convergence of many different skills and capabilities all working for this unified purpose. The nuclear workforce to support this autonomous future requires the traditional engineering backgrounds as well as new skills in data science, robotics, and telecommunications. None of these challenges are insurmountable with focused deployment of resources and efforts.

The autonomous future of nuclear power production is within the grasp of the next generation of nuclear operators with the technologies that are being developed today. As these technologies continue to be developed and integrated, the possibility comes ever closer to reality. It just takes solving each piece, one at a time, and then bringing them all together.

Idaho National Laboratory - Autonomy in the operation of advanced reactors

Vivek Agarwal and Christopher Ritter

Abstract

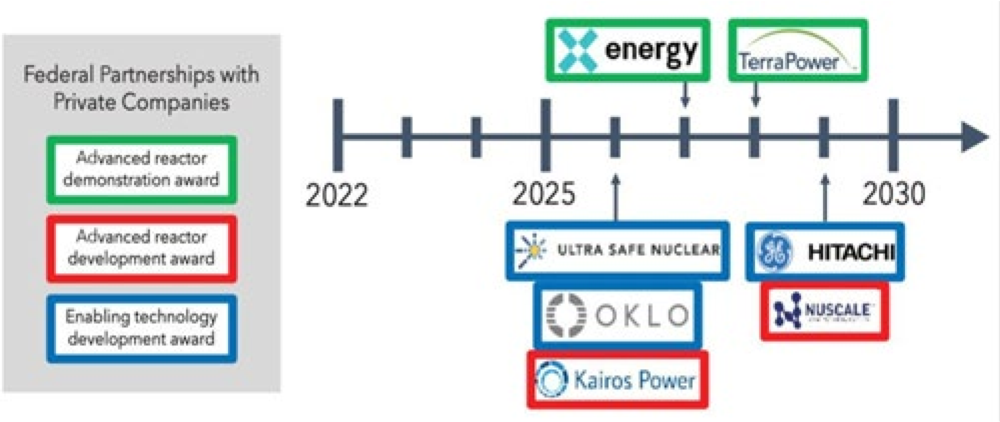
First-of-a-kind (FOAK) advanced reactors (ARs) including modular reactors and microreactors are important contributors to our clean energy future. These AR technologies are anticipated to penetrate non-traditional market (off-grid or microgrid) applications, expanding market size and potential as the United States (US) moves closer to sustainable nuclear power generation. The subsequent nth-of-a-kind (NOAK) reactors must be cost effective to penetrate and support expanded applications and markets at a price point that is acceptable and competitive. The concept of operations of NOAK ARs is expected to have more autonomy than FOAK ARs, enabled by autonomous control systems, advanced communication technologies, sensors and instrumentations, and artificial intelligence with minimal human involvement. The concept of autonomous operation is one disruptive innovation expected to inform cost-competitive energy from NOAK ARs and help shape the future of nuclear energy.

Introduction

Modular reactors, microreactors, and other advanced reactors (AR) technologies play a significant role in ensuring the US commitment to 100% clean energy by 2035 and net-zero carbon emissions by 2050. Several private, federal, and collaborative efforts in the US to accelerate nuclear energy capacity, including domestic advanced reactors demonstration projects (ARDPs) that were announced on 22 December 2020 (US DOE, 2020). This is in line with the Declaration to Triple Nuclear Energy (US DOE, 2023) during the 28th United Nations Climate Change Conference (COP28) in Dubai, United Arab Emirates. These FOAK reactors are diverse in their design and their concepts of operations differ while sharing a common goal to ensure that future reactor technologies boast numerous value propositions like low operating costs, high reliability, remote, autonomous, or semi-autonomous operations, and the flexibility to support expanded applications and markets. These FOAK ARDPs, including small modular reactors and microreactors, are expected to be completed in the late 2020s (see Figure 3.1) or early 2030s (in case of minor delays).

These FOAK AR demonstrations will facilitate lower costs and autonomous operation for subsequent NOAK reactors due to wide-scale deployment for use in traditional and non-traditional markets nationally and internationally and technology learning, based on operating experience. These markets include (but are not limited to) remote or off-grid applications, nuclear desalination, clean hydrogen production, process heat for industry, disaster relief (microreactors), distributed energy (microreactors), and isolated operations like remote mining, military, government facilities, and university campuses.

Figure 3.1 Expected timeline for selected ARDP supported by federal partnerships in the US



Source: Nuclear Innovation Alliance, 2022.

With significant potential to enable clean future energy, the current high price of AR technologies, compared to other energy sources across markets with differing operational paradigms is one of the key challenges facing the nuclear industry. One of the solutions to assure market acceptance at a price point that AR stakeholders are willing to pay is to achieve an operational paradigm shift of autonomous operation, enabled by autonomous control systems.

Autonomous operation of NOAK reactor technologies is a high-risk transition for AR stakeholders given several challenges, and it cannot be achieved in a single transition across all levels of automation (Alberti et al. 2023; US NRC, 2020). It is vital to advance both the technology readiness level (TRL) and the adoption readiness level (ARL) of autonomous controls, gradually. Technological advancements, regulatory requirements, market entry, and level of human interactions must be systematically introduced and managed to make progress towards achieving autonomous operation.

AR stakeholders and regulators are actively embracing the possibility of autonomous operations of NOAK AR technologies. The autonomous control systems and the technologies required to achieve effective autonomous operations need to be part of the design and development of ARs from the beginning, and some of the technical, regulatory, and market challenges are:

Technical challenges

There is a lack of comprehensive modelling and simulation (M&S) capabilities along with hardware-in-the-loop (HITL) testing of the concept of autonomous operation. This research of AR technologies in a representative experimental test bed presents a challenge to validating and implementing advanced control strategies. These M&S and HITL tests would help evaluate human-automation interactions, address cybersecurity concerns, identify hardware and software requirements, and quantify reliability of control strategies under different operating conditions to support expanded applications and markets. Also, autonomous control and operation are expected to use artificial intelligence (AI) and machine learning (ML) techniques. It is important to understand the reliability, resilience, scalability, and explainability aspects of the AI and ML that drive the optimal control actions.

Regulatory challenges

The Title 10 *Code of Federal Regulations* (10 CFR) 50.52 in combination with 10 CFR 50.47 provide the staffing requirements of nuclear power plants licensed under 10 CFR Part 55.

With advancements in digital technologies and passive safety design of ARs, the US Nuclear Regulatory Commission's (NRC) has a guidance on operator staffing levels. These operator staffing levels are different from the minimum specified in 10 CFR 50.54(m) are provided in NUREG-1791 (US NRC, 2005).

Autonomous operations of NOAK AR will require ground rules that inform any further revisions to the procedures and criteria in 10 CFR 50.54(m) and address the licensing challenges associated with autonomous control (US NRC, 2023). A similar outcome in the ongoing NRC effort on remote operations of ARs (US NRC, 2024) would be required.

Market (business) challenges

Reactor technologies have the potential to enter new markets. Examples include the X-energy and Dow chemical project (Dow Corporate, 2023) and use-cases of potential applications in Alaska (The University of Alaska, 2020). Entering these markets as an alternative to the current energy sources (diesel fuel in most cases) requires the operation and maintenance costs of nuclear energy (both heat and power) to be at an acceptable price point. The high-estimated operating cost of these ARs creates a challenge that can be addressed by developing technology-driven business models that include autonomous operations (Abou-Jaoude, Bolisetti, Foss 2022).

Idaho National Laboratory initiatives and innovations in autonomous operation

Idaho National Laboratory's (INL) Nuclear Science and Technology Directorate established the Fission Battery (FB) Initiative (Agarwal, Gehin, Ballout, 2021) in 2019 within the Nuclear Reactor Sustainment and Expanded Deployment Initiative to develop nuclear systems that provide battery-like functionality (i.e. plug-and-play). The vision of the FB Initiative is to define, focus, and co-ordinate disruptive innovations for fission battery attributes (economic, standardised, installed, unattended, and reliable) as shown in Figure 3.2. This would enable a simplified nuclear system and allow nuclear reactors to be used as a distributed source of energy for traditional and non-traditional market applications at a competitive price range compared to other energy sources.

Figure 3.2 Fission battery attributes

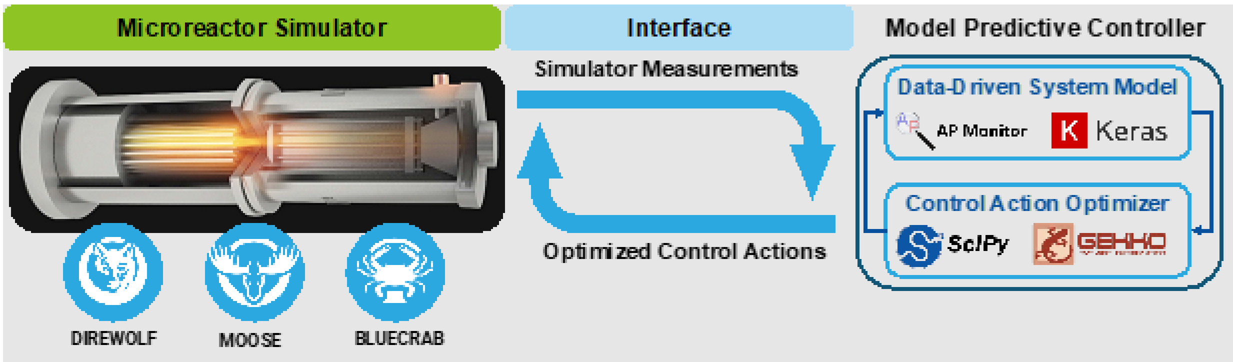
Source: Agarwal, V. et al, 2021.

INL is leading several paradigm-shifting innovative projects to achieve autonomous operation of NOAK ARs to address the unattended attribute of the FB initiative. Some of these research activities are mentioned below.

To address the need for autonomous operations (enabled by autonomous control systems) of these NOAK ARs, INL researchers developed an anticipatory controller technology called Autonomous Control fOr Reactor TechNologies (ACORN) (Lin, L. et al 2023c). ACORN is a first-of-its-kind simulation and AI-based anticipatory controller (see Figure 3.3) developed to achieve autonomous control of microreactors. ACORN leverages INL's Multiphysics Object-Oriented Simulation Environment (MOOSE) modelling and simulation (M&S) capabilities from DireWolf and BlueCRAB for capturing microreactor thermal and neutronic performance.

Microreactor simulators are integrated with anticipatory controllers that use AI techniques to optimise and provide optimal control actions. For details on the technology, see (Lin, L., Oncken, J., Agarwal, V. 2024). The technical capabilities of ACORN to proactively initiate optimal control actions under different operating conditions such as steady state and transient operation, flexible operation (i.e. load-following), and failure or degraded operation for different types of microreactors are summarised in (Lin, L. et al. 2023a, 2023b, 2024; Oncken, J. et al., 2023)

Figure 3.3 Anticipatory controller framework



Source: Abou-Jaoude, A. et al, 2022.

Although ACORN was developed for microreactor technologies, it can be expanded and adapted for other AR control systems. It also aligns with the functionality required by AR stakeholders. ACORN has the potential to achieve autonomous operation of microreactors and other reactor technologies by expanding its ability to respond to cyber events, accommodate new sensor information, and adapt to changing operating conditions (different applications result in different types of transients).

Ongoing digital twinning research at INL is to prove and verify full microreactor autonomy at scale. The Microreactor AGile Non-Nuclear Experimental Testbed (MAGNET) facility is a thermal testing facility available to test microreactor concepts in a non-fissile environment. A digital twin (DT) was demonstrated at MAGNET, streaming data from the facility in real-time to local computational capability with Deep Lynx. The MAGNET DT is composed of both a time series-based ML model and a MOOSE-based physics model. MOOSE includes a stochastic tools module to build reduced order models needed to use physics models in real-time. This MAGNET DT was able to perform an autonomous operation demonstration, predicting the facility state up to ten minutes in the future and controlling the facility in near real-time from these predictions (Wilsdon, K. et al. 2023). These DTs demonstrate significant milestones on the pathway to microreactor autonomy in the future.

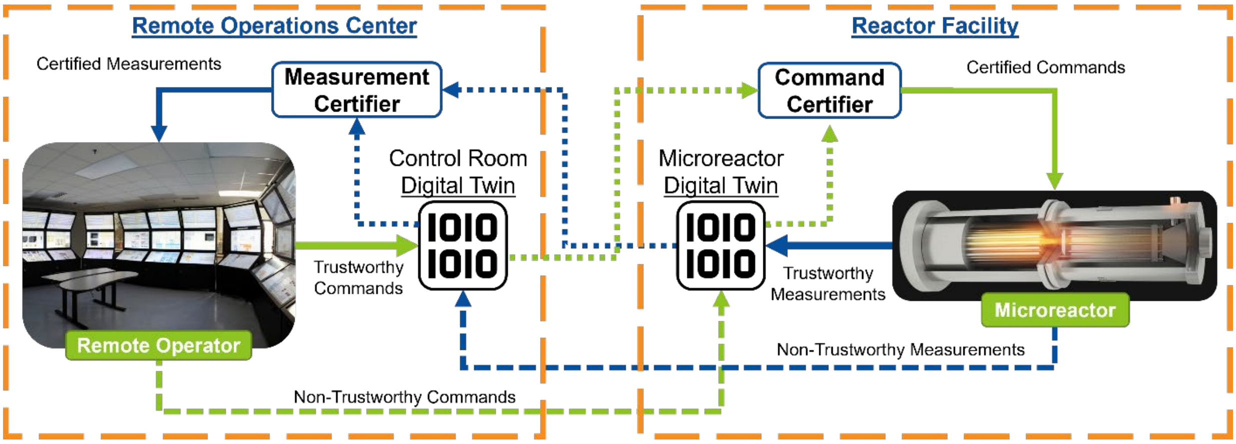
In parallel to autonomous concept of AR operations, interest has been expressed by AR stakeholders in remote operations and monitoring capability (US NRC, 2024). Ongoing research and development are addressing the challenges and opportunities associated with remote operations of ARs and have identified the need for a resilient remote operations framework (US NRC, 2023; Ulrich, T. et al, 2023; Stevens, K. et al., 2023a, 2024). The Digital Twin Certification System (DTCS) architecture is designed for the resilient remote operation of ARs. The DTCS introduces a novel concept of multiple independent DTs to provide independent verifications of state changes over time, producing a significant step towards depth of defence for remote operations.

This framework significantly raises the bar to mitigate unauthorised, unsafe, and unallowable commands as well as increase the trustworthiness of the system state information, such as sensor data or component status, sent from the microreactor to the remote operations centre (Stevens, K. et al., 2023b).

This DT-based remote operation and monitoring system and communication architecture will be deployed to INL's Human Systems Simulation Lab (HSSL) and Single Primary Heat Extraction and Removal Emulator (SPHERE) for in situ testing. This work provides a testbed for studying remote operations pertaining to microreactors, and the framework required to scale remote operations from the SPHERE platform to nuclear assets such as the Microreactor Applications Research Validation and

Evaluation Project (MARVEL).

Figure 3.4 Digital twin certification system architecture



Source: INL

Another example of achieving remote monitoring of a reactor using digital engineering and augmented reality was recently demonstrated (Stewart, R. et al., 2023). INL demonstrated the first DT of a nuclear reactor using near real-time streaming (seconds) of nuclear reactor data acquisition to Deep Lynx in the cloud and predict reactor anomalies.

The DT used two approaches for prediction: a surrogate model trained on reactor physics and a ML model trained on historical reactor operations. The demonstration used an AGN-201 reactor at Idaho State University (ISU), which peaks at only five watts of thermal output. INL and ISU performed over a dozen tests to verify the DT under various scenarios (Stewart, R. et al., 2023).

Comparison with other technologies

Most of the operating strategies currently available commercially or under development do not incorporate the anticipatory strategies ACORN does; rather they are based on reactive or feedback control systems (Eliasi, H., Menhaj, M., Davilu, H. 2012). Anticipatory control of ACORN is a paradigm shift approach compared to traditional proportional, integral, and differential controllers and even advanced automated control strategies in Williams, W. et al 2023; Farber, J. et al 2023; Dave, A. J. et al., 2023; Yu, J. et al., 2024; Ponciroli, R. et al., 2023). The efforts to develop reference governor-based controller (Dave, A. J. et al, 2023; Ponciroli, R. et al., 2023) results in sub-optimal solution (Rossiter, J. A., Kouvaritakis, B., 1998) compared to predictive control approach of ACORN.

The control technologies being developed under these programmes can be categorised as automated control strategies.

Framatome's Operator Assistance Predictive System (OAPS) (Framatome 2021) is one commercially available operator system which uses certain level of prediction to inform control strategies for the flexible operation and load-following of light-water reactors. Control systems for ARs need to adapt to wider ranges of load-following scenarios with faster and more drastic changes in reactor power compared to light-water reactors that are traditional baseload and have less dynamics even under flexible plant operation mode (Lindsley, E. et al., 2020).

In addition, the ACORN built-in diagnostic module allows for distinction of anomalies that are due to sensor malfunction, degradation, or any cyber threat for human-in-the-loop consideration compared to OAPS.

Conclusions and path forward

This paper presents INL's leadership in shaping the concepts of operations of AR by taking advantage of advancements in M&S, AI, ML, and DT technologies. The innovative ongoing research is at early stages of TRL and ARL and significant research and development efforts are required to enable autonomous and remote operations of NOAK ARs.

As part of path forward, INL is expanding its capabilities by developing resources like National Reactor Innovation Centre Demonstration and Operation of Microreactor Experiments Test bed, enabling TRL and ARL advancements and paving the path for commercialisation success of these innovative research projects.

Acknowledgements

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Backend of the fuel cycle

Advanced Research Projects Agency - Energy: Nuclear fuel cycle backend

While the international sentiment clearly expresses an interest in deploying nuclear energy to address climate change concerns, nuclear waste disposal can be a challenge to broader community acceptance. Disruptive technologies in nuclear waste disposal and recycling could play a critical role in enabling the COP28 declaration of tripling nuclear energy by 2050. This perspective will speak to the areas of disruptive innovation for the back end of the nuclear fuel cycle with special attention to the challenges and opportunities that present with the deployment of advanced fuel cycles.

Most previous nuclear fuel cycles have centred on light water reactors (LWRs). Future reactor deployment will involve LWRs and a variety of advanced reactors (ARs). While there are many types of advanced reactors, the most considered reactor types include:

- high-temperature gas reactors (HTGRs, TRISO fuelled);
- molten salt reactors (MSRs, either TRISO fuelled, or fuel dissolved in salt);
- sodium fast reactors (SFRs, metal fuelled).

While these different types of reactors can operate on the 3-5wt% U-235 enriched fuel classically used for large LWR reactors, many future reactors will be small modular reactors (SMRs) or microreactors and the power production economics are significantly improved by using high assay, low-enriched uranium (HALEU). The U-235 enrichment for HALEU is between 5 and 19.75wt% U-235. The higher U-235 enrichment allows for a higher capacity factor, due to longer refuelling cycles, and a smaller reactor geometry with relatively higher output compared to an LWR, due to the higher U-235 content.

The diversity of reactor and fuel types have different considerations and opportunities regarding recycling, transmutation, waste forms, waste disposal, and digital technologies. Regarding recycling, certain technologies have been developed that can improve the cost effectiveness of recycling while removing the production of pure plutonium streams.

Recycling could also leverage the high value that may remain in HALEU fuel following its use in a reactor. Regarding transmutation, novel light sources may provide improved power densities and higher capacity factors that would enable a pathway to cost-effective transmutation technologies. Regarding waste forms, no waste form has been identified for metallic or molten salt fuels and appropriate fuel conditioning steps might be needed to prepare the fuel for disposal. However, modern materials science could provide a means towards rapidly identifying appropriate waste forms. Regarding waste disposal, the advent of highly efficient bore hole technologies could serve as a cost-effective pathway to deep geological disposal. Finally, artificial intelligence and digital technologies could serve as a platform to allow for predictive maintenance, improved facility design and construction, and superior material tracking.

This perspective will comment on the disruptive technical opportunities for

- recycling
- transmutation
- waste forms
- waste disposal
- digital technologies.

Nuclear fuel recycling

Nuclear fuel recycling has the potential to significantly reduce overall volumes of high-level waste by >90% while improving the utilisation factor of nuclear fuel from 10-100x depending on the type of reactor being used. While used in various nations, including France, Russia, and the United Kingdom, nuclear fuel recycling has classically struggled with broader deployment due to concerns regarding cost and non-proliferation.

Some argue that the cost benefits of nuclear fuel recycling should consider the decreased costs associated with the development of additional repositories due to the increase in fuel utilisation. Frequently the cost comparison is made based on fuel cost of recycled fuel versus fresh uranium fuel.

Fuel recycled using conventional recycling technologies, like the Plutonium Uranium Redox EXtraction (PUREX) process, cost about 6-8x the cost of fresh fuel. The significant cost can be attributed to the capital and operational costs associated with nuclear fuel recycling.

In the past, recycling facilities have necessitated large capital infrastructure, especially concrete and steel, that increases facility cost. The size of the facility is partially driven by the volumes of secondary waste generated. In comparison, pyro-processing (i.e. molten salt electrochemistry) produces limited secondary waste. By limiting secondary waste, the facility size could be decreased. Additionally, automation and sensors for monitoring, materials accountancy, and operation could provide significant improvements in material accountancy and decrease costs.

Regarding non-proliferation, the production of pure plutonium streams is not desirable as access to such material is considered one of the most critical steps on the pathway to acquisition of a nuclear weapon. Modern separations chemistry and sensors can enable the development and use separation technologies that do not generate pure plutonium streams. Additionally, classically improved materials accountancy has been thought to only come with improved cost. Sensors and monitoring technologies can be developed such that they are dual use, enabling both process monitoring for improved performance and facility uptime, while tracking the presence of special nuclear material throughout the facility. Such technological development could have a significant impact on the uptake of non-proliferation technologies since an economic, not just a political incentive, would be associated with their use.

The following disruptive technologies are offered as key examples of enabling future nuclear fuel recycling:

1) **digital twins**: enable real time performance and materials accounting monitoring
2) **digital ledger technologies**: enable encrypted transmission of materials accountancy data
3) **atom efficient separations systems**: would limit the generation of secondary radioactive waste
4) **mixed actinide separations**: would prevent the production of pure plutonium streams
5) **sensors**: elemental, isotopic, and facility sensors that could facilitate development of digital twins.

Advanced Reactor Fuel Waste Forms

The management and disposal of used nuclear fuel (UNF) and high-level waste (HLW) from nuclear reactors pose significant challenges. These challenges are not only pertinent to reactors employing once-through fuel cycles but also to those utilising recycling technologies. Addressing these issues necessitates a multidisciplinary approach that draws from advancements in materials science, nuclear engineering, chemistry, and computational methods.

When developing new waste forms, several key properties are essential. The development of materials capable of incorporating a high volume of waste per unit mass or volume is crucial, as this can significantly reduce the footprint of final disposal sites. The minimisation of the rate at which these waste forms dissolve in groundwater is paramount for enhancing long-term storage safety. Additionally, these materials must possess a high tolerance to the heat generated by the decay of radioactive waste and be resistant to radiation damage to ensure structural integrity over millennia.

Economic viability is also a critical factor; materials and processes that are cost-effective and consume minimal energy are essential for sustainable operations. Ease of packaging is another important consideration, as streamlined packaging processes can reduce handling risks and costs, minimising exposure to workers. Finally, the compatibility of these materials with their disposal environments, whether in mined geological repositories or deep boreholes, is crucial for their stability and effectiveness.

In the realm of research and development, disruptive strategies are being employed to overcome these challenges. Modern computational tools, such as quantum chemistry, allow for the prediction of the behaviour and stability of potential waste form materials at the atomic level, significantly reducing the trial-and-error cycle in materials discovery.

Artificial intelligence (AI) and machine learning (ML) models are being used to accelerate the identification of novel materials by analysing existing datasets to predict properties and performance outcomes, thereby optimising waste form compositions for specific criteria.

Rapid synthesis and advanced manufacturing techniques, including high-throughput experimental techniques and additive manufacturing (such as 3D printing), are being implemented to quickly evaluate a wide range of materials compositions and structures and to create complex waste form geometries that optimise packing density and thermal management. Moreover, the scaling to large-scale production involves developing scalable manufacturing processes that maintain the integrity and performance of waste forms at industrial volumes and incorporating life cycle analysis from the early stages of material and process development to ensure sustainable large-scale deployment.

Waste disposal: deep boreholes

Advantages of deep boreholes over mined deep geological repositories

The disposal of waste in deep boreholes presents several potential advantages over mined deep geological repositories. Deep boreholes, typically drilled to depths of several kilometres, access geological formations that have been stable for millions of years. These offer a secure environment for the long-term isolation of nuclear waste from the biosphere. The surface footprint of a deep borehole facility is significantly smaller than that of a mined repository, which requires extensive surface infrastructure and underground tunnels. This smaller footprint and the ability to target specific deep geological formations may offer more flexibility in siting boreholes, potentially reducing political and community opposition. While the initial investment in drilling technology may be high, the overall cost of borehole disposal, including operation and closure, could be lower than that of constructing and maintaining a mined repository. Additionally, the concept of deep borehole disposal is simpler and could potentially be implemented more quickly than the construction of a mined repository.

Disruptive R&D for deep boreholes deployment

To deploy deep boreholes effectively, disruptive research and development in advanced drilling techniques are necessary to efficiently create deep boreholes of the required diameter and depth in various geological conditions. In the United States, there is a requirement for the ability to retrieve HLW before repository closure, necessitating the development and proof of placement and retrieval technologies. Research into materials and methods to ensure the long-term integrity of seals that isolate the nuclear waste within the boreholes is critical to prevent any leakage or migration of radioactive materials.

Innovations in remote monitoring technologies are also essential to ensure the safety and security of the waste disposed of in deep boreholes, at least until closure. Furthermore, designing robust waste canisters that can withstand the high pressures and temperatures at depth, as well as ensure the long-term containment and retrieval of radioactive materials before closure, is a pivotal aspect of this approach.

Transmutation

Nuclear transmutation is the conversion of one chemical element or isotope into another through bombardment with particles (e.g. photons, neutrons, protons, deuterons, other ions) or through radioactive decay. Nuclear transmutation has the capability to reduce the volume, radiotoxicity, and storage time of spent nuclear fuel. Generation of valuable isotopes, semiconductor production, and radioisotopes are also possible benefits.

There are multiple pathways for transmutation of spent nuclear fuel.

Accelerator-driven systems (ADS) use a high-powered proton beam that can generate neutrons through spallation. Spallation occurs when the proton beam causes excitation of the atoms in the spallation target (e.g. mercury, lead, lead-bismuth eutectic), when the atoms undergo relaxation, they expel neutrons. These neutrons can be used to transmute isotopes or generate electricity through the initiation of fission reactions. ADS can be run in both subcritical and critical modes, which offer different advantages. Subcritical systems are inherently safe as there is no sustained nuclear reaction and turning the proton beam off results in no power being produced from the reactor. Additionally, the fuel requirements for subcritical systems are less stringent than critical systems. (Aït Abderrahim, H. et al., 2010) Critical systems have stricter fuel requirements but provide increased power generation.

Accelerator driven transmutation of minor actinides has been demonstrated at the Kyoto laboratory in Japan. In Belgium, the MYRRHA (**M**ulti-purpose h**Y**brid **R**esearch **R**eactor for **H**igh-tech **A**pplications) project is under construction. This multi-purpose facility is a large-scale ADS that consists of a subcritical nuclear reactor driven by a high-power linear accelerator. The facility will have three test stations: fusion materials, radioisotope production, and transmutation. Currently, financing is through the Belgian government, but provision has been made for additional European funding. Advanced reactor designs have also shown to be effective at transmuting minor actinides (MAs) and long-lived fission products (LLFPs) from spent nuclear fuel.

Lead-cooled fast reactors are capable of transmuting both LLFPs and MAs simultaneously through mixing the LLFPs with a neutron moderator which softens the neutron energy spectrum in the vicinity of the LLFPs. This allows transmutation without affecting the neutron flux in the rest of the reactor. (Sun, X. Y. et al., 2022)

Current generation reactors have also been demonstrated to be able to transmute MAs and LLFPs, although the rates of transmutation in these systems are low. As these types of reactors currently make up nearly all the nuclear power sources in the United States, it is desirable to optimise current generation reactor technology to allow for effective transmutation of nuclear waste.

In addition to the neutron producing technologies listed above, both high-energy protons (generated through a high-energy accelerator) and photons (from synchrotrons or Laser-Compton Scattering sources) are also capable of transmutation of MAs and LLFPs.

Typically, these reaction rates are low due to their low cross sections for absorption of these particles. Targets can be designed to optimise the transmutation rates and the system can be designed to recycle the particles to minimise energy losses.

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Idaho National Laboratory - Closed fuel cycle

Monica Regalbuto

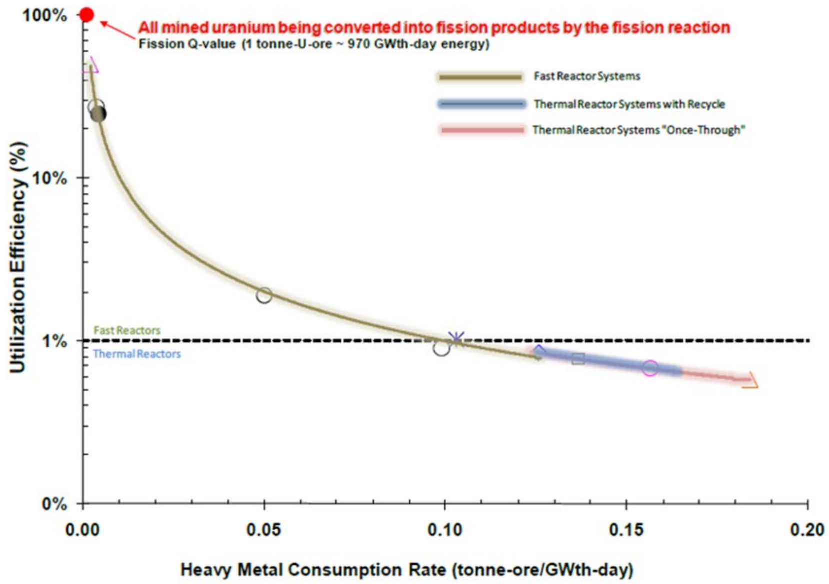
Nuclear power plants generate about a quarter of the world's low-carbon electricity supply. Current nuclear reactors are initially fuelled by uranium (U) enriched in the uranium-235 isotope, which is fissile as its atoms split apart easily, generating energy as heat that is then used to produce electricity. After its three to six years of useful life, the fuel is removed from the reactor and placed in a storage pool of circulating cooled water to absorb heat and block the radioactivity emitted by the fission products. Typically, the used fuel is then moved to dry storage casks in which they are stored for future reuse or disposal. Several countries have extensively investigated the recovery and reuse of materials from used nuclear fuels. The process of making reactor fuel and managing it after its use in a reactor is known as the fuel cycle.

Fuel cycles are typically referred to as opened or once-through, partially closed or limited recycling, and closed or continuous recycling. In the once-through fuel cycle the uranium fuel is loaded into the reactor and utilised once using only 5-6% of the energy value of the uranium contained in the fuel. Reactors that operate on an open-cycle mode consume (fission) approximately 0.7% of the original uranium mined; the other approximately 99% of the uranium is ultimately destined for disposal as waste.

The once-through fuel cycle is the least efficient way to utilise uranium resources and to minimise the fuel cycle waste produced. Today most of the commercial reactors deployed globally are light-water reactors (LWR) and operate using an open cycle. Removing and reusing the fissile materials improves uranium resource utilisation. For example, France, Russia, and Japan operate a limited recycling fuel cycle by recovering uranium and plutonium from the used LWR fuel and recycling them into fresh fuel. These countries realise about 0.85 % of the uranium energy from the original mined uranium. In this case, the amount of natural uranium needed to make LWR fuel can be reduced by up to 30% thereby decreasing all corresponding mining and enrichment needs.

Fuel cycles that involve fast reactors and continuous recycling increase uranium utilisation in a closed-loop that consumes 99% less uranium and produces 95% less high-level waste (HLW) than the once-through cycle. Using fast reactors could extend the uranium resource to 80% or more and eventually eliminates the need to mine and enrich uranium (Figure 3.5) and disposal of Pu. (Bayes, S.E. et al., 2010) This is achieved by breeding new fissile material from over 99% of uranium that is fertile. Numerous different fuel recycling scenarios have been analysed (Dixon, B.et al., 2020) Recycle of reprocessed U and Pu in thermal reactors will be limited to <1 % uranium utilisation efficiency. The real benefit of increasing uranium resource utilisation is, therefore, possible when there is a fleet of fast spectrum reactors that can utilise the reprocessed uranium and plutonium as fuel.

Figure 3.5 Uranium utilisation efficiency.



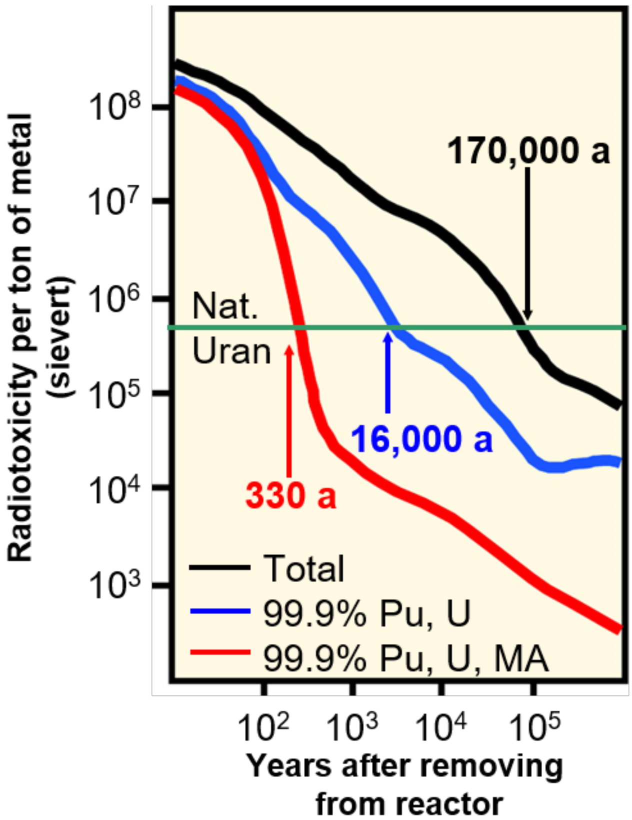
Source: INL

Recycling also helps management of nuclear waste by significantly reducing the volume of material to be disposed of as high-level waste to about one-fifth. In addition, the level of radioactivity in the waste from reprocessing is much smaller and after about 100 years falls much more rapidly than in used fuel itself.

As shown in Figure 3.6, the radiotoxicity of UNF takes ~170 000 years to decay to the level of natural uranium. By removing 99.9% of the U and Pu from the fuel, the decay time to reach the radiotoxicity of natural uranium is reduced to 16 000 years. If U, Pu and minor actinides (Np, Am, Cm) are also separated, the time is reduced to ~330 years.

In other words, reprocessing, including separation of minor actinides will reduce long-term radiotoxicity. Ultimately repository performance depends on repository conditions and is also driven by long-lived isotopes such as I-129, Cl-36, Se-79, and Tc-99 (Poinssot, C. et. al, 2012).

Figure 3.6 Radiotoxicity of UNF with and without recycling



Source: INL

Another waste management benefit is the durability of the high-level waste sent to a repository from reprocessing UNF. Reactor fuel, for example uranium oxide surrounded by zircalloy cladding, is designed for nuclear reactor performance, not long-term UNF stability. The UNF dissolves in proper geologic redox conditions and releases radionuclides. In comparison, the international standard for HLW is glass, which has been demonstrated to be a durable and stable waste form for tens of thousands of years. Other advanced waste forms, such as ceramics, based on natural analogues, may be stable for geologic time frames.

In addition, UNF recycling is a potential source of scarce, valuable strategic materials, Figure 3.7. Beyond fissile materials used to generate further energy, SNF contains rare earth elements (REE - Y, La, Ce, Pr, Nd, Pm, Sm, Eu, Gd, and Tb), platinum group metals (PGM - Ru, Rh, Pd, and Ag), noble gases (NG- He, Kr, and Xe), and a range of isotopes useful for medical and energy generation purposes, Figure 3.8. Given the environmental and socio-economic benefits of recovery of non-actinide resources in UNF recycling, there is a new interest in harvesting these materials from spent fuel.

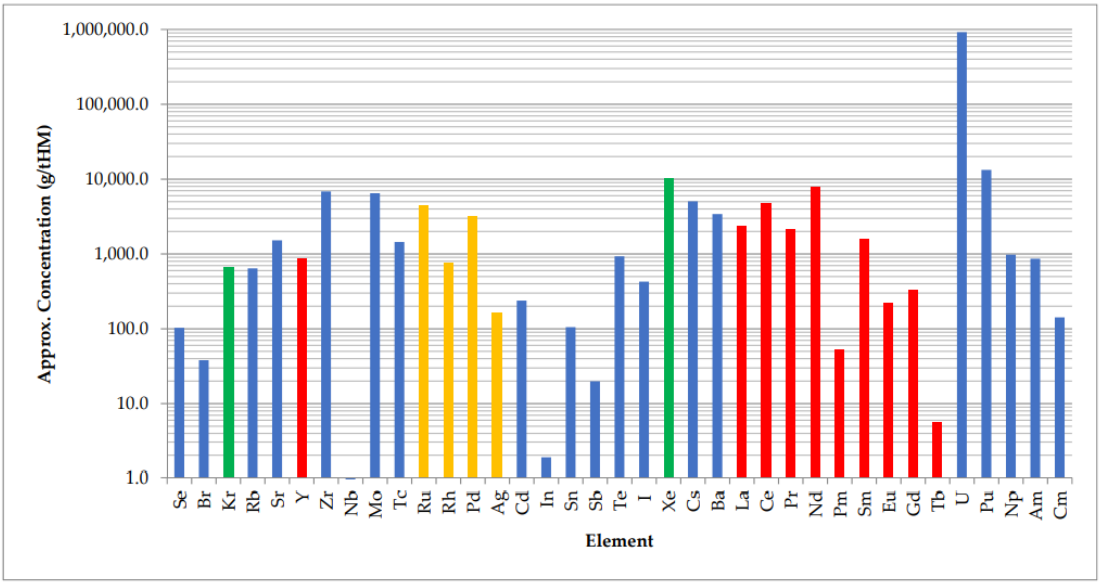
Figure 3.7 Periodic table of endangered elements

H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	Ln *	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	An *	Rf	Db	Sg	Bh	Hs	Mt	Ds	Rg	Cn	Nh	Fl	Mc	Lv	Ts	Og
		Ln *	La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
		An *	Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr

Green indicates plentiful supply; yellow indicates limited availability, future risk to supply; orange indicates rising threat from increased use; red indicates serious threat in the next 100 years; and white indicates synthetic element. Ln and An* refer to the lanthanide and actinide series presented at the bottom of the table, respectively.*

Source: Holdsworth, A. F. et al, 2023

Figure 3.8 Approximate elemental concentrations in HBU PWR SNF (5% initial 235U, 65 GWd/tHM B/U, 5-year post-reactor cooling)



PGMs highlighted in orange, NGs in green (not He), and REEs in red.

Source: Holdsworth, A. F. et al, 2023

The benefits of a closed fuel cycle are tangible and well known. So why hasn't it been implemented? Time to transition from current commercial LWRs to fast reactors and proliferation/environmental concerns related to moving towards a plutonium-based economy and associated fuel cycle. Expansion of nuclear capacity to meet net-zero goals requires deployment of advanced reactors later in the century coupled with advanced breed-and-burn fuels or fuel recycling to ensure fuel supply sustainability.

A likely deployment path would be two-pronged. In the near term, the needs will most likely be met with light-water reactor (LWR) technologies because they are known technologies with established supply chains and decades of construction and operational experience.

In the near-to-medium term, advanced reactors will have a role meeting clean energy and decarbonisation needs for non-grid applications. For example, industries that need clean, highly reliable power like data centres have strong value streams for capabilities that advanced reactors provide. Also, industries that are serious about decarbonising will find that using heat from nuclear reactors for their industrial processes will accelerate corporate efforts at decarbonising.

Flexible advanced reactor systems will also have a role in grid stabilisation as a complement to intermittent renewable energy sources. The first prong of the deployment path, LWRs for near-term grid applications, will create a buffer period for the second prong, demand for advanced reactors in grid stabilisation and non-grid applications, to pull the industry through the hurdles of getting the HALEU supply chain set up domestically and moving first-of-a-kind costs down the cost curve to nth-of-a-kind, market competitive costs.

Then, in the longer term, grid applications will likely evolve towards a larger share of advanced reactors due to higher thermal efficiency and higher fuel utilisation providing more energy with less waste. Significant expansion of nuclear capacity as called for by many net-zero studies requires additional advanced reactors later in the century coupled with advanced breed-and-burn fuels or fuel recycling to ensure fuel supply sustainability. Traditionally, it was envisioned that transition to a fast reactor economy will require harvesting plutonium from LWR used fuel to initially fuel the fast reactors, which in term will produce sufficient plutonium transitioning to a continuous recycle fuel cycle.

The continuous recycling fuel cycle includes breeding of fissile material in fast reactors instead of obtaining it from mining uranium. With the deployment of a HALEU supply chain to support the deployment of advanced reactors as described above, allows for less constrained transition to fast reactors and may be more economical (Dixon, B. et al., 2020)

Furthermore, spent nuclear fuel from fast reactors started on HALEU has much less transuranic radioactive waste (TRU) than it would if started on recovered LWR Pu. The benefits of start-up on HALEU include fewer new technologies required to initiate transition, major investments in fuel separation facilities can be strategically deployed, and lower fuel fabrication costs during initial transition. Transitioning using the emerging HALEU fuel cycle results in a more robust system that is better able to handle recycling disruptions without impacting reactor fuel availability. The new HALEU fuel cycle significantly increases the viability of deploying a timely and economically closed fuel cycle using fast reactors.

Other concerns related to deployment of closed fuel cycles relate to the use of plutonium-based fuels. A plutonium-based fuel cycle is associated by many with weapons production and environmental legacy liabilities. Deploying with confidence a civilian plutonium economy requires reducing proliferation risk while minimising environmental impact.

Recycling requires three critical steps: recovery of fissile materials (separations), reuse of fissile materials as fuels (fuel fabrication) and repurpose the fuel in a reactor licensed to operate with recycle fuels (transmutation reactor).

To be successful all three steps need to be co-ordinated and executed. Deployment of new advanced reactors provides a unique opportunity to address in an integrated fashion, power production, waste, and safeguards. The deployment of new advanced reactors has increased the knowledge and ability to account for special nuclear materials. This is done by the development of on-line instrumentation for continue systems such as pebble bed reactors and molten salt reactors. New tools are being demonstrated for early proliferation detection using AI and ML, automated multi-sensor data analytics, and digital twins.

In addition, new recycling technologies that do not separate pure plutonium using advanced aqueous and electrochemical processing couple with manufacture of recycle fuel significantly reduces proliferation risk as materials are used as soon as they are recovered. As new advanced reactors are being deployed, a new approach to address proliferation risk has emerged. This consists of managing inventories, new tracking tools and faster ways to detect diversion.

During weapons production, radioactive waste was not prioritised or properly managed, creating a costly environmental legacy. This is not the case for the nuclear industry which manages all radioactive waste in a safe and timely matter. Nuclear power is the only large-scale energy-producing technology that takes full responsibility for all its waste and fully costs this into the product. This practice is independent of an open or closed cycle. As new advanced reactors are deployed, more economical methods for waste management and final disposal continue to become available.

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Cybersecurity

Électricité de France: Utility experience - Innovation as DNA of civil nuclear cybersecurity

Introduction and selected scope

Cybersecurity is a key issue for the energy sector and its actors. One of its critical aspects is securing operational technology (OT) systems, which is the focus of this paper. While the associated threats and risks are growing (French National Cyber Security Agency (ANSSI), 2024), such environments bring specifics constraints and involves adapted approaches, both in terms of organisational and technological security controls.

This short note won't detail these well-documented aspects (Pietre-Cambacédès, L., Fourastier, Y., 2015), however, it is worth stressing that nuclear OT presents extra challenges such as long digital systems and facility life, stringent safety requirements, size and complexity of the facilities, and the associated cyber-physical phenomena, duration of projects from design to implementation.

In this context, the nuclear industry has always needed to stay aware and open to other industry innovations, and sometimes, to invent its own adapted solutions. This is true at the cybersecurity solutions and architecture level, but also at the principles and international guidance level. We'll develop some aspects of these subjects in the following paragraphs.

This culture of innovation has been a key success factor to maintain over time an appropriate level of cybersecurity in our domain, despite a fast-changing threat landscape.

Disruptive technologies

Innovation for cybersecurity has historically been focused on technologies. Already in the early 1990s, long before IPSec VPN democratisation, patented secured tunnel devices to remotely interact with selected industrial systems were designed and used. These had strict access policy and strong-cryptographic protection.

One-way data diodes have also been integrated for decades in industrial nuclear architectures (firstly with copper-based Ethernet technologies, then with optical-based devices), placing the nuclear industry among the pioneer adopters, within the defence domain.

Situations where strict one-way communication policy is inappropriate have also led to develop, at the end of the 2000s, an innovative network decoupling approach. This was based upon hardware-based controls for network or USB-based data-exchange. It has been patented and has been commercialised since the 2010s.

If innovation has often been driven by design considerations, nuclear operations have also led the way. This is well-illustrated by the development and deployment of an innovative password management solution. The issue is particularly challenging when network-based centralised management is not possible and when the number of systems is very high. One utility's nuclear fleet, with the help of R&D, has addressed it by the development of portable individual devices. This approach is continually enhanced. Evolutions lead by other industries in authentication (FIDO2…) are closely monitored.

The issue of maintenance and configuration laptops is another good example. An innovative approach has been developed, based on virtualisation. The issue is tackled by offering strengthened cybersecurity while integrating the need for diversity of maintenance/testing tools and associated suppliers.

Indeed, for several major technological issues identified in OT cybersecurity (perimeter protection, USB, maintenance laptop and others), one utility's nuclear entities have been ahead of market proposals, developing and deploying innovative solutions to protect its facilities. The cybersecurity market has sometimes bridged the gap, leading to a move towards COTS solutions; in other cases, whereas in other cases, the nuclear utility has contributed to creating the market.

Innovation also needed for architectures

Cybersecurity is not only a matter of cybersecurity components and technologies, but also a matter of OT architecture. If the use of cybersecurity levels and zones to structure architectures is now a well-established pillar (IAEA, 2011; IEC, 2019), the way on how systems and cybersecurity zones are segregated, monitored, and more globally protected, keeps on evolving. A particularly structuring challenge is how to implement these concepts with a high level of cybersecurity in the long run, whereas it is impossible to foresee attackers' capabilities evolutions.

A utility is currently working on innovative architectural concepts for its SMR, integrating by design detection and resilience capabilities made to last and ensure those capacity on long durations.

More generally, mastering architectural aspects is a cornerstone of cybersecurity when it gets increasingly harder to establish complete trust for all components, for different reasons, including complexity, supply chain issues, cybersecurity maturity.

In some very specific cases, being innovative sometimes means being able to have cyber-immune targeted key functions, with non-digital implementations.

Sharing at the national and international level

Nuclear cybersecurity is a team sport: For more than 20 years, the nuclear industry has maintained leading participation in national and international forums and institutions dealing with nuclear I&C cybersecurity. Work on international consensus has started in the 2000s, resulting in key international texts like the IAEA NSS17 (IAEA, 2011) and IEC 62645 (IEC, 2019). The effort is maintained to consolidate shared principles and structures (cybersecurity DiD, and graded approach, for example). This is done between operators but also states, regulators and industry, offering an adequate and strong baseline, while leaving room for cybersecurity innovations.

Always looking ahead

The nuclear industry has continually identified significant evolutions or disruption in digital technologies. It prepares adoption in a balanced manner, to benefit from the potential without compromising with cybersecurity. In some cases, those evolutions can even bring new tools for cybersecurity.

Software virtualisation is a good example. Bringing flexibility and solutions to obsolescence, it is finding its way into facilities; if it brings some new class of threats to consider, it also offers new cybersecurity solutions (e.g. see the aforementioned approach for maintenance and configuration laptops). The development of the Internet of Things (IoT) is another evolution to consider as it raises attack surface but may also create opportunities for distributed intrusion detection approach for instance.

When it comes to artificial intelligence, we are actively exploring both its usage to enhance cybersecurity, for instance, in detection by exploiting centralised logs, and the associated new threats.

Examples include automated generation of attack sequences; directed manipulation of programmable logical controllers. Advances in quantum computers and post-quantum cryptography are also closely followed.

Another field of active research is hybrid threats combining physical and cyber dimensions. Such scenarios involve new approaches to better cover potential scenarios, assess impacts, but also determine the most appropriate security measures. A nuclear utility has recently been actively involved in a major European research project (Praetorian, n.d.) in the area.

A broader perspective

This short paper has more particularly developed OT cybersecurity related considerations. Of course, innovation and cybersecurity for nuclear facilities is to be tackled more widely, including IT aspects, protection of information (including design know-how), and cybersecurity as a large-scale co-operation enabler, needed to succeed in increasingly complex engineering and construction projects.

On this last area, innovations driven by blockchains usages, and best practices from other complex engineering industries (aeronautics) are closely looked upon. Organisational and human dimensions such as training, human factors, and crisis management are also key dimensions for an effective cybersecurity programme. Innovations and disruptive approaches are also needed in the area. For all cybersecurity aspects, the nuclear industry is constantly looking ahead, with a strong innovation and practice-sharing culture.

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Idaho National Laboratory - Cybersecurity and disruptive technology, impacts on nuclear power

Katya Le Blanc

Introduction

Disruptive technologies have the potential to change the way nuclear systems are designed, regulated, operated, and how they are used. Many of these technologies bring networked computer systems into contexts they weren't historically in and often they connect or integrate systems that were previously isolated. Consequently, they bring with them implications for cybersecurity.

Existing approaches to securing and regulating nuclear facilities are based on an operating paradigm that assumes a small digital footprint in the control system with strong logical separation between safety systems and other parts of the control system (i.e. no communication or data transfer between systems). While many reactor developers are not considering disruptive technologies in their first deployment of new concepts, they see the use of these technologies as essential to enable more economic and efficient operations for their nth-of-a-kind deployments.

Though there are wide range of emerging technologies that could impact nuclear energy, the ones considered in this section as they relate cyber security are technologies that enable automation, technologies that can change how we manufacture and build plants, and new operating or business models for use of nuclear.

Safety and simplicity

The degree to which cyber security is a concern for implementation of disruptive technology in next generation nuclear facilities depends on the system design. Many proposed designs will be much simpler and rely more on passive or inherent safety than previous designs. Simple and passively safe designs rely on fewer direct actions to operate the system. As a result, there may be fewer sensors, controllers, and communications pathways than would be needed for a large, complex facility. This may also result in fewer devices and pathways to analyse in terms of vulnerabilities and attack pathways. Therefore, passive safety and simplicity may enable the use of disruptive technology. Conversely, for systems that lack passive safety and simplicity, cyber security may be a barrier to implementing disruptive technology.

Automation

Developers of new reactor technologies are assuming largely digital instrumentation and control with very few (if any) analogue backups. Many of the disruptive technologies also rely on digital control systems to enable the data collection, monitoring, and control capabilities.

Because digital control systems rely on components with embedded general-purpose computers and networked computers and software, it opens the possibility for them to be targeted by cyber-attack. Disruptive technologies that enable automation including digital twins and data-driven automation techniques, like artificial intelligence (AI) and machine learning (ML), may add additional considerations to the cyber security landscape.

Though there are many definitions of digital twins, for the purpose of this summary a digital twin is a virtual replica of a system that mirrors the physical assets and predicts future behaviour. Thus, a digital twin includes a digital model (or simulation) of the system and the ability to update the model with operating data from the system it is mirroring.

Digital twins are essentially specialised software, therefore the cyber security considerations from them are like any software system. The cybersecurity risk will stem from what the systems are used for and what they are connected to. Digital twins that are isolated from the control system and used as additional information for human operators will have different implications than a digital twin that is integrated into the control system and used for predictive control.

In most cases, standard cyber security control and practices apply as they would to any control system software. The main barrier to implementation is likely to be regulatory acceptance.

One special security implication of digital twin is that the simulation model needs to be carefully protected to ensure that it remains confidential so adversaries can't use it to gain knowledge of the system.

Like digital twins, AI and ML-driven automation can be thought of as specialised software and largely treated as any software that is implemented in a nuclear facility. However, there are a couple of exceptions. Despite research exploring explainable and trustworthy AI, data-driven methods are still highly opaque to humans. Effective cybersecurity depends on a thorough understanding of the expected behaviour of systems and the constraints and limitations of reliable operation. To date, AI systems can't provide that. Additionally, AI systems can be comprised in unique ways that are hard to predict and often very hard to detect. Like digital twins, acceptance (both by industry and regulators) is the largest barrier to adoption.

While the previous discussion was related to securing AI-driven automation, AI can also be used as a security tool itself. Many intrusion detection systems already incorporate AI, and there is research and development investing in making this system more sophisticated. One potential barrier to employing these technologies is that many aspects of security depend largely on the specific context of the system and great care should be taken to ensure the systems provide actionable security information without too many false positives.

New operational concepts

The final considerations are how new business models and new uses of nuclear power impact the cybersecurity posture of the systems. Concepts like integrated energy, load following, and fleet-based operation will establish new connections between nuclear power systems and external entities. Historically nuclear facilities have operated as isolated islands, with no control signals coming from external sources. Future concepts may integrate nuclear plants in ways that require additional consideration of how to ensure integrity of control signals coming to the facility.

Korea Atomic Energy Research Institute – History and concepts of Cybersecurity in the nuclear industry

This section defines and provides an overview of the history and concepts associated with cybersecurity, as well as highlighting some of the benefits and opportunities, as well as challenges.

History of cybersecurity

The history of cybersecurity in the nuclear sector began with the digitisation of nuclear facility controls, initially focused on isolation and redundancy for safety. As digital integration grew, so did exposure to cyber threats, shifting the perspective to view cybersecurity as crucial to nuclear safety and security.

Significant milestones

Historical milestones include:

- the terrorist attacks of 11 September 2001, emphasising critical infrastructure vulnerabilities, leading to increased security measures
- NRC Order EA-02-026 in February 2002 and EA-03-086 in April 2003, mandating cybersecurity measures against terrorism and radiological sabotage
- NUREG/CR-6847 in October 2004 and NEI 04-04 in November 2005, developing systematic cybersecurity assessment methods and programmes for nuclear power plants
- RG 5.71 in January 2010 and KINAC RS-015 in 2016, providing detailed guidance and establishing cybersecurity requirements
- ongoing efforts, include revising RG 5.71(DG-5061) in February 2022 and developing a new cybersecurity approach, NRC, 10 CFR 73.110.

Disruptive aspects for the nuclear industry

The rapid integration of digital technology and advanced reactors (ARs), including small modular reactors (SMRs), has increased the importance of cybersecurity in the nuclear industry. Though not traditionally seen as disruptive, nuclear cybersecurity is essential for operational safety amid growing cyber threats.

Cybersecurity is considered disruptive because disruptive technologies are reshaping defence strategies, enhancing resilience, and fortifying systems against sophisticated cyber threat. These challenges are further compounded by AI-driven autonomous operations, remote control capabilities, and new digital platforms. Consequently, cybersecurity is not just an add-on, but a crucial foundation for implementing disruptive technologies, ensuring the nuclear industry's innovative and efficient evolution.

Disruptive technologies contributions to cybersecurity

While nuclear power plants have traditionally relied on proven technologies, the appearance of innovative technologies from SMRs and various ARs introduces new challenges, including unexpected cyber threats. These innovations necessitate a shift to a more thorough cybersecurity strategy that incorporates "security by design" across the entire life cycle of nuclear facilities and ensures "security for the supply chain." This approach is vital for tackling the novel cyber threats that emerge with these advancements. It underscores the importance of viewing cybersecurity as both critical and potentially disruptive in the nuclear industry.

Status of cybersecurity and related technologies for enabling implementation

Current cybersecurity measures in operational nuclear power plants are primarily focused on regulations that highlight operational and managerial actions. There is a notable lack of cybersecurity technology tailored to ARs that utilise AI for autonomous operations and remote control. While existing security protocols are technically prepared to counter cyber threats, they do not comprehensively address the unique requirements of AR environments employing AI. This highlights the necessity for improved regulatory and technological strategies for cybersecurity in these sophisticated settings.

Current and future research

In the nuclear power sector's cybersecurity landscape, plants are adopting technical, operational, and management security controls aligned with their country's regulatory standards, like the US NRC RG 5.71 and Korea's KINAC RS-015. These regulations lay the groundwork for strengthening cybersecurity at nuclear sites, covering various protective measures. Future research will aim to integrate “Security by Design” into the nuclear development process, crucial for new nuclear technologies. This includes tackling cyber threats to AI and ML-driven autonomous operations and enhancing the security of remote operations through encryption.

Associated policies

Nations worldwide are creating or improving their cybersecurity policies for nuclear facilities to protect digital systems against cyber-attacks. The International Atomic Energy Agency (IAEA) offers comprehensive guidance and support to its members to enhance their defences against cyber threats. Through its Nuclear Security Series documents, the IAEA advises on nuclear security, including cybersecurity, helping countries build robust regulatory frameworks and effective cybersecurity strategies. Additionally, the IAEA focuses on the cybersecurity of emerging nuclear technologies like Small Modular Reactors (SMRs), collaborating with member state experts to update and develop relevant policies for this changing field.

Associated initiatives

Efforts to improve cybersecurity measures in nuclear facilities focus on developing, implementing, and constantly improving cybersecurity programmes. These initiatives involve collaboration between regulatory agencies, nuclear operators, and cybersecurity specialists to guarantee the effectiveness and regulatory compliance of cybersecurity actions. The International Atomic Energy Agency (IAEA) emphasises cybersecurity's role in SMRs and other advanced nuclear technologies. It actively runs projects and technical meetings, collaborating with experts from its member states to develop policies suited to these technological advancements. This global co-operation seeks to tackle the specific cybersecurity challenges introduced by new nuclear technologies, ensuring that facilities remain protected against the evolving cyber threat landscape.

Relationship of cyber security to the nuclear sector

Use cases and problems addressed

The primary objective of cybersecurity innovations in the nuclear sector is to protect the digital computers, communication systems, and networks in nuclear facilities from potential cyber-attacks. This goal is vital for the continuous and safe operation of systems essential to the facility's safety, security, and emergency preparedness. Applications include securing systems that control reactor functions, preserving data integrity, and protecting internal and external communication pathways. The significance of these innovations lies in their capacity to prevent cyber threats, thus blocking unauthorised access or damage to nuclear facilities. This protection is crucial for public health, safety, and national security.

Value and impact
The importance of cybersecurity in the nuclear sector lies on ensuring operational integrity, public safety, and national security by defending against cyber threats. Effective cybersecurity measures prevent catastrophic outcomes by blocking unauthorised access and sabotage. These measures eliminate the risk of unauthorised individuals gaining access to sensitive nuclear materials or engaging in the sabotage of critical infrastructure. They enhance the resilience of nuclear facilities against cyber incidents, supporting safe nuclear energy production and securing sensitive information. This protection is vital for public confidence and national defence. This makes cybersecurity a critical component of the nuclear industry's overall safety and security strategy.

Areas for observation
Monitoring efforts should concentrate on identifying evolving cyber threats, keeping up with advancements in cybersecurity technology, adapting to regulatory updates, and understanding the cybersecurity status of other essential infrastructure sectors. Additionally, it's crucial to be vigilant about potential insider threats and any vulnerabilities within the supply chain.

Key indicators for timing of implementation
Key indicators suggesting the right time to implement the cybersecurity technology might include a noticeable increase in cyber-attacks targeting critical infrastructure, significant advancements in hacking techniques that pose new threats, updates in regulatory frameworks that necessitate stronger cybersecurity measures, and the emergence of new cybersecurity technologies that provide enhanced protection capabilities.

Relevance during low technology readiness level
Even when a technology is in the early stages of development, it's crucial to monitor it because of the constantly changing nature of cyber threats and the technology's potential to provide new solutions to these emerging challenges. Being aware of such technologies early on can help in adapting and incorporating them in a timely manner, ensuring that security measures stay one step ahead of potential threats.

Cost implications and value for money
The cost involved in adopting cybersecurity measures should be balanced against the possible consequences of cyber-attacks. Investing in cybersecurity is justified when the cost of preventive actions is less than the potential damage caused by cyber incidents, such as operational disruptions, financial losses, data loss, and public trust loss.

Workforce implications
Implementing advanced cybersecurity technologies demands a skilled workforce to operate and maintain these systems effectively. This necessity may result in the requirement for extra training, as well as the potential need to recruit additional staff or specialists in cybersecurity. Furthermore, this could also enhance the overall security culture within an organisation, making it more resilient against cyber threats through a well-informed and skilled team.

Advantages and disadvantages of the innovation concept

Cybersecurity technology significantly improves defence mechanisms against on-line threats targeting advanced nuclear facilities. This ensures these sites comply with established international cybersecurity regulations. Additionally, it plays a crucial role in enhancing international co-operation and collaboration in nuclear security. By adopting such technology, nuclear installations become safer and more dependable, while also fostering a stronger, united global front against the challenges posed by cyber vulnerabilities, ensuring a more secure nuclear future.

The disadvantages of cybersecurity technology include the challenge of integrating these measures with current nuclear regulations and practices, the rapid evolution of cyber threats that could outpace current defence methods, and the substantial investment required in both technology and skilled staff to address these challenges effectively.

4. Disrupting Industries

Alternative fuel

Commissariat à l'énergie atomique - Nuclear in non-traditional sectors: Production of e-fuels from nuclear energy

History of e-fuels

With the necessity to decarbonise hard-to-abate sectors such as the aviation industry, and, for Europe, the ambitious targets set by the Fit-for-55 legislation package, the search for new ways to produce synthetic aviation fuels from low-carbon energy sources has gained significant momentum over the past few years. Producing significant amounts of SAF (several 100kt/year by 2035 in Europe to comply with the regulation) requires tremendous amounts of low-carbon energy. This is primarily for H_2 production through electrolysis and to a lesser extent for carbon capture.

Driven by the necessity to set up innovative production processes which maximise the SAF output in terms of energy input (heat and power), the CEA has been working on fully integrating the different steps of the process, taking advantage of the capacity of SMRs to provide low carbon heat and power in a flexible way.

The work carried out was to find the optimal way to combine it with HTSE for H2 production, DAC for CO_2 capture, and thermo-chemical processes for producing the molecules.

E-fuels as a disruptor to nuclear

E-fuel production requires a very different operating scheme for the nuclear unit, which is integrated in a wider process, and enables a heat management on the secondary circuit. This takes advantage of the exo-thermal processes downstream. It profoundly changes the optimisation of the overall process and leads to technical and operational configurations of the energy conversion systems which are very different from the standard setup.

Enabling technologies for nuclear e-fuel production

The first technology enabling these concepts are SMR/AMRs which provide a source of low- carbon heat that can be sited very close to the H2 production and CO_2 capture units, with a flexible way of managing the heat / power output. Tailored intermediate systems with innovative heat and power management throughout the process are also key to the overall efficiency of such concepts. Finally, the high temperature steam electrolysis process for H2 production (and possibly syngas with co-electrolysis), significantly improves the yield in terms of power consumption. This is a critical factor for the production at the scale needed.

Status of nuclear-enabled e-fuels

Technology readiness level
This concept is fully compatible with heat produced from PWR-type nuclear units which can be located near H2 production sites and / or CO_2 capture units. This depends to some extent on the availability of LWR-type SMRs but can also be implemented with more novel AMR concepts.

The HTSE technology is already available at the MW scale but requires further work to be scaled up above the 100MW level. The same goes for direct air capture for CO2, which is not currently available at very high scales.

As far as energy management systems are concerned, the basic components are available, but their management will require some work to implement in the safety and operational constraints of the process.

Current and future research
The main areas of research include the energy management systems, and the scale-up of the HTSE process, along with the development of SMRs/AMRs, allowing heat and power generation.

Relevant policies and innovation initiatives
To some extent, co-localisation of H2 production sites and nuclear sites might require additional policies to prescribe the rules related to the safe operation of both activities.

To our knowledge, several countries have undertaken modelling and experimental validation work on this topic, to reach, in a step-wise manner, the full industrial scale for e-fuel production.

State of R&D funding
Some public and private funding exists for such development driven in Europe, in particular, by the Fit-for-55 legislation.

Relationship of e-fuels and the nuclear sector

The main rational behind this concept is to take advantage of dispatchable low-carbon heat provided by nuclear to further decarbonise hard-to-abate sectors such as the long-range aviation industry.

Value and impact
The value resides in the ability to replace current fuels by SAFs, creating new markets for the nuclear industry. This concept will improve the business opportunities for nuclear vendors.

Anticipated evolutions and key indicators
SAF are still heavily relying on the legislation to rise in terms of market share in the aviation industry, and as such the policies environment is of prime importance.
Key indicators include the availability of SMRs, and of HTSE and CO_2 capture technology at the scale needed for SAF production.

Cost and resource implications
The business case at the time is driven primarily by the need to abide with the policy and is otherwise associated with the CO_2 price set on aviation fuel.

Given the amounts of SAF to be produced to respect the European legislation, it is expected that such processes would significantly increase the need for low-carbon energy (renewables and nuclear) involved in SAF production.

Chemical industry

Dow Chemical - Process heat from small modular reactors

The history of process heat from nuclear

Dow completed a thorough analysis of our largest manufacturing sites to understand the sources of carbon dioxide emissions and develop a strategic plan on how best to reduce these emissions to enable meeting Dow's publicly stated sustainability goals[18]. The innovative concept is to generate steam from small modular reactors to use as process heat in the manufacturing of materials, rather than incumbent approaches of natural gas fired boilers or cogeneration.

Disruption factors

To date, nuclear energy has been only used to generate electricity for grid applications and has not been directly linked to a manufacturing site. This innovation is to use nuclear energy for combined heat and power. Further, the vision is for the nuclear reactor to be co-located and integrated into Dow's manufacturing operations and the collective system optimised together. This may require the SMR to be load following and/or rapidly switch between process heat and electricity generation.

The integration of the nuclear plant and the chemical plant requires innovation in process design, which most likely will be standard-unit operations and equipment (i.e. heat exchangers) to be configured in new ways. Advanced process control will be required to ensure safe, environmentally sustainable, reliable and economically-optimised operations. This includes advanced co-ordination of planned turnarounds and unplanned events. In some cases, the temperature and/or the pressure of the nuclear-generated process heat may need to be boosted, which will also require new innovations.

Status

Technology-readiness level

The current technology-readiness level (TRL) is TRL 6. The ongoing research is evaluating the optimal combination of SMR technology for a given process heat application in manufacturing plants, as well as the specific integration process flowsheet, operation, and control.

The requirements for quantity, quality, reliability, location, and affordability of process heat vary widely. As such, some manufacturing applications are better suited for SMR technology than others. Future research should explore designing SMRs that deliver process heat at the target conditions to minimise the complexity of the integration (e.g. temperature or pressure boosting, energy storage, isolation loops).

Related policies and innovation initiatives

Co-location of a nuclear plant and manufacturing may change the hazard scenarios required for regulatory compliance. The appropriate nuclear island boundaries for load following and integration may require evaluation of existing policies where only electrons are exports without exchange of process streams.

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18 https://corporate.dow.com/en-us/science-and-sustainability/commits-to-reduce-emissions-and-waste.html

Dow and X-energy are collaborating to site four of X-energy's XE-100 reactors at Dow's site in Seadrift, TX. This initiative is driving needs in research, policy, the supply chain, and regulation.

R&D funding status

The project is supported by the US Department of Energy Advanced Reactor and Development Program. Dow also has a DOW GAIN proposal to evaluate other Dow sites and SMR technologies. Additional government support will likely be required to further de-risk future demonstration units.

Value, impact and anticipated evolutions

Chemical manufacturing is a hard-to-abate sector that currently has limited technology options available for decarbonisation. The successful implementation of SMR technology by Dow and X-energy would be a strong viability signal. The value is to demonstrate SMR technology generating process heat at scale and providing actual process, operational, and economic data to compare with other options. These include hydrogen combustion, oxy-combustion with carbon capture and sequestration, or complete process redesign through electrification.

Success could launch the SMR industry, including HALEU and related supply chains. The time is now for implementation of this process.

Cost and resource implications

The delivered cost of process heat must be competitive with the alternatives listed above. The integration will require a workforce that is trained in both nuclear and manufacturing operations, and in advanced process control.

Advantages and disadvantages

The advantage is that there is high confidence in the technology. The disadvantage is that the economics and timelines have yet to be demonstrated for a first-of-a-kind and that the learning curve associated with nth-of-a-kind will deliver lower fixed and variable costs and reduced project timelines.

Other information and references

Steam is the driver for co-location of nuclear reactors with manufacturing sites. Local power generation is also a desired output that increases reliability and minimises changes to the external electrical grid.

A nuclear plant design for reliable steam requires back-up reactors, and when not needed for steam, those reactors can send decarbonised electricity to the local/regional grid. There is an inherent synergy to design reliability and grid decarbonisation with non-variable energy sources, which could lead to new business models and incentives.

Data Centres

Idaho National Laboratory - Impact of data centre market growth on the nuclear industry

Paul Talbot, Abdalla Abou Jaoude, Gabriel J. Soto, Botros Hanna, Jakub Toman, Tim McJunkin, and Aaron Epiney

Introduction

While data centres and their unique needs have been part of the US power system for some time, recent rapid growth in data centres invites a careful look at opportunities for innovative deployment of existing and advanced nuclear.

In recent news, Microsoft has begun exploring the fitness of advanced nuclear power sources for its data centres (Calma, J., 2023), and Amazon recently purchased a data centre immediately adjacent to the Susquehanna nuclear power station (American Nuclear Society, 2024). Nuclear power plants can provide high-density energy with a proven track record of high reliability and uptime for its existing reactor fleet, up to 93% (EIA, 2024).

With high energy, reliability, and zero-carbon as priorities for data centres, nuclear stands in a unique position to meet these needs. Data centres have achieved high technology readiness level and are already looking to nuclear power to be a source of clean firm energy.

Sources of impact

Rapid growth of data centres due to the increased use of artificial intelligence (AI) applications including large language models (LLM) is having a significant impact on energy demand worldwide. Data centres require high reliability, up to 99.999%, and to meet climate goals, are striving towards zero-carbon electricity sources. This impacts the nuclear industry in three ways: the growth of demand due to increased data centre deployment, the potential profitability model of data centres as co-generation sites with flexible operation, and high reliability requirements.

Energy demand forecast

The most direct impact of data centres on nuclear growth is the remarkable energy need for data centre operation. The International Energy Agency (IEA) estimated that 2022 global data centre energy use was 220 to 240 TWh in 2022, 1-1.3% of global demand, with an additional 110 TWh from cryptocurrency mining (IEA, 2024).

The IEA further projects significant growth in demand in this area despite improvements in data centre energy efficiency, including growth from 2022 to 2026 in the United States (US) from 190 to 250 TWh, in Europe (EU) from 100 to 150 TWh, and in the People's Republic of China (CN) from 225 to 300 TWh. Supplying energy needs for this growth requires on the order of 175 TWh, or seven full-sized nuclear reactors. Projections for data centre grown in China alone suggests over 400 TWh of data centre energy usage by 2030 (Liu, W. et al., 2021).

For comparison, a 3 GW existing large nuclear power plant with 92.5% up-time yields approximately 25 TWh annually. Likewise, a 50 MW small modular reactor (SMR) generates roughly 0.4 TWh annually, and a 10 MW microreactor (uR) generates roughly 0.08 TWh annually. Thus, global data centre and cryptocurrency use in 2022, based on the projections above, would require exclusive use of between 13 and 18 large nuclear power plants, 750 to 1000 SMR, or 4000 to 5500 uR to meet existing demand. To meet additional projected 2026 demand in the US, EU, and CN, another 6 large nuclear power plants, 360 SMR, or 1800 uR would be required. This presents a remarkable opportunity for growth in nuclear power to support the growing need for electricity, especially given the clean, firm energy nuclear can provide.

Flexible operation as a co-generation facility

In the US, the Public Utility Regulatory Policies Act of 1978 (PURPA) established a new class of generating facilities that would receive special rate and regulatory treatment (US Federal Energy Regulatory Commission, 2024). This applies to small production facilities (80 MW or less) whose primary source of energy is from variable renewable sources. It is also a co-generation facility that sequentially produces another form of useful thermal energy such as heat or steam in a way that is more efficient than the separate production of both forms of energy. The benefits of qualified facility (QF) status include: the right to sell energy or capacity to a utility, the right to purchase certain services from utilities, and relief from certain regulatory burdens. Prices for QF can be seen in (PG&E, n.d.).

If a data centre included integrated nuclear power as part of its extended campus, curtailing some data centre operations could flexibly provide capacity or energy from the nuclear power plant that could then be sold to the grid. This flexible operation could not only relieve high-pressure energy demands from the grid, but also provide another revenue source for the data centre, increasing the attractiveness to data centres as nuclear customers.

Data centre reliability requirements

Data centres often need to be continuously accessible to a wide variety of customers in many locations. As a result, data centres frequently see reliability needs upward of 99.999%. Directly integrating nuclear generation with data centres provides clean, firm (non-variable) baseload energy to match the needs of the data centre. Further decarbonisation opportunities, such as using thermal heat or nuclear-produced hydrogen for backup energy storage, or operating backup generators that consume synthetic fuel produced from nuclear heat and electricity, offer additional zero-carbon benefits of nuclear data centre integration. The only other viable zero-carbon energy sources are variable renewable energy sources such as wind and solar, which require substantial investment in energy storage to guarantee baseload energy requirements. According to recent research at Idaho National Laboratory sponsored under the Gateway for Accelerated Innovation in Nuclear, the same baseload power that a nuclear plant produces requires orders of magnitude more installed wind and solar generation plus over one 100 GW hours of additional electrical battery storage to provide baseload power. This is not including additional battery storage for backup.

While a mix of nuclear energy and renewable sources may be ideal in many regions, nuclear is consistently part of a reliable clean firm energy solution that matches data centre needs.

Conclusions

Why should the nuclear industry engage with the data centre industry and monitor progress? Traditional use of nuclear power for grid electricity has led to economic crisis for many plants in the US Increasing variability due to large wind and solar installations has cut into the baseload need for large generation sources including nuclear. Meanwhile, growth of advanced nuclear to include a wide spectrum of technologies and capacities opens the door to directly serving data centres, whether individual distributed generators at the uR scale, full campuses at the SMR scale, or sited with existing nuclear power. As shown by recent public announcements and acquisitions by large data centre corporations such as Microsoft and Amazon, nuclear is a viable potential partner for data centre operations and may be the needed impetus for the first commercial deployments of advanced nuclear reactors in the US.

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Energy storage

Idaho National Laboratory - Energy storage systems

Rami Saeed, Travis L. McLing, and Eric J. Dufek

Thermal energy storage (TES)

Existing nuclear power plants serve as critical baseload generators, meeting the steady electricity demands of the grid. However, the variable nature of electricity demand poses challenges for their efficient operation. Thermal energy storage (TES) emerges as a promising solution to address these challenges while also unlocking additional benefits beyond power production.

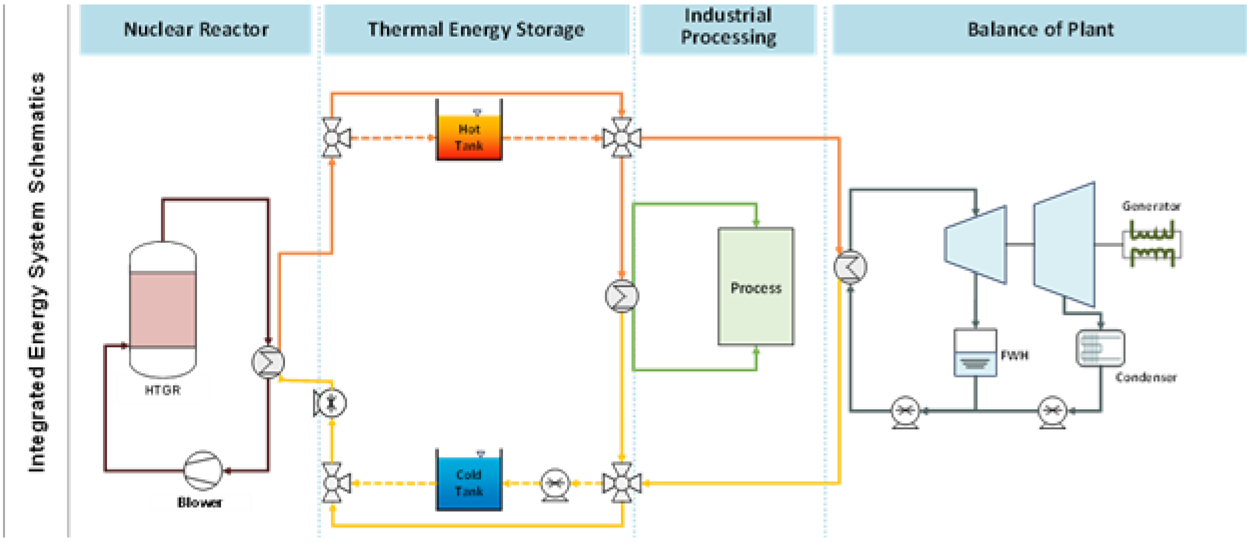
Traditionally, nuclear power plants operate optimally at a constant power level, known as the baseload condition. Deviating from this mode, such as during low-demand periods, can incur economic penalties due to decreased capacity factors and increased equipment wear. TES technologies address these issues by enabling reactors to adapt to varying demand profiles.

One significant advantage of coupling nuclear reactors with thermal storage systems lies in preserving the nuclear energy in its original form (heat) before undergoing any energy transformation, thus minimising potential energy losses. TES systems store excess energy during periods of low demand or high renewable generation. This stored thermal energy can then be used during peak demand or low renewable generation periods, ensuring more flexible power production without compromising reactor efficiency or longevity. By smoothing out power output fluctuations, thermal storage decouples the reactor for these variabilities which leads to enhanced economics and improved grid integration.

Furthermore, thermal storage extends the utility of nuclear energy beyond electricity generation. By decoupling heat production in the reactor core from immediate electricity generation, reactors can integrate seamlessly into industrial processes requiring thermal energy. This facilitates cogeneration, where nuclear plants supply both clean electricity and heat to industrial facilities, reducing reliance on fossil fuels and aiding decarbonisation efforts.

Research efforts, such as those by the Idaho National Laboratory team, have demonstrated the feasibility and effectiveness of coupling various reactor technologies with TES systems (Saeed, R., 2024). Studies using materials like molten salt thermal storage have shown how TES maintains reactor power output at a constant level while efficiently managing fluctuating electricity demand and facilitating heat delivery for industrial decarbonisation. Figure 4.1illustrates a conceptual block diagram of a TES system integrated with a nuclear reactor for combined heat and power applications.

Figure 4.1 Nuclear reactor with thermal storage for combined heat and power applications



Source: (Coleman, J. et al, 2017).

Geologic reservoir thermal energy storage

Grid-scale energy storage has been identified by the US Department of Energy's (DOE) Energy Storage Grand Challenge as a necessary technology to support the continued build-out of intermittent renewable energy resources required to attain a carbon-free energy future.

To meet this goal, the 2018 Department of Energy Research and Innovation Act mandated the creation of a comprehensive programme to accelerate the development and commercialisation of next generation energy storage technologies.

One of numerous energy storage technology options is the storage of excess energy as heated geothermal brine in suitable geologic formations. This concept, known as reservoir thermal energy storage (RTES), geologic thermal energy storage (GeoTES), aquifer thermal energy storage (ATES), etc., relies on the storage of waste thermal energy from nuclear, industry, data centres, etc. in geologic formations for recovery and use in large-scale direct use geothermal (e.g. district heating, industrial processes) and electrical power generation applications. This thermal energy is derived from excess or waste heat from any heat source, such as concentrated solar or from conventional thermal/nuclear generation, data centres, industrial processes, etc.

As such, RTES can potentially play a significant role in meeting the energy storage shortfall in the coming decades. RTES can provide energy arbitrage through both the storage and production of thermal energy stored in geologic formations for direct use applications and can serve as a source of hot fluids that can be used to generate electricity to support peak demand ramping, thus easing stress on transmission and distribution. This energy storage option has geographic benefits in that energy can be stored locally or regionally depending on the various needs/loads. RTES can also be located across an enormous geographic area, without the need for a traditional hydrothermal resource but where thermal gradients and hydrogeology allow economic exploitation of subsurface heat.

The operation of a RTES system encompasses three basic steps: (1) convert excess electricity to heat (or unwanted excess hot water) and store in a suitable geologic reservoir when economically feasible (e.g. excess electricity produced by intermittent sources); (2) heat the subsurface over a long period of time (which could be combined with desalination and/or pressure management of large-scale carbon capture, utilisation, and storage (CCUS) projects); and (3) produce the heat thereafter when needed for direct use or the generation of electricity using geothermal technology.

The proposed solution is simple, efficient, and relies very little on external, unmanageable factors. RTES hybrid systems has great potential to improve operational performance, mitigation of both subsurface and surface infrastructure issues, and provide decades of system operation. Additionally, the adoption of RTES projects internationally projects provide valuable lessons associated with exploration, initiation, operation, and sustainable maintenance of RTES.

The results of results of research conducted at Idaho National Laboratory help define future RTES research projects that will facilitate successful future deployment of such systems and make RTES a more viable option for energy storage in the US.

Electrochemical energy storage

Batteries and other electrochemical devices provide the opportunity to store the electricity generated by nuclear power plants when demand is low. For standard battery systems this is analogous to the support that broadly applies to different forms of electricity generation with storage opportunities from short to mid-duration of 10+ hours.

Parallel with battery systems, the electrochemical production of H_2 using an electrolyser and coupling the system with a fuel cell opens a route to store energy chemically. When coupled with effective storage media this can significantly enhance the duration of storage from hours to months providing the opportunity for seasonal electrochemical storage. The coupled electrolyser-fuel cell systems additionally can benefit from the use of quality, high temperature thermal energy to reduce kinetic limitations of both the forward and reverse of the water splitting process. Recent advances in solid oxide technology have significantly increased the performance of high temperature electrolysers and increased overall effectiveness and utility of these systems.

Batteries as the other primary form of electrochemical storage technology are seeing broad adoption to provide grid stability to an increasingly electrified society. Coupling of nuclear power generation with batteries serves as a key opportunity to advance transportation electrification. Currently transportation accounts for ~25% of all energy use in the United States. While most trips occur within a short distance from a primary home location for light duty consumer vehicles, long range trips and the movement of goods across the country require the ability to support high-power, distributed charging. A single charging event presents little difficulty for existing power infrastructure, but coupling multiple high-power events could readily result in multiple MW fluctuations in demand that both fluctuates with time of day and season, and which is expected to increase as electric vehicle adoption increases and the type, range and fast charge capability of vehicles advances.

To account for the increased need for electrical demand there will need to be alignment of the expansion of electricity generation, transmission, and distribution. While feasible in some locations, the distributed nature of transportation is likely to limit some forms of infrastructure development. In these instances, close coupling of localised power generation and electrical energy storage such as batteries will be needed to provide the necessary energy for transportation and the ability to rapidly shave the peak demand associated with multiple high-power charging events.

While batteries needed for large-scale energy storage can exceed 100 MW, the systems often considered for Behind the Metre support of high-power charging tend to be smaller (1-10 MW) and capable of variable discharge rates to align with the increased charging rates for new fast charging electric vehicles. When paired with H_2 production and storage the ability to serve both battery and fuel cell electric vehicles using combined nuclear, battery and H_2 infrastructure presents the opportunity to dramatically change how the future of transportation evolves.

University of New Mexico – Energy storage

In recent years, with the increasing integration of renewable energy sources into the power grid, the coupling of nuclear power plants with energy storage systems has gained traction.

Energy storage systems offer a complementary solution by storing surplus electricity during periods of low demand and delivering it during peak demand, thereby enhancing grid stability and accommodating the intermittent nature of renewables. There are many energy storage technologies. Thermal energy storage (TES) using molten salts for advanced nuclear reactors is considered a particularly promising innovative concept that is detailed in the following sections.

Molten salts possess desirable properties such as high boiling points, low viscosity, low vapour pressure, and high volumetric heat capacities for sensible thermal energy storage.

The choice of chemical mixture for molten salt storage is crucial, aiming for the lowest possible melting point (and highest boiling point) to maximise the available temperature range. Salts commonly used for storage, such as sodium nitrate ($NaNO_3$) and potassium nitrate (KNO_3), exhibit melting points ranging between 200 and 400°C and volumetric heat capacities between 1 500 and 3 500 kJ/m^3°C. In practical implementation, molten salts are heated and stored in insulated containers during off-peak hours. When energy is required, the salt is pumped into a steam generator to boil water, driving a turbine to generate electricity.

Various cycles such as the Rankine, Brayton, and Air-Brayton cycles can facilitate the conversion of thermal energy to electricity. Alternatively, stored heat can be used directly for high-temperature processes like hydrogen production and coal-to-liquid conversion, eliminating the thermodynamic costs associated with electricity conversion.

The cooled salt is then pumped back to the storage tank for reheating and reuse. Two configurations exist for molten salt TES systems: the two-tank TES and thermocline systems. The two-tank TES system uses molten salt as both the heat transfer and storage fluid, consisting of separate hot and cold storage tanks. In contrast, the thermocline system employs a single tank where hot and cold salts are separated by a vertical temperature gradient, preventing mixing. This system operates through charging and discharging cycles, where salt is heated during charging and cooled during discharging.

Nuclear disruption factors

Molten salt thermal energy storage (MSTES) technology is considered disruptive within the nuclear industry due to its unique advantages over conventional nuclear power plants and other thermal energy storage technologies.

MSTES systems offer flexibility in power generation by storing excess thermal energy produced during periods of low demand, subsequently releasing it during peak demand times. This adaptability optimises the use of nuclear assets, contrasting with conventional nuclear plants that typically operate at a constant output level, often resulting in inefficiencies during low-demand periods. Additionally, high-temperature molten salt thermal energy storage enhances the efficiency of nuclear power plants by allowing surplus heat to be stored and used during peak demand, potentially increasing revenue for operators.

Furthermore, MSTES enables nuclear plants to operate in a load-following mode, adjusting output to match fluctuations in electricity demand, essential for integrating nuclear power into modern grids with high levels of renewable energy. This capability reduces the need for backup power generation, enhancing grid stability.

As an outcome, MSTES systems offer potential cost savings by optimising nuclear plant operation, reducing the necessity for additional capacity to meet peak demand, thereby improving the economic viability of nuclear energy. Additionally, the inherent safety and environmental benefits of molten salt thermal energy storage contribute to mitigating climate change by reducing greenhouse gas emissions and minimising environmental impact.

Overall, MSTES technology presents a transformative solution within the nuclear industry, aligning with sustainability goals and enhancing the competitiveness of nuclear energy in the evolving energy landscape.

Enabling disruptive technologies

Molten salt thermal energy storage is a disruptive technology that significantly contributes to enabling the implementation of thermal energy storage systems in the nuclear industry. This technology offers several advantages that enhance the viability and effectiveness of thermal energy storage systems:

High energy density
Molten salt thermal energy storage systems have high energy density, allowing them to store large amounts of heat efficiently. This high energy density enables the systems to effectively capture and retain excess heat generated by nuclear reactors, ensuring reliable energy storage for future use.

High temperature capability
Molten salt can operate at extremely high temperatures, making it well-suited for storing heat from nuclear reactors, which often operate at elevated temperatures. This capability ensures that molten salt thermal energy storage systems can effectively capture and use the excess heat produced by nuclear power plants.

Long duration storage
Molten salt thermal energy storage systems can store heat for extended periods, ranging from several hours to days. This long-duration storage capacity aligns with the intermittent nature of renewable energy sources and enables the smooth integration of nuclear energy into the energy grid by providing a reliable source of stored heat during periods of high demand or low renewable energy availability.

Cost-effectiveness
Molten salt thermal energy storage systems offer a cost-effective solution for energy storage compared to other technologies. The abundance of salt, and its relatively low cost, make molten salt storage economically attractive for large-scale energy storage applications, such as those required in the nuclear industry.

Safety and reliability
Molten salt thermal energy storage systems have proven to be safe and reliable in operation. The use of stable salts and the absence of flammable materials contribute to their robustness and minimise the risk of accidents or malfunctions, ensuring the continued operation of nuclear power plants with enhanced safety measures.

In summary, molten salt thermal energy storage technology serves as a disruptive enabler for the implementation of thermal energy storage systems in the nuclear industry. Its high energy density, temperature capability, long duration storage, cost-effectiveness and safety features make it a crucial component in realising the potential of thermal energy storage to enhance the efficiency, reliability and sustainability of nuclear power generation.

Status

Technical readiness level (TRL)
Molten salt thermal energy storage stands at a noteworthy technical readiness level, particularly in applications like concentrated solar power (CSP) plants, where it has been successfully demonstrated on commercial scales (TRL 9). However, its readiness for integration with nuclear reactors may require further refinement to address specific challenges and ensure seamless compatibility with nuclear power plant operations (TRL less than 9). Advancements in materials science, system design, integration, and safety protocols are continuously enhancing the TRL of molten salt thermal energy storage systems for nuclear applications.

Current and future research
Ongoing research in molten salt thermal energy storage is multifaceted, focusing on various aspects to enhance system performance and feasibility. Studies are exploring advanced salt formulations to improve thermal properties, reduce corrosion, and increase overall system efficiency. Additionally, research efforts are directed towards developing innovative storage tank designs and heat exchanger technologies to optimise heat transfer processes and enhance system durability. Future research trajectories may include investigating alternative heat transfer fluids to further enhance system performance, exploring new materials for storage tanks to improve longevity, and developing advanced control and monitoring systems for real-time optimisation and predictive maintenance.

Policies associated with this innovation

Policies regarding molten salt thermal energy storage in the nuclear industry are evolving within the regulatory frameworks governing nuclear power generation and energy storage technologies.

While specific regulations or standards may vary across jurisdictions, there is a growing emphasis on ensuring the safety and environmental compatibility of thermal energy storage systems, particularly when integrated with nuclear reactors.

Government policies aimed at promoting renewable energy and energy storage technologies indirectly support the development and deployment of molten salt thermal energy storage by providing incentives or subsidies for research, development, and deployment.

For example, federal initiatives such as the Renewable Energy Grant Program and Federal Loan Guarantee Program, aimed at incentivising investment in pioneering CSP technologies, stand poised to propel the advancement of molten salt energy storage systems.

Associated Initiatives

Various initiatives and collaborative efforts are underway to advance molten salt thermal energy storage technology. In the US, there are EFRC' MSEE, EERC's DEGREE, ARPA-E's DAYS, among others.

State of funding for research and development

Funding for research and development in molten salt thermal energy storage varies based on government priorities, industry investments, and available grant opportunities. As energy storage technologies, including molten salt thermal energy storage, gain prominence in the transition towards a low-carbon energy future, funding support is increasing. Funding agencies include the US Department of Energy's NEUP, ARPA-E, EERE, SETO, among others.

Relationship with the nuclear sector

There are several opportunities to use this technology within the nuclear sector and related energy systems as outlined below.

Grid instability
Molten salt thermal energy storage addresses the intermittent renewable energy sources by storing excess energy during off-peak periods and releasing it during peak demand, thus stabilising the grid.

Energy storage for nuclear power
Molten salt thermal energy storage can store excess heat from nuclear reactors during low demand periods, enhancing the flexibility and efficiency of nuclear power generation.

Industrial applications
It can also be used in industrial processes to store and recover heat, reducing energy consumption and improving overall efficiency.

Value and impact
Molten salt thermal energy storage provides value by enhancing energy reliability, reducing reliance on fossil fuels, and facilitating the integration of renewable energy into the grid. Additionally, it optimises nuclear power generation, leading to cost savings and environmental benefits.

The impact includes reducing greenhouse gas emissions, enhancing energy security, and promoting the transition to a sustainable energy future. It also offers economic benefits by creating new opportunities for nuclear industries and strengthening the competitiveness of renewable and nuclear energy technologies.

What to watch
Key considerations include technological advancements, cost reductions, regulatory developments, market trends, and energy policy changes affecting the adoption and implementation of molten salt thermal energy storage.

Key indicators for implementation
Indicators include TRL, cost-effectiveness, regulatory policy, market demand, and the need for flexible and sustainable energy solutions. Advancements in these areas signal readiness for implementation.

Lower technology readiness level and nuclear interest
Despite the lower technology readiness level within a nuclear application, the industry should monitor molten salt thermal energy storage due to its potential to enhance nuclear power plant flexibility, improve grid stability, and support renewable energy integration.

Cost implications and feasibility
Cost implications depend on factors such as system integration, materials, and operational requirements. It becomes economically viable when benefits such as reduced cost of special materials in high temperatures.

Workforce Implications
Implementation may require skilled labour for system design, integration, installation, operation, and maintenance. Workforce implications include job creation and opportunities for training and skill development in renewable energy and energy storage technologies.

Advantages and disadvantages of the innovation concept

Molten salt thermal energy storage offers several advantages that make it an attractive option for energy storage applications.

Its high energy density allows for efficient storage of excess heat generated by nuclear reactors, providing a reliable and flexible energy supply to meet fluctuating demand. The ability to operate at high temperatures makes molten salt suitable for storing heat from nuclear reactors, enhancing the overall efficiency and flexibility of nuclear power generation.

Additionally, the long duration storage capability of molten salt enables nuclear power plants to store excess heat during periods of low demand and release it when needed, thereby optimising plant operation and grid stability.

However, there are specific challenges associated with integrating molten salt thermal energy storage into nuclear power plants:

- Corrosion and material compatibility issues need to be carefully addressed to ensure the reliability and safety of storage systems.
- The complexity of system design, including the need for sophisticated control and monitoring systems, presents additional challenges in the nuclear industry where safety is paramount.
- Heat loss over time and limited operating temperature ranges may also impact the effectiveness of thermal energy storage systems in nuclear applications.
- Environmental considerations, such as energy consumption during production and disposal of molten salt, must be carefully managed to minimise the environmental impact of nuclear power generation.

Overall, while molten salt thermal energy storage offers promising opportunities for enhancing the efficiency and flexibility of nuclear power plants, addressing these challenges is essential to ensure its successful implementation in the nuclear industry.

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Smart Cities

Electric Power Research Institute - Smart Cities

Frank Sharp

Introduction

EPRI has been researching lighting for more than 25 years and has been conducting field research on LED-based street lighting, smart city lighting, and smart cities for more than 15 years.

Today, smart city technologies are being deployed in numerous countries and in cities of a few thousand to millions of people. The expanded use of smart city technologies makes their operational load profile relevant to the grid planners and load forecasters. This relevance resulted in EPRI conducting laboratory and field evaluation on grid tied, off grid, and hybrid (which can take energy from grid tied and off grid energy sources) smart or connected city solutions.

The term smart city is somewhat ambiguous, but the following description of smart city was developed by EPRI's Technology Innovation group for their June 2017 whitepaper entitled *The Role of Digital Utilities in Smart Cities*[19.]:

> "A smart city uses digital technologies or Information and Communication Technologies (ICT) to achieve a more integrated, digitally connected, and resilient environment aimed at improving quality of everyday life, from essential services to leisure activities, optimizing the city's assets and infrastructure including utility services (gas, water, and electricity), transportation (roads, rail, and other public transport networks), housing (private, social, and multi-occupancy), and government services (health, policing, and education)[1]."

As the description outlines, the primary goal of a smart city is to interconnect previously discrete systems to improve efficiency and optimise resources. This can be accomplished in a variety of ways and to various degrees as each city has its own unique features and challenges. Over time most cities move through stages of establishment, growth, maturation, and reconstruction / redevelopment. In each of these phases, the deployment and use of smart city infrastructure plays a different role. For example, cities that are experiencing population growth, but have limited resources and space for new infrastructure will use smart city technologies differently than a city experiencing flat to declining population growth that is interested in smart city technologies to attract new businesses and residents. Whatever the circumstances, smart city technologies have the potential to increase utility-to-resident or business-to-resident connectivity while improving system performance by providing new sensors and data for grid modernisation.

Later in 2017, EPRI's End Use Customer Technology Group – which houses EPRI's lighting research team - built on the work of EPRI's TI group and published a whitepaper titled - *Smart City Lighting: Industry Overview and Demonstration* (EPRI, 2017). Both documents outline the potential need for utilities to invest and implement smart city technology to become more flexible, resilient, and reliable. These papers encouraged utilities to recognise the role that utilities can play in implementing smart city technologies. They also identified the core technologies and trends that drive deployment with the goal of helping utilities identify communication infrastructure that can connect smart metres, streetlights, and many other smart city technologies.

1. *The Role of Digital Utilities in Smart Cities: Leveraging Utility Information and Communication Technologies*. EPRI, Palo Alto, CA: 2017. 3002011385.

Discussion

The term smart city can include a wide variety of technologies, but generally includes any technology that is mounted in exterior applications – commonly on poles – that collects or provides new streams of information. Examples include smart streetlights, connected infrastructure, wayfinding, intelligent inverters, Wi-Fi hotspots, EV chargers, powerline monitoring, digital commerce, and the integration of the plethora of the Internet of Things (IoT) devices like connected appliances and data collection / monitoring technologies. Each of these technologies provides data that can be used to drive city development and engagement. This generated data can also be used to improve grid reliability and reduce ongoing maintenance costs by effectively locating and predicting potential failures. These benefits help to improve overall utility services and programmes – including generation planning.

The diversity of smart city loads, paired with their potential community impact, means that utilities may need to consider factors beyond grid services and power delivery when collaborating with smart cities. This is because a key for the proper use of smart city concepts is the delivery of services that best align with the city as it evolves. This means that deployed technologies need to be capable of adapting and changing with the requests of residents and businesses for new or improved services. Thus, in most cases, smart cities are the outgrowth of a community wanting to deliver new and diverse means to engage with and improve the experience of people visiting a location. Fortunately, many of these services like EV charging, distributed energy generation and storage, high speed data connectivity, cellular services, real time transportation / road data, energy data, environmental data, timely community information, and advertisement may also provide revenue streams for utilities and municipalities to help offset the additional costs associated with deploying and maintaining smart city systems compared to traditional infrastructure.

Many smart city services and opportunities revolve around data. Some of these opportunities are in community service, but others focus on delivering services. One key example of how data from these systems can be used is the real-time delivery of collected information to grid monitors, municipal services, and centralised utility locations. Such data can help with assuring and maintaining grid reliability and operation. It can also help with identifying power and safety issues that are developing. Collected data can also be delivered to connected smart devices, mobile phones, emergency services, and contracted organisations.

Though smart cities can take a range of forms, connected exterior / street lighting is the most common. In fact, smart street lighting, which includes both controllable exterior lighting and smart city applications, is a rapidly growing market with a projected growth rate of **19.2%** from **USD 2.41 billion in 2022 to USD 8.23 billion by 2029 (**Fortune Business Insights, n.d.). This growth, paired with the facts that 1) smart city technologies can be housed on the light pole to reduce the need for additional space usage, 2) that many utilities own or maintain streetlights, and 3) that light poles provide an easily leverageable asset that can improve safety and deliver community benefit all result light poles being the key to smart cities.

Street lighting has been a key asset to maintain stable night-time load and in allowing generation assets – including nuclear facilities – to remain active overnight. This potentially could change with the increased use of LED based outdoor fixtures which commonly resulted in a 50% or more decrease in lighting load per fixture.

In 2017, outdoor fixtures comprised < 2% of US lighting installations but consume 24% of lighting energy use (US DOE, n.d.). Outdoor lighting is also the lighting market segment which saw the largest percent of LED conversion (Elliott, C., 2020). Note, recent trends have seen any energy saved by the LED based fixture installation consumed by the expansion of 24/7/365 (8 760 hour) operational or available loads like EV charging, data centres, and large-scale controlled environment agriculture (CEA).

Although LED street lighting typically reduces the average night-time load of a fixture, the addition of other smart city assets like digital signage, façade lighting, speakers/cameras, and environmental sensors results in new continuous loads being added to the grid. These loads vary in scale from a few watts to several hundred watts and often require changes or updates to distribution services as they are continuous, unlike night-time lighting which is commonly controlled with a dusk to dawn sensor or timer. Pole based smart city deployments can also see the addition of service driven loads like EV charging which have to be available at all times. Regardless of their consumption and load profile, these loads also typically require continuous connectivity. This may result in an increased need for local Internet / data centre services. These added continuous loads – pole level through data centre scale – may result in an increased need for the stable generation provided by nuclear plants.

Building on this need for stable energy, some smart city deployments aim to pair these new or modified loads with "green" storage and low to no CO_2 energy generation like that provided by nuclear power. Such deployments also often consider customer and/or utility scale solar, biomass gas, and wind as key assets to service smart city loads during cycles of high utilisation and/or by storage systems (typically battery based) during peak events. This co-ordination of generation, storage, and technology energy usage is often driven by co-ordinating long term grid and city planning with energy efficient and environmentally friendly generation and technology solutions.

Key benefits that smart city systems typically address, and deliver are intelligent grid functionality, increased safety/security, expanded communication of information, increased home, and building automation/connectivity, exterior lighting control, and integration of shared intelligent transportation assets. Many of these have not been historically part of the services provided, or supported, by utilities and municipalities. The loads and technologies listed above - smart homes/buildings, connected utility loads (i.e. smart streetlighting and infrastructure), and integrated transportation (i.e. connected / autonomous vehicles, electric buses, and car sharing programmes) – can all potentially be powered by nuclear energy.

These loads may also provide utilities with energy efficiency (EE) / demand response (DR) tools and provide some load stabilisation, and potentially load growth opportunities, due to their increasing number. These impacts may result because, though individually small, these additional loads may in large quantities become noticeable. Note, many of these applications are service based and may require utilities to more deeply evaluate how municipal and industrial customers connect and interface with both the traditional grid and emerging generation and storage solutions.

Although smart cities offer the advantages of additional connectivity and services mentioned above, these benefits come with added initial technology cost and additional energy usage due to added technologies. Smart city technologies also typically have ongoing support and management expenses. These higher initial and ongoing costs, paired with the additional cost of staff to support and maintain the additional features within a smart city solution may offset any energy and maintenance cost gained by their deployment.

Additionally, though there are a lot of opportunities around smart city solutions, there are also numerous questions. Some of the larger questions around these systems include:

- Do these systems work as claimed?
- How complex are they to deploy and operate?
- Do they offer payback?
- If so, what is their ROI?
- What is the additional energy impact of deploying these services?
- Is there actual monetary value for the data they create?
- Is there long-term community or CSR (corporate social responsibility) value in these systems?

- Are these systems truly mature enough for broad deployment?
- Are there grid or additional network security risks around their operation?
- Do these systems communicate effectively?

The successful operation of smart city solutions requires effective communication. Currently, there are a wide variety of wired and wireless communication protocols used by smart city technologies. They are not always compatible. Thus, it is often required that each piece of smart infrastructure be vetted. This ensures its ability to communicate with other deployed technologies, existing or proposed data collectors and/or the utilised central management system to insure effective and efficient integrated operation.

Note, even if compatibility is ensured, effective and efficient integrated operation also requires reliable and accessible communication infrastructure – i.e. high-speed fibre, low cost / high speed cellular, etc. – to function correctly. This may require additional cost to establish.

A key question around smart cities is if revenue can be generated for utilities and municipalities from the data provided by smart city deployments. A few of the *potential* data or access driven revenue opportunities often mentioned, include:

- the sale of advertising on LED signage
- the sale of environmental and traffic data to weather providers, news outlets, livery providers and city and emergency services
- delivering of video / audio for security, tracking, gunshot detection, accident reporting, and parking services
- remote device or asset monitoring
- sale of electricity for pole-based EV charging

Today none of the above offer an established revenue stream that allows for a simple ROI to be calculated based on revenue creation, but such streams may develop in coming years. Currently, most smart city assets do not provide sufficient revenue to offset their higher initial or ongoing operational costs. Thus, most smart city installations today are based on community service and engagement drivers and are not based on energy savings or revenue driven goals.

Conclusion

Smart cities offer the potential ability to combine a range of technologies to create unique functional and scalable solutions for cities of all sizes. These scalable solutions can assist in city planning, delivery of government services, energy utilisation, mobility, maximisation of exterior space usage, increased retail / societal interactions, and can deliver real time data from a range of deployable technologies.

These potential benefits are key drivers to smart city deployments as today most smart city technologies are deployed largely to address city and resident goals for increased communication, improved safety, and expanded engagement. Smart cities are typically not deployed for the purposes of energy efficiency, cost recovery, or revenue generation as smart city infrastructure typically results in increased energy consumption due to added loads, higher initial acquisition cost, expansion or modification of existing distribution infrastructure, and additional ongoing operational costs.

From a nuclear power perspective, the expansion of smart cities likely results in an increased number of loads which require continuous operation, or which must be available continuously even when not active. Most of these loads are fairly small in terms of their individual demand, but cumulatively they may represent a trend that will help flatten or increase the demand for overnight energy. This increased need for stable and reliable energy delivery aligns well with the energy provided by nuclear power. The zero

CO_2 emissions of a nuclear power may also help support the goals of many deploying smart city solutions who desire to pair these smart city technologies with low-to-no CO_2 emission generation and storage solutions.

Smart cities are likely to continue to expand in the near-to-medium term based on current market predictions. This expansion is likely to result in additional development and innovation for smart city technologies. Expanded development and use of smart city solutions may also result in additional utility and municipal benefits like energy management, additional customer / resident engagement programmes, and the creation of reliable revenue streams from the services and data provided by smart city technologies. As a result, EPRI will continue to track and monitor the development and use of smart city technologies in a range of applications and cities.

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Marine industry

CORE POWER - Nuclear for marine applications

History of nuclear technology in marine environments

Nuclear technology in marine environments is predominantly utilised for military applications, powering navies with nuclear-powered submarines, surface vessels, and aircraft carriers. Outside of these applications, nuclear technology has been used to power the floating nuclear power plant Lomonosov, and civil merchant ships beginning in the 1960s, including the American NS Savannah, the German Otto Hahn, Japanese Mutsu, and Russian Sevmorput. All but the Russian vessel have been decommissioned due to challenges associated with cost and efficiency.

Opportunities and enablers for disruption

The development of advanced reactors for marine environments will create entirely new markets for the nuclear industry and will require developing design criteria for unique environmental conditions. As shipping and other energy-intensive industries look to decarbonise, advanced nuclear technologies can ensure that solutions provided are both competitive and sustainable.

The development of small modular reactors (SMRs) has opened the doors to the widespread commercialisation of new nuclear technologies for various industries. These advanced reactors are a fraction of the size of conventional nuclear power reactors. Smaller physical footprints permit SMRs to be sited in locations not suitable for large nuclear plants. The modularity of these new reactor designs also makes it possible for systems and components to be made in factories and then transported to the site for assembly elsewhere. By cutting costs and construction timelines, SMRs can be more affordable than large nuclear reactors.

Moreover, many contemporary SMR designs, particularly molten salt reactors (MSRs) and other non-pressurised reactor technologies, have advanced safety features that can reduce a reactor's emergency planning zone (EPZ) requirements. This innovation allows SMRs to be located closer to the end-users, which leads to reduced heat and/or power losses and reduced infrastructure development needs. Site-bound EPZs allow these new ambient-pressure SMRs to be mobile.

Certain criteria help determine which advanced nuclear technologies are best suited for maritime applications. A reactor design that can operate for long periods between refuelling can prevent the handling of spent nuclear fuels in ports and further mitigates issues related to nuclear proliferation. Second, non-pressurised reactor systems that do not rely on active safety features can shut down automatically in the event of an emergency. These characteristics of walk-away safety are crucial in a maritime environment. Lastly, marine environments require reactor designs that can be made small, mass-manufactured, and type-approved. This will make them affordable and easier to finance while ensuring creation of well-designed and vigorous training regimes for operators and stakeholders.

Two advanced nuclear reactor designs stand out as they meet these three criteria well. Molten Salt Reactors (MSRs) are a possible choice for the very largest ships with a power demand of more than 20MWe performing very long voyages, while Heat Pipe microreactors (HPRs) fit the criteria well for ships with power demand between 5MWe and 20MWe.

Status and opportunities for disruption

As there are multiple advanced reactors that can be used in the marine environment, the technology readiness level (TRL) is dependent on which technology is applied. MSR development is currently at TRL 4, while other reactor designs, such as HPRs, may be at a 6 or 7 TRL.

Research into advanced nuclear reactors for marine environments is ongoing. The Marine Nuclear Applications Group (MNAG) within the Department of Energy's Nuclear Reactor Innovation Center at Idaho National Laboratory, produced reports on *Advanced Commercial Nuclear for Maritime* and *Challenges and Opportunities for Commercial Maritime Surface Vessel Nuclear Propulsion*. Upcoming MNAG reports will focus on the regulatory and licensing landscape and the economic and environmental impacts the technology application will have on both industries. The IAEA has also begun to conduct research on advanced reactors in marine environments. In 2023, they produced a publication on SMRs for Marine-based power plants and are in the process of working with a consultancy on publishing a *Technical Report on Design Safety and Security Considerations of Floating Nuclear Power Plants*. The World Nuclear Transport Institute (WNTI) is a member of both the MNAG and the FNPP Consultancy, as well as hosting their own Maritime Applications and Nuclear Propulsion Working Group that produces research on transportable nuclear power plants in marine environments.

Outside of policies supporting the deployment of advanced reactors and fuel security for said reactors, there are no policies in place specifically focused on the commercial use of advanced reactors in marine environments. CORE POWER is involved in various research and development opportunities surrounding marinised advanced nuclear reactors. In 2023, CORE POWER reached the USD 100M funding milestone and plans to utilise that funding for collaborations with various stakeholders, including reactor developers, research institutes, and government agencies on further R&D.

Value and impact of nuclear in the marine sector

The International Maritime Organization has received unanimous approval from its member states to mandate a 50% reduction in greenhouse gas (GHG) emissions from shipping, compared to its 2008 total, by (or around) the year 2050. This means an actual GHG emission reduction of almost 90% by 2050. MSRs are the most suitable technology to achieve this goal. Not only do they offer the option of generating the fewest direct and indirect emissions, both at sea and onshore, but MSRs also offer the solution with the lowest private costs over the lifetime of the vessel. In addition, MSRs are great candidates owing to their inherent safety features, meaning that nuclear regulations like emergency planning zones will not conflict with the commercial operations of the vessels. This technology will be revolutionary for shipping, building a new competitive advantage by enabling vessels to go fast for longer with zero fuel price volatility.

Beyond shipping, advanced reactors fit for marine environments can also play a pivotal role in other industries seeking to decarbonise. For example, floating nuclear power plants can supply electricity to the offshore oil and gas projects. Floating nuclear power plants can also provide clean electricity to produce green hydrogen and synthetic fuels, as well as for desalination operations and energy-demanding data centres. Moreover, floating nuclear power plants can be deployed in disaster-stricken areas to instantly supply clean, reliable, and robust energy.

Future opportunities and timing

Commercial nuclear shipping is currently governed by Safety of Life at Sea (SOLAS) Chapter VIII and its supplementary regulation, Resolution A491(XII), *The Code of Safety for Nuclear Merchant Ships*, which was adopted in 1981. These regulations are prescriptive and only address ships using pressurised water reactor (PWR)-type reactors whose turbines directly drive the propellor shafts.

These regulations will require updating to reflect the new technologies and risk-based safety cultures of the 21st century. This process has already begun with significant input from CORE POWER. Our organisation participates in productive discussions with the UK Maritime and Coastguard Agency (MCA), US Coast Guard, other IMO Member States, and IMO NGOs, such as the World Nuclear Transport Institute (WNTI), regarding bringing changes to these regulations to the IMO. Additionally, the Nuclear Energy Maritime Organisation (NEMO) was founded in 2024 to bring together industry organisations with the aim to assist nuclear and maritime regulators in the development of appropriate future-oriented standards and rules for the deployment, operation and decommissioning of floating nuclear power.

CORE POWER is also actively participating in discussions at the IAEA, which is the intergovernmental nuclear regulator, and who is expected to support the IMO with any changes to the maritime nuclear regulations. We estimate that the international regulatory environment will be complete by the time of deployment of the first reactors in ~2030, and we are working at a national and international level to facilitate this. Vessels trading in national waters or floating power stations can operate under individual national regulations as soon as they are implemented.

The timing for implementing nuclear-powered containership technology appears opportune based on several key indicators. Firstly, the market is in a developmental phase investigating several GHG reducing or eliminating technologies, including nuclear. This indicates a growing interest in and potential demand for such innovative solutions. Secondly, this existing demand for decarbonising technologies outweighs the availability, suggesting an untapped market opportunity. Moreover, China's recent announcement of its plans to build nuclear-powered container ships underscores the global momentum towards adopting this technology. Considering these factors and the impact, it seems prudent to explore the feasibility of integrating nuclear-powered container ships into our operations to capitalise on the emerging market trends and gain a competitive advantage.

Value proposition of nuclear-powered solutions

Today, energy in marine environments mainly comes from fossil fuels. Fossil fuelled ships are characterised by low capital expenditure (CAPEX) and very high operating cost (OPEX), and that operating cost will only increase as fossil fuel scarcity increases. Nuclear-powered assets however have high CAPEX and very low OPEX, meaning that these vessels, with a large utilisation factor and a long operating life, will be cheaper to run when powered by nuclear than by both fossil and green fuels.

Historically, civilian nuclear ships suffered from the costs of specialised infrastructure. The *NS Savannah* was expensive as it was the only vessel using specialised nuclear shore staff and servicing facilities. Modular design and factory assembly of nuclear-powered vessels have the potential to considerably decrease time and construction costs, creating economies of scale that mitigate the challenges of operating one vessel over an entire fleet.

Mass production can lead to a reduction in costs. In the operating phase, a larger fleet could share fixed costs among multiple vessels. With regards to the balance-of-plant and platform cost, modular ship-yard construction will enable the nuclear industry to escape the current chronic time and cost inefficiencies typical of on-land nuclear, which can be related to large-scale stick-built prototype construction.

By reviewing similar industries, such as aeronautical, where large-scale technologically advanced and safety-oriented products have made this transition from 1st-of-a-kind to nth, CORE POWER modelling suggests that adopting this manufacturing process will reduce construction costs by approximately 20-50% compared to first -of-a-kind, with the potential to exceed this.

Further reading

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Idaho National Laboratory - Multi-industry disruptive progress utilising advanced nuclear-maritime applications

Sanjay Mukhi

Abstract
Advanced nuclear holds promise for disrupting maritime applications by offering expanded vessel range and sustainability, while reducing reliance on fossil fuels. There have only been only a handful of civilian vessels to harness nuclear technology, including:

- **United States:** The NS Savannah, a cargo and passenger vessel operating from 1962–1972, fitted with 74 megawatts-thermal (MWth) power.
- **Germany:** The Otto Hahn, a cargo vessel operating from 1968–1979 with 38 MWth power.
- **Japan:** The Mutsu, the general cargo vessel, which faced public objections that prohibited the carriage of cargo (1972–1996), was installed with 35 MWth power.
- **Russia:** The nuclear icebreaker fleet began with the Lenin, launched in 1957, and grew to a fleet of seven modern vessels owned and operated by the state agency Rosatom. These vessels serve necessary ice operations and navigational support in the Arctic. The cargo vessel Sevmorput is installed with 135 MWth to assist with ice operations in the Arctic.

By using advanced reactors on a range of vessels classes, opportunities exist to decarbonise a variety of industries and develop new revenue generating pathways. The National Reactor Innovation Centre (NRIC) is developing test beds that will enable the implantation of these advanced nuclear reactor concepts. Currently, NRIC is developing engineering requirements necessary for a testing platform to aid in the testing of reactors for maritime applications. Additionally, NRIC and INL are supporting the American Bureau of Shipping with a DOE iFOA exploring these concepts as well as two Nuclear Energy University Program (NEUP) Awards focused on maritime nuclear.

Progress is being made domestically and internationally on maritime nuclear. NRIC hosts the Maritime Nuclear Applications Group (MNAG), which brings together industry members from over 120 different organisations. The group drives new research and acts as a resource hub for those interested in developing maritime nuclear applications. The Department of Energy has been funding maritime nuclear research and the MNAG. Regulatory feasibility poses a significant hurdle, which is being examined by MNAG and continued work will need to be done in the domestic and international regulatory space to allow this technology to move forward.

This disruptive technology decarbonises vessels that use dirty bunker fuels. This technology also enables ships to put energy back on the grid while at port, improve global commerce and supply chain efficiencies by enabling ships to move faster. It supports desalination, allowing for more efficient data centres that are on floating barges, and it enables decarbonising dredging activities and the offshore oil and gas production industry.

There are upwards of thousands of reactors that could be deployed to decarbonise a wide variety of maritime industries by 2050 if the technology is developed, which would enable a large reduction in greenhouse gases from a variety of coastal industries.

This technology would improve global commerce, increase energy on the grid, increase desalinated water, and enable black-start capabilities for coastal communities suffering from natural disasters.

Oil and gas companies are currently looking to decarbonise their offshore assets, which advanced nuclear reactors could support. Within the next decade, many vessels will need to be decommissioned and vessel owners and operators are asking if nuclear powered vessels will be ready now so they can make investment

decisions. Investment decisions will also be tied to how competitive this technology is with the cost of fuel. If the cost of fuel goes down, it makes these applications less appealing unless there is a large carbon tax or if there are investment tax credits. We have broadly evaluated these economic conditions to determine break-even costs for this disruptive technology to take hold in the market.

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Mining industry

Saskatchewan Mining Association – Mining end user point of view on SMRs

Abstract

The Saskatchewan Mining Association (SMA) represents the mining and exploration sector in Saskatchewan and our members recognise and support the reduction of Canada's Greenhouse Gas (GHG) emissions. The SMA is a signatory to Canada's Small Modular Reactor (SMR) Action Plan and is strongly supportive of the collective efforts of all parties to develop and deploy SMRs in Saskatchewan. With an existing federal *Reduction of Carbon Dioxide Emissions from Coal-fired Generation of Electricity Regulations* and a newly proposed federal *Clean Electricity Regulations (CER)*, Saskatchewan will need to replace approximately 3 600 MW of carbon-based electricity generation with non-emitting generation by 2035. As a result of these material changes to our electricity supply, Saskatchewan's mining sector faces significant cost and operational challenges over the coming decade(s). This brief will explore, from an end-user point of view, the reciprocating disruption of the SMR industry, supply chain, and the mining sector.

Introduction

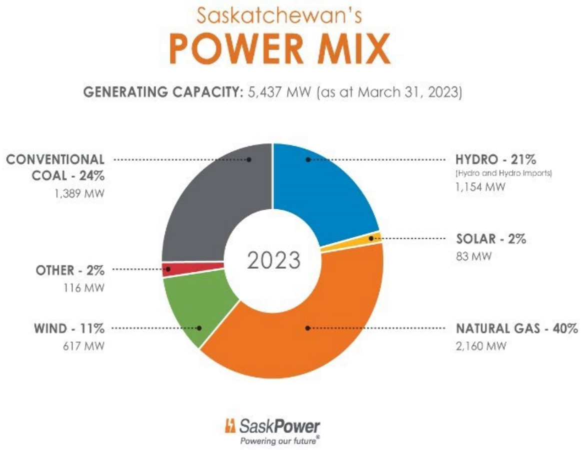
The Saskatchewan Mining Association (SMA) is the voice of the mining industry in Saskatchewan and has the role of liaison and consultant with government and the public to ensure the safe, profitable and sustainable development of the mineral resources of the province. The SMA represents over 45 mining and exploration companies. Environmental protection and stewardship are important to SMA members as demonstrated by their commitment to environmental planning, monitoring, compliance and reclamation. Our members are also among the largest industrial employers of Indigenous people in Canada.

In 2022, Saskatchewan's mining sector claimed the top spot in Canada in terms of mineral production value, reaching CAD 19.5 billion. The province's potash industry held the global lead with 37% of worldwide sales, while its uranium sector ranked second globally with 15% of uranium sales.

Annually, our industry contributes roughly CA$2 billion in federal and provincial royalties and taxes, constituting about 12% of Saskatchewan's GDP. Notably, Saskatchewan boasts deposits or occurrences of 23 out of 31 of Canada's critical minerals, which are essential for the nation's transition to a net-zero economy by 2050.

The SMA and its members endorse efforts to reduce greenhouse gas emissions in Canada. We believe that nuclear power, along with Direct Air Capture (DAC) Carbon Capture and Storage (CCS) and Carbon Capture Utilization and Storage (CCUS) technologies, will be pivotal in meeting the requirements of Canada's proposed CER. However, this transition must be conducted reasonably and economically. Recognising that 84% of Canada already relies on non-emitting electricity sources, we acknowledge that regions like Saskatchewan, constrained by geographical factors and reliance on coal and natural gas for approximately 64% of Saskatchewan's generating capacity (see Figure 4.3) will require a longer timeline and increased financial support from both federal and provincial governments to transition our grid to non-emitting sources.

Figure 4.2 SaskPower Energy Supply Mix



Source: SaskPower

Possible applications for SMRs

The Government of Saskatchewan has identified that approximately 3 500 megawatts (MW) of existing baseload electricity comes from emitting sources and they project that an additional 7 000 MW will be required to support Saskatchewan's economy by 2035 (SaskPower, n.d.d). The SMA believes that significant nuclear assets, in the form of SMRs, will need to be deployed to deliver safe, reliable, and affordable baseload power. Significant efforts by all levels of government, with support from industry and the public, will be needed to deliver the non-emitting electricity a net-zero economy demands.

Application of SMRs in Saskatchewan's mining sector

The mining sector in Saskatchewan will be both a disruptor as well as being disrupted by the introduction of SMRs. They will be disrupted in that baseload power, provided by the utility provider (SaskPower), will transition from emitting sources (coal and natural gas) to nuclear as well as increased deployment of renewables, geothermal and battery storage operations. They will act as the disruptor in that mining will be able to take advantage of both the heat and power provided by SMRs, which hasn't been the case to date.

Use of nuclear heat in mining
Saskatchewan's solution potash mines currently utilise natural gas in large boilers to generate onsite electricity and use the waste heat to increase the temperature of salt brine that is being injected into solution mining caverns that are approximately 1 100 metres below surface to help improve potash (KCl) recovery. Natural gas is also used in product drying and shaft heating. Reducing or eliminating natural gas usage in mining, and in particular solution mining operations, would dramatically reduce GHG emissions.

Use of nuclear power in mining
As large power users (approximately 3.5 TWh/year) Saskatchewan's mining sector provides significant opportunities for SMR vendors in the 100 MWe or less range.

SMRs that provide the flexibility of a combined heat/power option will be of biggest benefit to solution mining/milling operations; however, conventional mining/milling operations would also benefit from this option, albeit with decreased heat demand.

Advantages and disadvantages

Advantages
There appear to be three main advantages related to the deployment of SMRs in the mining sector:

- multiple options for heat/power reactors in the sub-100 MWe range
- scalability of SMR design allows for tailoring of heat/power options as demand changes over the lifespan of the mine/mill
- for remote mining and milling operations, it allows SMRs to be built proximal to the operation.

Although northern operations are all grid connected, they have been impacted during forest fires taking down power poles as well as significant disruptions due to lightning strikes. The Island Falls Hydro Power station to the McArthur River uranium mine and the Cigar Lake uranium mine has 350 km of power lines.

With SMRs there is no need for long linear corridors for power lines so there is less risk of fire and lighting impacts. SMRs could significantly reduce or eliminate diesel backup requirements and enhance the opportunity to electrify mining equipment. Reducing the number of long linear corridors would also be less impactful to the environment, including on Boreal caribou, a threatened species in northern Saskatchewan.

Disadvantages
Because SMRs have not yet been deployed in Saskatchewan or Canada, there are several unknowns, that until we have some operating experience with them, are issues that we see more as uncertainties than disadvantages.

Those include timelines for deployment. Multiple SMR technologies are in the development and CNSC vendor review process. There is currently a lengthy federal impact assessment process for SMRs with a rating of 200 MWt as well as a subsequent CNSC construction and licensing process.

Another is uncertainty with respect to the nuclear supply chain and lack of skilled labour including:

- Cost uncertainty: there is no operational experience with respect to the delivered cost of heat/power.
- Uncertainty related to who will be the owner and/or operator of the SMR.
- Uncertainty around the acceptance of an SMR by the local community and/or Indigenous peoples.
- Reluctance to be first; there is always some increased comfort being able to learn from the experiences of others that go first.

Challenges and enablers

International
In addition to increasing national support for nuclear energy, there was clear support for nuclear at COP28 in Dubai when they included nuclear as one of the solutions to climate change in the First Global Stocktake document. (United Nations, 2023)

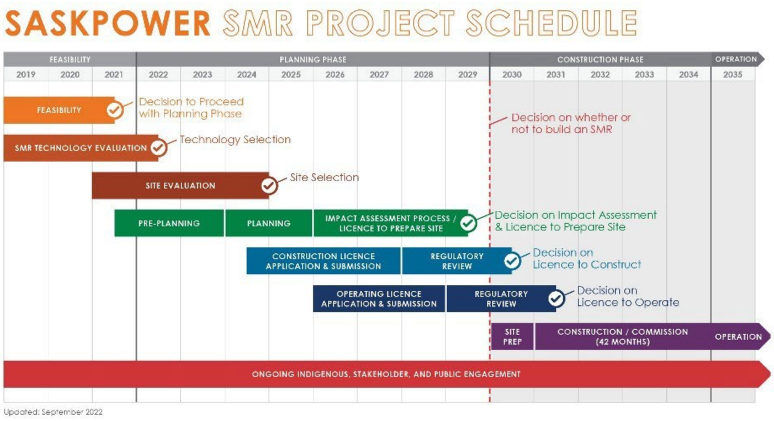
National
The SMA currently sees the Government of Canada as being both an enabler and obstacle to responsible, rapid deployment of nuclear in Canada. From an enabling standpoint, Natural Resources Canada has been a champion of nuclear and has worked to foster an environment that supports nuclear development and deployment. The Canadian Nuclear Safety Commission (CNSC) has stepped up their regulatory game to help ensure that SMR designs are reviewed in a responsible and timely fashion, and we expect that they will put similar effort into ensuring that construction and operating licensing proceeds in a like manner.

The obstacle continues to be an overly onerous and time-consuming environmental impact assessment process. The SMA has recommended to the Impact Assessment Agency of Canada (letter from B. Sigurdson to T. Hubbard, 16 February 2024) that the environmental assessment process be delivered through the provincial *The Environmental Assessment Act (*Government of Saskatchewan, n.d.) and that licensing should be carried out by the CNSC, a world-recognised leader as a lifecycle regulator of both uranium mining as well as nuclear power generating facilities.

Provincial
The Government of Saskatchewan has been very supportive of the opportunity to deploy SMRs in Saskatchewan through the utility provider (SaskPower). Although Saskatchewan is a premier uranium mining jurisdiction, we have limited experience with nuclear reactors. The Saskatchewan Research Council's (SRC's) SLOWPOKE-2 nuclear research reactor was safely and successfully decommissioned after 38 years of successful operation with decommissioning being completed in 2021 (CNSC, n.d.).

In 2019 the governments of Saskatchewan, Ontario and New Brunswick signed a Memorandum of Understanding (MOU), which commits the parties to collaborate on the development and deployment of innovative, versatile and scalable nuclear reactors (i.e. SMRs) (Government of Saskatchewan, 2019). A strategic plan to advance SMR reactor deployment was released in 2022. It included the province of Alberta as a signatory in addition to Saskatchewan, Ontario and New Brunswick.

Figure 4.3 SaskPower SMR Project Schedule



Source. SaskPower, n.d.b.

The evaluation of the feasibility of deploying SMRs began in 2019 by SaskPower and it has selected GE Hitachi's BWRX-300 as the grid-scale SMR that could be operational somewhere between 2034-2035 (see Figure 4.4)

Financing

Implementing the CER in Canada will significantly raise electricity costs, particularly in Saskatchewan. The capital cost for CER compliance in Saskatchewan is projected at $46 billion, making it one of the most heavily impacted jurisdictions due to its unique grid characteristics and Indigenous population, especially in the northern regions (SaskPower, n.d.d). As one of the major customers of SaskPower it is only reasonable to anticipate that the mining sector will bear a significant cost burden in the form of increased power rates in the future.

The federal government is providing some funding for nuclear and has recently recognised nuclear as an eligible green expenditure under the Green Bond Framework which is helpful (Government of Canada, 2023).

However, the government has failed to include nuclear in the recently announced federal clean hydrogen tax credit, which has been proposed to bolster investment in clean energy (Konopelny, A., Collopy, T., 2024). With the natural synergies between non-emitting nuclear energy and the production of hydrogen, this is disappointing.

Supply chain

As Canada accelerates its transition to clean energy, addressing supply chain and resource issues becomes imperative. There is already a global shortage of critical parts for power generation technologies exacerbated by the increasing adoption of clean energy solutions worldwide. This shortage could worsen as more countries embrace clean technologies, underscoring the need for proactive measures to mitigate supply chain disruptions.

Engagement

SaskPower undertook an extensive regional evaluation process (REP) centred on two possible locations for the BWRX-300 reactor(s). This was a well-executed process that actively sought the input of all stakeholders and rightsholders. Based on a survey of participants, the REP was deemed to be successful, and SaskPower will continue to engage stakeholders and rightsholders throughout the environmental assessment, licensing, and lifecycle phases. (SaskPower, n.d.c)

Workforce

The provincial Crown Investments Corporation (responsible for SaskPower) commissioned a study in 2023, which was presented at the 6 November 2023, Nuclear Workforce Leadership Forum. This report highlighted factors and trends, including the increasing national and international competition for labour talent. This competition for labour talent is not isolated to one occupation but spans all occupations. This poses a significant risk to the timely deployment of new nuclear assets in Saskatchewan and across Canada.

Conclusions

The SMA and its members support Canada's efforts to achieve a net-zero economy by 2050 and believe that government should be technology-agnostic with respect to how jurisdictions within Canada work towards decarbonising both their electrical grids, as well as hard to abate sectors such as mining.

While we believe that nuclear will play a large role in decarbonising the economy, we also recognise that this is not a short-term proposition and that significant efforts will need to be made by all parties to ensure the safe, responsible and timely deployment of this important technology.

In the near-term (i.e. prior to deployment of SMRs), we have recommended to government that fossil fuel generation should not be excluded from electricity generating options providing the electricity grid achieves net-zero requirements through mechanisms like DAC, CCS, CCUS, natural offsets, and others.

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Non-electric applications

Generation IV International Forum (GIF) - Generation IV reactors and innovations for non-electric applications of nuclear heat

Introduction

Established in 2001, the Generation IV International Forum (GIF) is a co-operative international endeavour bringing together 13 countries, as well as Euratom (representing the 27 European Union members), to co-ordinate research and development on advanced nuclear energy systems and make them available for industrial deployment by 2030.

GIF provides a forum for collaborative R&D on six reactor concepts and a variety of cross-cutting issues. The six reactor concepts, also known as Generation IV (Gen IV) concepts, are: gas-cooled fast reactor, lead-cooled fast reactor, molten salt reactor, sodium-cooled fast reactor, supercritical water-cooled reactor, and very-high-temperature reactor. The priorities for GIF in the near-term focus on accelerating the readiness of fourth generation nuclear systems to meet net-zero targets.

In 2002, GIF released the Gen IV Roadmap, which identifies potential applications for these reactors in addition to electricity production, including desalination, district heating, hydrogen production, and high-temperature process heat. A collaborative research and development project focused on hydrogen production using the VHTR system began in 2008. A dedicated cross-cutting task force was established in October 2021 to address non-electric applications of nuclear energy broadly. This Non-Electric Applications of Nuclear Heat Task Force (NEANH TF) aims to provide its members and other stakeholders with the appropriate knowledge and access to innovative energy system design, analysis, and optimisation tools to allow decision makers to find optimal energy system solutions for different socio-economic and geographical contexts.

The NEANH TF is currently working to advance several initiatives to explore the opportunity for non-electric applications and hybrid systems, which leverage and integrate multiple energy sources with multiple energy demands. This has included developing and maintaining a database of relevant studies and activities and developing a network of energy end-users beyond the nuclear sector who may benefit from fission-generated heat and electricity. The Task Force is currently working to advance techno-economic analysis of coupled systems to understand the economic opportunity, readiness, and timelines for these systems.

Motivation for using nuclear energy for non-electric and hybrid systems

Since the selection of the six Gen IV systems, new challenges have arisen in the energy production sector, and the understanding of energy systems and the potential role of nuclear energy has largely evolved during the last 20 years with governments globally working to ensure security of energy supply and to drastically reduce CO_2 emissions. The urgent need to address climate change and enhance the security of energy supply serves as a critical motivation for innovation in the nuclear energy sector given its benefits around deployment flexibility and product flexibility.

The decarbonisation of electricity generation alone is insufficient to meet the challenging CO_2 emission reduction targets. Energy demand from the industrial and the transportation sectors are evolving and offer significant potential for further emission reductions through the direct use of nuclear-generated heat or process intermediates that may be produced using nuclear heat and electricity (GIF, 2022b).

Nuclear energy has been used for some non-electric industrial applications for several decades (IAEA, 2017), but these systems have faced strong economic competition, particularly from inexpensive natural gas in the absence of emissions restrictions or carbon taxes. Natural gas prices are highly volatile in many jurisdictions, triggering strong interest in alternatives. Natural gas combined with carbon capture, utilisation, and storage (CCUS) also faces challenges in a future decarbonised world due to life cycle emissions associated with upstream methane leakage.

Consequently, the economics of nuclear energy systems must be re-evaluated to consider new constraints and parameters (NEA, 2022). The near future will be characterised by a rapid evolution of energy supply strategies to meet increasing worldwide energy demand, while simultaneously taking steps towards lifecycle decarbonisation of all the energy supply chains and infrastructures.

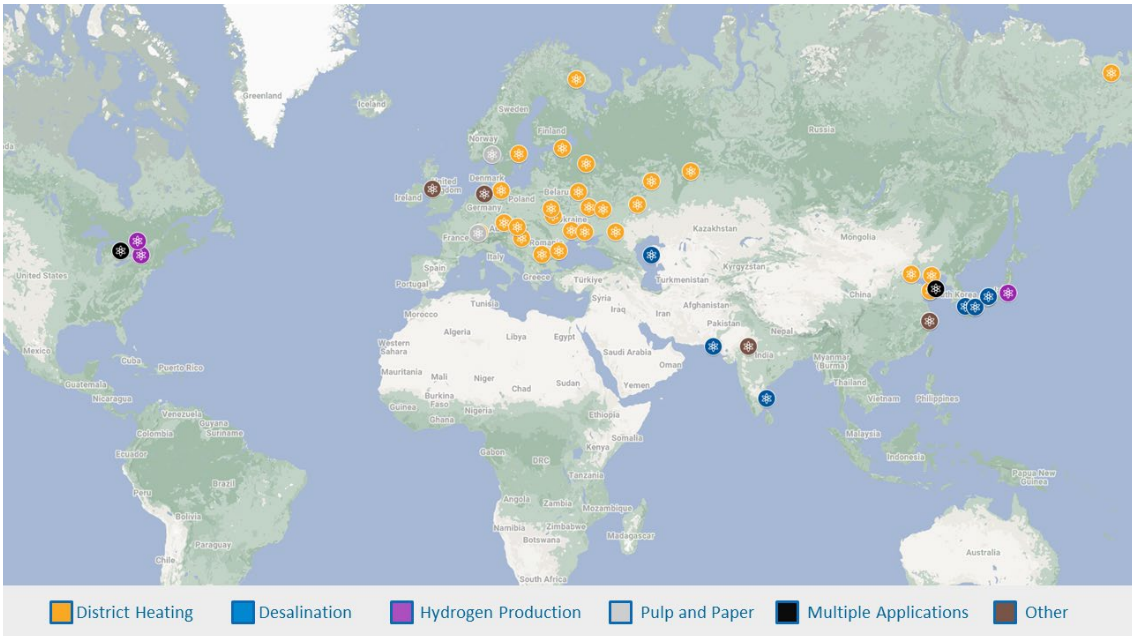
History of nuclear energy for non-electric applications

There is experience in the use of nuclear energy in off-grid and co-generation applications, as well as in hybrid systems that leverage multiple generation systems to support multiple energy demands. These past examples have been characterised by the NEANH TF and other international organisations (e.g. through the Power Reactor Information System (PRIS) database (IAEA, 2023) developed and maintained by the IAEA).

Historical data reveals that more than 750 reactor-years of experience using nuclear energy for non-grid applications, primarily using water-cooled reactor technologies. This represents less than 0.5% of the total nuclear thermal output generated by the global fleet of over 440 reactors.

- **District Heating:** Approximately 43 reactors have contributed to district heating solutions, accumulating around 500 reactor-years of experience. These reactors have typically provided an average of 5% of their thermal output for heating, with the capacity ranging from 5 to 240 MWth and temperatures typically below 150°C.
- **Desalination:** At least 17 nuclear reactors have been used for the commercial desalination of water for community use, amassing roughly 250 reactor-years of operational experience. These installations have predominantly utilised thermal processes like multi-effect distillation and multi-stage flash distillation, operating at temperatures below 130°C.
- **Industrial Process Heat:** A small number of reactors have also been used for industrial heat applications, including a salt refinery from the Stade PWR in Germany, a cardboard factory from the Gösgen site in Switzerland, a fuel plant at the Calder Hall MAGNOX facility in the UK, and heavy water production and other applications at Bruce Power in Canada.

Figure 4.4 Geographical distribution of past or existing demonstrations or commercial systems where nuclear heat has been applied to non-electric applications



Source: GIF, 2024.

Through an extensive review of existing literature, the NEANH TF has also identified more than 60 studies or reports with varied analysis on global heat markets, as well as the use of nuclear energy to support hydrogen production, oil and gas, mining, synthetic fuels production, district heating, chemicals manufacturing, desalination, and co-generation applications broadly.

In recent years, there has been renewed interest in using nuclear energy for non-electric applications, including among industrial end-users of heat. The NEANH TF and other related international initiatives are reviewing this historical context to understand the opportunity to advance innovation in the nuclear sector to respond to the urgency and scale of the challenge to achieve global CO_2 emission reduction targets. Ongoing efforts will benefit from past initiatives which explored the opportunity for nuclear energy to support non-electric applications, including the Next Generation Nuclear Plant (NGNP) Industry Alliance established in 2010, and the EUROPAIRS (End user requirement for process heat applications with innovative reactors for sustainable energy supply) project funded by the European Commission in 2009.

Global activity and considerations for non-electric applications and hybrid-energy systems

The NEANH TF is among several domestic and international working groups or collaborative efforts that have been established to explore the opportunity to use nuclear energy for non-electric applications and in hybrid energy systems.

At least 25 relevant international or domestic initiatives have been identified, with a notable focus on using nuclear energy to produce hydrogen. Other groups exist with a targeted focus on oil and gas applications, desalination, and others. The NEANH TF is working to stay aligned with other international initiatives to leverage overlapping mandates related to this area of work.

Modelling tools to support the exploration and evaluation of nuclear heat applications are also being developed by national laboratories and other interested parties globally. The NEANH TF has identified 13 modelling tools with relevance to hydrogen production, desalination, and general cogeneration, which are being used to assess the feasibility, efficiency, and environmental impact of integrating nuclear technology with these various energy systems.

These activities have helped to identify a range of challenges or uncertainties that may also exist when implementing NEANH systems. For instance, there may be additional costs, or hazards, associated with coupling reactor systems with industrial applications, both of which have distinct regulatory structures. There may also be conflicting priorities for heat utilisation between the coupled industry's needs and electricity demand. Communication will be essential to ensure that relevant parties have the data and information they need to make informed decisions. This includes technological suitability, but also an understanding of system costs and regulatory or waste management processes (GIF 2022b).

In addition to the significant interest in non-electric markets that has arisen through the development of Gen IV reactors and small modular reactors (SMRs), several planned demonstrations or commercial systems are also underway, signalling strong interest and investment in the field.

Demonstration projects of non-electric systems around the world include:

- The Tianwan Nuclear Power Plant in China that is aiming for steam integration into petrochemical manufacturing within the year.
- Multiple hydrogen production demonstrations at the Nine Mile Point, Davis–Besse, and Prairie Island nuclear power stations in the United States by 2024.
- Various international projects across the UK, Korea, Japan, Canada, and Argentina, which are set to showcase the application of Gen III and Gen IV technologies in desalination, hydrogen production, and chemical manufacturing processes.

GIF activities for Generation IV nuclear technologies for non-electric applications and hybrid energy systems

Through the NEANH TF, GIF is working to identify and overcome challenges associated with deploying Gen-IV technologies for non-electric applications from a range of technical, economic, regulatory, and societal perspectives.

To inform these solutions GIF is engaging directly with industry, including both the nuclear sector and potential end users of heat. In October 2022 a full-day in-person workshop was held in Toronto, Canada, to connect GIF to the high temperature community outside the nuclear field.

The event was well-attended with more than 150 participants including Gen IV reactor developers, energy system modellers, industrial energy users, researchers, and other stakeholders (GIF, 2022a). A follow up workshop is taking place in April 2024, in Busan, Korea, in close co-operation with the Korea Atomic Energy Research Institute on the margins of the 39th Korea Atomic Power Annual Conference.

The NEANH TF is also engaging more broadly with other related stakeholders and the public. In 2023, the Task Force completed the initial NEANH Database, a global repository of activities relevant to non-electric applications coupled with nuclear energy systems. It includes studies, collaborative initiatives, past or existing demonstrations or commercial systems, planned systems, and modelling tools. The NEANH TF is currently working to convert the database into a digital database hosted on the GIF website to improve user experience and data accessibility to allow additional items to be submitted by stakeholders for review and inclusion.

Presently, the Task Force is conducting system analysis and evaluating key performance indicators for nuclear energy systems connected to non-electric applications. This analytical work aims to include both a subjective analysis of system readiness and provide an evaluation of relevant systems through modelling and expert insights. The initial focus is on the potential for a high-temperature gas-cooled reactor to produce hydrogen through high-temperature steam electrolysis. In the future, additional systems and Gen IV reactor technologies will be similarly explored.

Finally, the NEANH TF is working to make necessary information available to regulators globally to inform domestic regulatory decisions on non-electric and hybrid applications of nuclear energy. NEANH TF will continue working with international partners to advance this work and look for additional opportunities to share information and analyses related to non-electric systems for innovative nuclear energy technologies.

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Idaho National Laboratory - Impact of industrial sectors on the nuclear industry (nuclear beyond electricity)

S.M. Bragg-Sitton

Electricity demands in developed countries around the world account for approximately one-third of overall energy use and one-third of CO_2 emissions. As such, providing clean energy to support the electricity grid is an essential step towards a decarbonised future, but that is just Step 1.

Increased electrification of industry and transportation will support further decarbonisation, but not all industrial processes and transportation sectors (e.g. heavy-duty trucking, aviation, maritime) can or should be electrified when energy use efficiency, resource limitations, and space limitations are considered.

Most energy demands traditionally have been met via generators that support a single energy sector. Nuclear energy, for example, has mostly supported electricity production, with limited examples in which nuclear fission systems have supported other sectors. However, nuclear energy primarily produces heat from the fission process. That heat is carried by a working fluid (e.g. steam) to a turbine for electricity production at an efficiency of 30-40%.

The chemicals and fuels industries draw some electricity from the grid, but most large industrial facilities independently co-generate heat and power using fossil resources to support their energy demands, contributing to approximately 20 percent of CO_2 total emissions. Many of these processes require heat or steam rather than electricity, as such, efficiencies could be significantly impacted if electrification routes alone are selected.

The transportation sector contributes most of the remaining emissions. In recent years the transportation sector has been more directly linked to the grid with the increasing adoption of electric vehicles, but it is still responsible for more than one-third of CO_2 emissions.

The prevailing low-carbon generation sources for electricity, industry, and transportation ultimately will come down to economics, but it is increasingly clear that options analysis should include not only the energy intensity, reliability, resilience, and security of generation sources but also the associated energy storage needs and cross-sector energy supply possibilities. Nuclear energy resources that produce both heat and electricity can both support the grid and divert energy to a secondary, off-grid electricity or thermal energy user.

Abating emissions from industrial processes presents a greater challenge than decarbonising the grid due to limited options for non-emitting sources of heat. Electrification may help (assuming electricity is sourced from non-emitting generators, including nuclear), but some processes require a direct heat source to maintain efficiency and economic competitiveness.

Similarly, today's transportation sector primarily relies on internal combustion engines that use liquid fuels. Although most light-duty electric vehicles (i.e. passenger vehicles) can switch to plug-in batteries with the build-out of charging infrastructure, and electric buses and trains can support commuter systems, heavy-duty transport vehicles, maritime vessels, and aircraft cannot be easily electrified. For these vehicles, hydrogen fuel cells or synthetic liquid fuels produced with renewable carbon sources can significantly reduce greenhouse gases (GHGs) and other pollutants. These options will further increase the demand for non-emitting thermal and electrical energy sources.

An integrated energy system (IES) can offer non-emitting energy solutions that leverage desirable attributes of each energy resource. This could include a shift from the single-output systems commonly used today (e.g. generators operating independently to support electric grid demand) to other configurations, such as multi-input multi-output systems integrating multiple resources to provide both heat and electricity to multiple energy users (Arent et al. 2021). While some CO_2-emitting multi-output (cogeneration) systems are in operation today, IES development efforts focus on providing heat and electricity to multiple energy users without CO_2 or other GHG emissions.

Nuclear energy is the primary source of non-emitting thermal energy and can flexibly provide clean heat and electricity to hard-to-abate industrial processes. Deploying nuclear and renewables in a more tightly co-ordinated, integrated approach can link energy demands across the electric, industrial, and transportation sectors to optimise energy generation and use, maintain the grid reliability and resilience offered by thermal generators, and support decarbonisation of industry and transportation.

This section discusses key opportunities for innovative use of nuclear energy to support the current and future growing energy demands beyond the grid. Many of these applications can directly leverage the high-quality heat and steam from nuclear fission systems, in addition to providing reliable, resilient electricity. The advent of advanced, high temperature nuclear energy systems and modular reactors that can be deployed at a range of power levels and have multiple units further refine the ability of nuclear energy to support the wide range of growing energy demands.

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Space industry

Canadian Space Agency - Pioneering Lunar Sustainability with Nuclear Power: Advancing Innovation and Leadership in Space and Earth Applications

Abstract

The sustainable exploration of the Moon necessitates reliable power sources to endure prolonged periods during lunar nights. Nuclear power, specifically fission systems, has emerged as a promising solution to this challenge. With its high energy density, nuclear technology offers a dependable and sustainable energy source, overcoming the limitations of solar arrays and batteries. Businesses may capitalise on this emerging market, offering technological developments and operational services tailored to lunar energy needs. Opportunities span from technology development for deep space missions to operational services providing power on the lunar surface. Canada, with its expertise in nuclear science and technology, is conducting preparatory activities to explore leadership in this frontier, leveraging synergies between space and terrestrial nuclear sectors. The development of a lunar nuclear power system not only fosters economic growth and international collaboration but also advances research and commercialisation efforts on Earth, particularly in the realm of micro/small modular reactors (MNRs and SMRs). This initiative propels Canada towards a cleaner and more sustainable energy future while strengthening its position as a global leader in nuclear research, innovation, and space exploration.

Introduction

Space nuclear power systems (SNPS) have been used in the past 60 years to advance space and planetary exploration and knowledge of our solar system and beyond. With proven reliability and longevity, SNPS have been the standard for over six decades of nuclear-enabled space exploration to overcome limitations of alternative power systems such as solar arrays or batteries. Humanity is poised to embark on a new age of space exploration creating a global demand for SNPS technologies to be developed to make interplanetary missions faster, more efficient and economical. SNPS have been receiving increasing attention and funding through space agencies to enhance existing capabilities to develop new technologies (i.e. increase technology readiness levels) that would enable never-before achieved feats such as long-duration human lunar missions.

The sustainable exploration of the Moon will require reliable sources of electrical and thermal power. While solar energy represents a viable technology, it will not be sufficient to survive extended nights on the lunar surface, which can take up to 14 continuous days. Nuclear power, particularly fission power systems, present a promising technology to survive these lunar nights while providing reliable, safe, and sustainable power.

Due its high energy density, nuclear technologies can overcome limitations of alternative power systems such as solar arrays or batteries. Moreover, nuclear power sources can provide the energy required to operate rovers, research equipment, commercial activities, and other systems on the lunar surface, maintain lunar habitats, and conduct energy-demanding activities such as space mining. As such, nuclear power is considered a key technology to enable a sustained human presence in space (ISECG, 2018).

The business model and market are expected to be defined by technology development (for space and/or terrestrial applications) and by services offered on the lunar surface. In a lunar economy, end-users could range from government agencies and space agencies to private enterprises and research institutions. Specifically, for lunar nuclear power systems:

- **Technology development:** Space business opportunities would originate from technology development for lunar and planetary exploration missions. This could involve the sale of a complete nuclear system, or its related technologies/subsystems for other deep space exploration missions to other locations on the Moon or on Mars, for example.

- **Energy production and distribution as a service:** Business opportunities could arise from the provision of operational services using the fission nuclear power system. Operators could charge based on a per-watt usage to clients and users on the lunar surface, following a similar model as terrestrial power plants.
- **Spin-off technologies into terrestrial markets:** Developing a lunar nuclear power system will help boost research and development in micro/small modular reactor (MMR/SMR) technologies, thus supporting its potential for expanded use in terrestrial settings. Commercial return in the terrestrial market could take the forms of sales of the system and licensing of the technology.

SNPS are disruptive to the nuclear industry because the environments in space are technically challenging and differ substantially in their fundamental conditions such as gravity, temperature, and pressure. In addition, the launch of such technologies requires stringent safety features to protect the Earth and its population while maintenance opportunities in space are minimal and costly. These challenges drive the complex designs of space fission reactors and radioisotope power systems, which differ from terrestrial designs. This will challenge the nuclear industry to develop novel space-ready technologies based on existing terrestrial applications. These challenges will create greater opportunities for terrestrial organisations in the private sector which will be disruptive to the nuclear industry. As a result, the implementation of SNPS will not be solely driven by government. It will be strongly supported by the private sector with potentially greater long-term investments from industry as space nuclear capabilities continue to mature in Canada.

To mature Canada’s expertise and prepare for a potential major contribution of delivering a nuclear power system on the Moon, the Canadian Space Agency (CSA) is undertaking preparatory activities with federal government partners, Canadian industry, R&D organisations, academia, and international space agency partners.

Possible applications

Radioisotope production for radioisotope power systems

Radioisotope power systems (RPS) provide the necessary power for spacecrafts over many decades and supply long-term heat or electricity in the cold temperatures of space, without any maintenance. RPS are considered a critical technology for spacecrafts and rovers to survive the lunar night, providing sufficient heat and electricity to vital systems.

There is a growing global demand for radioisotopes including Plutonium-238 (Pu-238) to support future deep space exploration missions. For example, radioisotopes are used in RTGs (Radioisotope Thermoelectric Generators) and RHUs (Radioisotope Heater Units) as part of RPS in rovers and spacecrafts.

The report of the Nuclear Power and Propulsion Gap Assessment Team (NPP GAT) (ISECG, 2023) speaks to the importance of supplemental Pu-238 production and how Canada Deuterium Uranium (CANDU) reactors can be used to support the irradiation of source material to produce Pu-238 for use in RPS. While other international suppliers of Pu-238 may be at capacity in terms of their production capabilities, Canada is well positioned to enter this niche area of nuclear power generation and supply Pu-238 isotopes using its existing nuclear reactors and isotope production infrastructure.

Nuclear fission surface power

CSA is currently engaging in preparatory activities and conceptual studies for the development of a micro modular reactor (MMR) that will provide fission surface power to enable the exploration of the Moon and Mars and to support a sustained human presence. Fission surface power reactors can provide electrical and thermal power for a period spanning over several decades. Use cases include supplying electricity for spacecrafts, rovers, science missions, and communication systems, as well as providing heat to habitats, space mining activities, and other systems to survive the harsh lunar night.

Advantages and disadvantages

Space nuclear power systems will allow for the investigation of major and direct spin-off benefits for terrestrial use (e.g. reactor deployment, industry systems, spin-in applications, remote community grid support). Moreover, the Government of Canada is targeting to achieve net-zero emissions by 2050 with the development and deployment of sustainable and clean energy sources (Government of Canada, 2023). Nuclear energy systems such as MMRs and SMRs, are considered a zero-emission clean energy source and given synergies with space energy needs, will consequently play an integral role in addressing climate change in Canada (e.g. Northern Canada) and on Earth.

Pursuing space nuclear power sources will further strengthen Canada's expertise in the nuclear industry and will develop the talent pool in Canada. From a commercial perspective, there are benefits to the commercial sector in Canada which allows industry an opportunity to enter new revenue streams.

Although many benefits exists for pursuing SNPS in Canada, developing a nuclear power system will require a high level of investment. Given the novelty of SNPS, it is anticipated that these projects would be at risk for costly overruns and delays. In the case where the system is developed with international partners, there are also significant financial risks arising from schedule delays caused by budgetary obstacles among mission partners. In addition, there are technical risks with SNPS as a high degree of uncertainty exists regarding whether terrestrial reactor designs used in Canada can be adapted to a space environment due to a variety of factors (weight limitations, fluctuating temperature profiles, etc.) (Euroconsult for the Canadian Space Agency, 2022).

Challenges and enablers

There are several potential interrelated risks and challenges for the development of a lunar nuclear power system. The specific risks vary depending on the development approach of nuclear capabilities (i.e. adaptation of a foreign design, or development of a domestic concept). The list below provides a qualitative assessment of the risks that could arise in developing such a system:

Technical
Considerable technical challenges associated with the development, launch, and deployment of a space nuclear fission system, including operating a system in a harsh space environment, mass limitations, autonomous operation, and waste management.

Financing
Developing a nuclear power system will require a significant level of investment and may originate from both public and private organisations.

Regulatory and legal
Domestic frameworks need to account for space nuclear power systems informed by international guidance on space nuclear power systems. Launch authorisations for nuclear power systems may need to be developed/aligned.

Deployment
International partnerships required depending on the domestic launch capabilities.

Conclusions

Space nuclear power systems provide disruptive technologies and business models to the nuclear industry. Expanding into a new era for space exploration will depend on high-energy solutions to power deep space vehicles, operate in harsh environments, and increase mission flexibility. These innovative nuclear technologies are required to make advances in scientific objectives and human exploration.

Nuclear power is a key core capability to enable sustainable lunar activities. The plans from space agencies and commercial organisations for future crewed and robotic missions to the Moon will raise power demand. Nuclear power, particularly fission power systems, present a promising supplement to survive lunar nights and supplement solar power. As a Tier 1 nuclear nation, Canada has a long-standing leadership in nuclear science and technology for terrestrial applications. The country could leverage the potential synergies between space and terrestrial nuclear sectors for the development of the system.

There are high potential benefits for Canada that could stem from the development of a lunar nuclear power system. It would foster new commercial partnerships, nurture international collaboration, promote economic growth, and strengthen Canada as a world leader in research, technology, and innovation. The development of the space system will further push research in nuclear technology and support commercialisation efforts on Earth. SMRs are being pursued in Canada for several applications, such as remote applications and industrial heating. Northern communities would benefit from access to a reliable and clean energy source, thus supporting Canada's vision for clean energy.

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Acronyms

Acronym	Definition
CANDU	Canada Deuterium Uranium
GAT	Gap Assessment Team
CSA	Canadian Space Agency
GER	Global Exploration Roadmap
ISECG	International Space Exploration Coordination Group
MMR	Micro Modular Reactor
NPP	Nuclear Power and Propulsion
Pu-238	Plutonium-238
RHU	Radioisotope Heater Unit
RPS	Radioisotope Power Systems
RTG	Radioisotope Thermoelectric Generator
SMR	Small Modular Reactor
SNPS	Space Nuclear Power Systems

European Space Agency - Nuclear power and propulsion in space

A well-understood non-traditional application of nuclear technology is its use in space exploration. The high power and energy density of nuclear technology makes it ideal for achieving unprecedented performance in a field that is driven by minimising system mass and maximising system performance.

Early application of nuclear technology dates to the 1960s but was limited to the use of heat from radioisotope decay and the deployment of rather limited fission devices in Earth orbit.

Early programmes to exploit the full capabilities of nuclear system, such as the NERVA/ROVER nuclear thermal propulsion programme of the United States have been halted just short of achieving flight demonstration. In the frame of the renewed interest and urgency in space exploration, it is time to solve the imminent transportation and energy challenges on Moon and Mars. The challenging requirements for successful operations in the space environment will drive nuclear systems innovation in the fields of resilient fuel, high-temperature heat exchange, system and shielding mass and more. In this briefing, the case of nuclear power and propulsion in space is addressed.

History of nuclear in space

Nuclear power has been used in space exploration since the 1960s, mainly for radioisotope thermal generators and heater units in the cold, dark environments of the Moon and Mars.

Small fission devices have been used as resilient power sources in Earth orbit. Technology development programmes have been funded continuously since then, albeit on a low level after the mid-1970s.

Recent developments ("Kilopower/KRUSTY" Moon surface reactor and "DRACO" nuclear thermal propulsion demonstrator) in the United States have seen increased investments. In line with the recent trend of commercial space investments, private companies have also shown interest in the technology.

Nuclear, space and enabling disruptors

The challenging requirements of space exploration (both, with and without astronauts) will yield benefits and solutions in lightweight shielding, high-temperature heat rejection, and low-maintenance, which might be less important (and thus less funded) in traditional, terrestrial applications.

Current concepts for nuclear power and propulsion systems for space exploration apply disruptive technologies in:

a. resilient fuel: coated fuel particles
b. material and design solutions for extreme power-dense reactors for nuclear thermal propulsion
c. heat exchange: heat exchangers, and radiators including new materials
d. shielding: application of lightweight materials for neutron shielding e.g. borated polyethylene
e. autonomous and low- (or zero) maintenance operation

Status, next steps and innovation for advancement

Space nuclear reactors are at a technology readiness level (TRL) of nine. But new concepts are at TRL5, with a TRL8 for space nuclear propulsion and new concepts at TRL3.

Studies of low-mass fission reactors for the Moon and Mars surface, nuclear thermal and electric propulsion examples include: Kilopower/KRUSTY (US), Rolls Royce surface reactors (UK), DRACO flight demonstration (US), and ENDURE (ESA).

Relevant policy for advancement includes ESA safety policy on the use of nuclear power in space, UN resolution 47/68.

The International Space Exploration Coordination Group (ISECG) has tasked a Nuclear Action Team (NAT) to facilitate communication between the ISECG member agencies on nuclear power and propulsion technology development programmes. A report on an international technology gap assessment published by the ISECG is available (ISECG, 2023).

Various projects and programmes are funded by NASA, ESA, and other space agencies. Currently, DRACO is the only funded flight programme.

Key aspects relevant to market development include resiliency, safety, and operational cost of terrestrial plants.

Applications, value proposition and impact

The application of the technology includes highly encapsulated, autonomously operating small power reactors. As well, it could include exploitation of high-temperature space reactors and heat exchange for industrial process heat.

The value cannot yet be quantified, but it is assumed that the creation of a new market in small reactors with new application will generate a new revenue stream.

We expect a higher level of acceptance of nuclear technology due to its application in such a challenging environment as space exploration. Also, the impact could be a more diverse application space.

Future developments to watch

It is important to follow the funding trajectory of ongoing programmes (DRACO, surface reactors), the development of key space customers, e.g. industry-scale in situ resource utilisation, and the appearance of potential technical challenges in material science.

The right time for application is now. Finding out that industry-scale in situ resource utilisation doesn’t work without nuclear technology would be too late. We already have space programmes not being implemented because the lack of access to high power and energy-dense solutions.

Space nuclear is not low-TRL however for low-TRL concepts (e.g. “nuclear lightbulb”) long-lead development times are required due to the regulatory framework, which is particularly severe in the space nuclear field.

Cost and resources

Space nuclear power reactor development programmes are expected to be in the single-digit billion € range. Given the moderate-to-high TRL of current concepts and the need to make systems available to customers as soon as possible, this investment is justified now.

In space engineering, we are looking at ~EUR 350k/FTE, i.e. a typical 10-year agency programme would require 300 FTE for that period (roughly). The challenge is that the population in the global work force with skills in the nuclear AND space field (both engineering and management) is very small.

Advantages and disadvantages

In general, the disadvantage of space nuclear power and propulsion is the high regulatory burden and the challenge of public acceptance. While these are challenges well-known to the nuclear community, they are particularly severe in the space nuclear field. It should be noted, however, that public acceptance has improved significantly from the days of the Cassini mission launch (1997). The advantage is the enabling of previously completely unthinkable capabilities such as fully reusable lunar shuttles, resource extraction from the Moon, Mars, and Asteroids, and permanent, sustainable human presence in the solar system.

References

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Idaho National Laboratory

Introduction

Space Reactor development goes back to the 1960s with programmes that tested and developed a wide variety of reactors for producing electricity, Systems for Nuclear Auxiliary Power (e.g. SNAP), as well for propulsion Nuclear Engine for Rocket Vehicle Applications (NERVA) but only one reactor has been launched to space (SNAP10A). Over the subsequent decades, space reactors have been revisited with interest that ebbs and flows. In the last few years, interest has been surging indicating a strong and present need for the capability.

Disruption factors

If space reactors were to become in high demand due to space exploration needs, it would create a stronger market for nuclear technology and components that are suited for space applications, which would have some difference compared to most conventional terrestrial reactor applications. Specifically, placing a higher priority on lightweight components, and high resiliency. This would have a strong synergy with micro reactors for terrestrial applications, as they share many of the same requirements.

Disruptive technologies include lightweight, low-volume neutron shielding materials, solid metal hydride moderator designs that retain hydrogen at high temperatures. Lightweight and efficient power conversion systems, and resilient instrument and control components.

Status of nuclear in space

The technology readiness level (TRL) for space reactors should be considered application dependent. Space reactor concepts could be developed where all component TRL > 6, and conversely, there may be concepts with requirements that push the boundaries of what possible leveraging lower (3 or less) TRL solutions.

Research and development at the National Laboratories and NASA are rich in the space reactor area and are shared annually at a variety of conferences, such as Nuclear Emerging Technologies for Space (NETS).

Two recent policies important to space reactors are Space Policy Directive 6 (SPD-6) and National Security Presidential Memorandum–20 (NSPM-20). These policies help shape the landscape for what is needed and how these applications will be overseen.

Currently a variety of space reactor programmes are being pursued with support from various government agencies; Fission Surface Power (FSP), Nuclear Thermal Propulsion (NTP, Joint Emergent Technology Supplying On-orbit Nuclear Power (JETSON), and Demonstration Rocket for Agile Cislunar Operations (DRACO) just to name a few.

The most recent congressional language for FY24 highlighted investments of up to $180M just within NASA space nuclear projects, including both power and propulsion initiatives.

Value proposition and impact

Space reactors can be a key component of a space economy, providing power for both science missions as well as resource development like converting lunar ice to water or rocket fuel. The impact of space reactors can be profound on humanity. As we continue to explore our immediate surrounds, have reliable, sun-independent power source is vital to human exploration of the Moon, Mars and beyond. It’s a key enabler for humanity to become a multi-planet species.

Next steps, costs and resources

Space reactors have been produced and operated in the past, so there are no major barriers to implementation.

Space reactor interest has been growing in recent years, as has the size and amount of space reactor development programmes. This of course leads to a demand for scientists, engineers, and technicians. The field is exciting and compelling and would expect to see an increased interest at the university level to match the growing demands.

Additional references

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5. Disruptive Business and Markets Models

Last Energy - Innovating on the Nuclear Delivery Model

Abstract

To realise a breakthrough in the development of nuclear power at scale requires an alignment between the product and technology with the underlying business model. The principal issue to be addressed is not in fact a technical problem of reactor design or physics, but a question of manufacturability, deliverability and financing. To this end, Last Energy has designed a micro nuclear power plant and an operating and financing model that can rapidly scale to meet customer demand for clean, base-load power.

Small and micro nuclear reactors hold the promise of addressing the cost of nuclear development through modern manufacturing techniques and replicability. To make good on this promise, however, they must find a scalable market niche and bring to it a standardised and financeable product that can be delivered quickly. The industrial and commercial sector is an ideal application for micro nuclear power. To serve this market, Last Energy takes end-to-end responsibility for design, delivery and operations of its power plant, selling power directly to customers while leveraging private financing without the need for public subsidies or guarantees.

Introduction

Nuclear power has proven itself historically as the most effective way to decarbonise electricity generation at scale, is demonstrably one of the safest sources of energy ever created, and provides stable, baseload electricity, ideal to both underpin an electrical grid as well as provide direct-wire power to energy-hungry industries. What nuclear power hasn't been is easy to deliver, having developed a deserved reputation for running over-budget and over-time. Commercial nuclear power has also been dominated by the development of large, gigawatt scale reactors, which can only be developed and financed with the co-ordinated support and financing of state-backed entities and/or financing mechanisms.

Last Energy was founded to address the core constraints that have held back the nuclear industry from the type of growth its early proponents envisioned. By leveraging proven reactor technology and focusing on innovating around a new delivery model for the industry, we can unlock nuclear energy at scale, quickly. We start by taking a customer-led approach, focusing on how to deliver a product that meets the requirements of our customers for a rapidly deployable, replicable, and financeable product that can provide affordable clean power.

There are four pillars to this new model for development: 1) Develop a fully factory fabricated nuclear power plant; 2) Sell electricity directly to customers through a familiar power purchasing agreement (PPA) structure; 3) Leverage fully private financing, requiring no government or taxpayer funding; and 4) Simplify the process by taking end-to-end responsibility for everything from development to operation and decommissioning.

Distinct in the nuclear industry, Last Energy takes end-to-end responsibility for the delivery of power from its plants, from plant design and licensing to fabrication, development and plant operations. This model aligns our incentives as a company with that of our customers, financiers, and regulatory partners. Customers enter into long-term power purchase agreements that secure a stable and affordable supply of energy while requiring no upfront capital investment. Last Energy secures private financing, requiring no government support, and opening new avenues for private capital to invest in carbon-free power projects.

Possible applications

Given its cost and complexity, gigawatt-scale nuclear energy, with costs exceeding USD -40 Bn, will always require the support or guarantees of governments. Such power plants have a place in the portfolio of solutions going forward, but leave many market niches unfilled, and cannot access a significant amount of capital that could be deployed for want of a right-sized solution.

The latent commercial and industrial demand for clean base-load power has quickly emerged as micro and SMR nuclear solutions have come to market. In just its first year of commercial activities, Last Energy secured commitments for 55 units of its 20MWe power plant, representing over USS 37 Bn in total electricity under contract.

To scale nuclear quickly and move the industry along the experience curve, Last Energy has designed a product for a market segment that has room to deploy not one or two reactors per decade, but hundreds per year. Last Energy's PWR-20 micro nuclear power plant has exactly these qualities. Industrial energy users are highly sensitive to the price of power, want long-term price stability, face energy supply and transmission constraints, require a steady (not-intermittent) supply of electricity, and are looking for carbon-free energy sources, including both electricity and heat. Nuclear is the only clean energy solution that can deliver those qualities.

The attractiveness of this offering to commercial customers is based on several factors. First, leveraging a long-term power purchasing agreement contracting structure simplifies and de-risks the initial commitment from the customer, aligning the incentives of the customer with the developer/operator. Customers secure stable, long-term power contracts and do not have to commit any capital up front.

Micro nuclear power that can be delivered at or near the point of demand and connected via direct wire gives industrial customers the ability to decouple their operations and growth from the limitations of existing generation and transmission infrastructure.

Historically, the time and cost associated with large nuclear builds has been the principal barrier to widespread development and adoption. Last Energy's model addresses these challenges in a holistic way. The cost to deliver a Last Energy PWR-20 is approximately USD 100 million. At such a reduced price point, comparable to wind or solar developments of a similar size, investors take on significantly less portfolio risk without an outsize bet on large, unproven new nuclear technology.

Advantages and disadvantages

The nuclear industry has not been held back by a lack of appropriate technology, but by an inability to competitively deliver electricity to its end customers. The industry must take a customer-led approach to the development and deployment of its product, designing a replicable, financeable product that can provide affordable power to customers.

By targeting the industrial sector with micro-nuclear power, Last Energy is not only growing the nuclear sector and aligning to broader goals around decarbonisation, decentralisation and grid reliability, but making nuclear power more accessible to segments that it would otherwise not be able to reach. The power plant product fits the needs of the end-customer, providing carbon-free baseload power at or near the source of demand.

Another key advantage is the use of a familiar contracting structure. When applied to small-scale nuclear, power-purchase agreements work independently of fluctuating energy prices and public support, which mitigates risks for both energy producers and buyers and facilitates the delivery of carbon-free power.

Around the world, large energy off takers and corporate energy buyers use the power purchase agreement to secure stable long-term energy supply. In 2023, it was estimated that the global PPA market was growing at an annual growth rate of over 31%, and valued at over USD 28Bn, with the commercial sector representing over 50% of that number.

Leveraging PPAs to attract private capital and accelerate growth in the nuclear sector is a familiar pathway to other sectors in the energy industry, starting with the boom in natural gas power plants in the early 1990s and then extending into the renewables space, where it was used extensively by companies like First Solar (now the largest solar OEM).

Widely used today, the model has extended into Energy-as-a-Service providers like Bloom Energy or Fuel Cell Energy. Contracting and financing micro nuclear through purely private means projects can accelerate quickly through the early stages of project development without the need for securing public funds.

Conclusions, further plans and recommendations

For the past 40 years, the nuclear industry has effectively delivered a single type of project to a very limited set of customers. Utility-scale reactors, requiring massive public subsidies and a heroic commitment on the part of developers, financiers and utilities to see them through to completion, taking decades from planning to commissioning. However, if we look outside the nuclear sector, we see that other business models can dramatically accelerate our ability to contract, develop, finance and deliver new nuclear projects.

Demand for clean base-load power has never been stronger, particularly among industrial customers who feel the dual pressures of exposure to energy price volatility and increasing carbon costs and mandates. Nuclear must take a customer-led approach, delivering a product that is right-sized to meet the needs of its customers, can be deployed quickly, and access private financing. Last Energy is leveraging the predominant business model among independent power producers and applying it to the nuclear sector, creating a robust marketplace of nuclear solutions for energy users who are seeking carbon free, baseload energy. By focusing on the customer and bringing innovation to the nuclear delivery model, Last Energy is inverting the traditional focus of the nuclear industry, which typically prioritises the development of new technologies over delivering affordable products that can be financed and operated and commercially scaled.

6. Challenges and Enablers

Competitiveness Implications

Third Way - Global Competition Landscape for Nuclear Innovation and Advanced Reactors

R. Norman, A. Ahn, and R. Price

Abstract
Many nations of the world have settled on the conclusion that the world needs more nuclear power to meet global climate goals and foster durable energy security. This paper focuses on the global competition landscape to address what nuclear exporting countries are best positioned to provide new advanced nuclear capacity globally; and how OECD countries can become more competitive against non-Western challengers in the global market. Nuclear fuel supply chain and first-of-a-kind financing are identified as the critical challenges to Western competitiveness in the scaling of innovative nuclear technologies. Despite this, the authors recognise three critical enablers, original equipment manufacturers, international nuclear energy agreements, and large industrial end-users, that can be leveraged to enhance Western market penetration. This paper finds that strategic co-ordination on implementation of national policies will be essential to maximise the competitiveness of Western nuclear exporters and ensuring reliability of early projects. Further, the authors assert that, without increased co-ordination, Western countries are at a significant risk of competing among each other for private capital, supply chains, and near-term customers in ways that will be unproductive to long-term competitiveness.

Introduction

The US has been able to establish an early advantage in advanced reactor technology due to its mature regulatory infrastructure and legacy of technical leadership among industry and government. These comparative advantages have been bolstered by the significant investments at the national level. Meanwhile, the United Kingdom, France, and Korea have continued their support for nuclear energy and play key roles in driving co-operation and investment for nuclear innovation. Beyond the West-aligned countries, the global competition landscape for nuclear energy is dominated by two major competitors–Russia and China.

The implications of this competition landscape will depend on how well states address the key challenges and leverage the major enablers to deploy new nuclear technology. These key challenges are the nuclear fuel supply chain and first-of-a-kind financing for emerging technologies. Enabling the competitiveness of Western countries, however, are a broad base of original equipment manufacturers, early international nuclear co-operation agreements in viable near-term markets, and a robust new class of industrial end-users for nuclear reactors.

Challenges

Nuclear fuel supply chain
Russia and China collectively host 54% of global enrichment capacity. (UxC, 2022) Currently, Russia is the largest uranium enrichment supplier on the global market and competes with enrichers in the UK, Germany, Netherlands, France, China, and the United States. Russian state-owned businesses provided 35% of global enrichment in 2021 and are projected to provide 30% of global supply in 2035. (UxC, 2022, 2023a) In the near term, the US and allies will have to navigate an increasingly volatile global market for enriched uranium products where Russia holds an outsized influence on price and supply.

Without significant expansion of Western enrichment capacity, global enrichment needs will exceed annual non-Russian supply by 6% to 20% through 2038. (UxC, 2023b) In addition to nuclear fuel cycle capacity needed for LEU, many advanced reactors will require a secure supply chain for high-assay low-enriched uranium (HALEU). Currently, Russia is the only commercial supplier of HALEU. However, the US and UK have passed policies and committed funding to develop HALEU.

First-of-a-Kind Financing

Small modular reactors (SMRs) have the potential to be more affordable than conventional large light water nuclear reactors due to their standardised modular design, which allows for degrees of factory pre-fabrication and efficient installation. Additionally, many advanced reactors harness novel design characteristics to improve efficiency and simplify plant construction, thereby reducing overnight costs.

However, financing for first-of-a-kind (FOAK) and early deployments, the initial builds that bring down costs for nth-of-a-kind (NOAK) builds, remains a significant challenge. Investors and developers face financial uncertainty on FOAK projects due to immature supply chains, limited project cost profiles, and untested construction timelines. Private and commercial investors are typically less aggressive in providing financing for such undemonstrated designs. Rather, these investors tend to provide capital to technologies that have mitigated commercial risks and can provide more certainty on costs and performance.

These headwinds are exacerbated by indispensable FOAK costs for activities to finalise design and develop construction capabilities including licensing, fuel fabrication, etc. (Norman, R. et al., 2024) Therefore, it is essential to support new deployments via public-private and market-based partnerships. Risk-sharing through these models can ensure that early projects have sufficient backing to overcome hurdles, such as inflationary pressures and construction issues that can sharply impact costs.

Enablers

Original Equipment Manufacturers (OEM)

A 2022 analysis conducted by Boston Consulting Group (BCG) estimated 28 global SMR projects at various stages and capacity. (Boston Consulting Group, 2023) There are three operational “SMRs” globally, located in Russia and China. Despite the undeniable lead of foreign competitors on early technology, US and Western allies host the bulk of innovation companies for advanced nuclear. Third Way’s 2022 Advanced Nuclear Map shows that there are nearly 150 advanced reactor firms globally, the majority of them based in the US and Western Europe. (Ahn, A., Allen, T., 2022)

Policies in the US and European countries in support of nuclear energy are also driving investment in multiple new technologies. The US has pursued an Advanced Reactor Demonstration Program that is funding two commercial demonstrations through public-private partnerships. The programme will also advance research and testing that will de-risk five other reactor technologies. OECD countries could expand RD&D activities to bring a wide range of new technology and manufacturing capabilities to the global market by co-ordinating Western investments in technology across different scales and supply chains.

International nuclear co-operation agreements

By far, Russia is the world’s leading exporter of nuclear power plants. However, international co-operation agreements provide a blueprint for accelerating deployment growth. For some countries, such as the United States, certain bilateral agreements are required before major nuclear hardware and equipment can be exported. Many bilateral MOUs do not contain explicit terms for exports but support civil nuclear development activities through knowledge-sharing, training, and regulatory development. With co-operation among OECD nuclear exporters on financing, engineering, procurement, and construction, these agreements can represent a significant market that is accessible to Western nuclear firms.

The US holds a considerable number of export agreements that can enable growth; over 60% of the US' civil nuclear development agreements are in viable near-term markets that are either ready or potentially ready for nuclear power by 2030. (Ahn, A. et al., 2023) As such, these agreements can provide a head start into export markets and provide a platform to foster long-term energy partnership with Western states.

Emergence of large industrial end-users
Large multinational industrial end-users have made recent forays into procuring nuclear energy to expand their operations. In March 2024, Amazon Web Services announced an acquisition of a 960 MW nuclear powered data centre campus in the United States, with plans to add capacity. (American Nuclear Society, 2024)

Additionally, Google, Microsoft, and Nucor announced a joint initiative to scale deployment of first-of-a-kind clean energy projects by aggregating industry demand. (Texier, M., 2024) Likewise, the European Industrial Alliance on Small Modular Reactors aims to accelerate the development, demonstration, and deployment of SMRs in Europe by the early 2030s by exploring new financing options and engaging potential industrial end users. Large multinational industrial end users tend to be concentrated in industrialised Western nations and present a new class of well-capitalised, high demand customers that aren't as active in the markets currently being served by Russia and China.

Considerations to implementation

To effectively deploy disruptive new nuclear technologies and support the growth of the supply chain, workforce, and manufacturing capacity needed, states must consider how to implement policies that are strategically co-operative.

Co-ordination on investments and growth of the nuclear fuel cycle
The Sapporo 5 agreement between the US, Canada, France, Japan, and the UK to mobilise USD 4.2B for the global nuclear energy supply chain presents an opportunity to enhance existing relationships through co-ordination of these investments. (US Department of Energy, 2023a) The US has passed significant funding for uranium enrichment and conversion capacity which may be more strategically directed if implemented in partnership to existing multinational enrichment activities. Further, multilateral co-operation on the fuel cycle could expand to include commitments on raw uranium procurement from allied states, providing a signal to industries in partner countries that could direct private investments towards scaling production.

Co-operative financing and construction of new nuclear
The challenges of FOAK deployment are unavoidable for any new technology. Many countries have implemented programmes for early domestic technology demonstrations aimed at commercialising national or Indigenous technology. However, Western states could benefit significantly by collaborating multilaterally on international deployments of Western technologies. This partnership could provide opportunities to combine strengths in the OEM, EPC, and financing segments for the advanced nuclear value chains and spread benefits across collaborators. A successful model for co-operation among nuclear exporting OECD nations, including modifications of and improved co-ordination to the OECD Arrangement on export credits, would help drive competitive offerings and strengthen long-term international nuclear energy co-operation (OECD, 2023).

Developing competitive critical manufacturing
The US Department of Energy released a *Pathways to Commercial Liftoff* analysis that highlighted the shortage of N-stamp manufacturers for large forgings and low capacity of small forging capacity. (US Department of Energy, 2023b) To support a global nuclear industry at the scale required to triple global

nuclear capacity, states should consider how strategic investments and diversification of expertise and capacity can support a secure component manufacturing supply chain.

Conclusions

Global competitiveness of Western advanced nuclear industries will depend significantly on the ability of OECD states to work collaboratively in addressing the key challenges. In addition to building out the non-Russian fuel cycle supply chain, the US and European allies will need to leverage international capital for new nuclear projects in a way that exponentially grows private investment, rather than exhausts it. To do so, models for de-risking early projects and enabling new customers will be essential.

Co-operative models to implement an effective multilateral nuclear exports regime could help combat advantages of Russian and Chinese enterprises when scoping agreements in emerging markets. Without meaningful co-operation among Western states, there is a much greater risk that national policies may be implemented in ways that disincentivise international co-operation in these areas, or worse, place allied countries in unproductive competition with each other.

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Insurance implications

Nuclear Risk Insurers (NRI) - Enabling Innovation and Sustainability in the Evolving Nuclear Industry Through Risk Assessment and Coverage

Abstract

The origin of nuclear insurance dates to 1956 with the birth of the civil nuclear industry. Since then, the nuclear insurance and the international nuclear pooling system have been instrumental in supporting the growth of the industry, adapting and responding to the nuclear operators' needs. Nuclear insurance relies on the technical understanding of the subject matter and the adoption of new technologies may impact the insured risk profile. An accurate technical assessment of the insurance risk, based on the sharing of information is essential to provide an efficient and effective coverage.

As it happened in the early days, nuclear insurance can continue to be an enabler in the development of first-of-a-kind SMRs, MMRs and AMRs as well as supporting the integration of other disruptive technologies aimed at improving standards, efficiency and safety of the nuclear applications.

However, nuclear insurance is a commercial product backed by private financial capitals. Pricing adequacy, careful reserving, earning patterns and profitability need to satisfy the requirements of a viable business proposition for insurance companies to continue supporting the nuclear industry in the foreseeable future.

Implementation challenges and enablers for insurance implications

The origin of nuclear insurance is closely tied to the birth of the civil nuclear power industry. The insurance industry originally adapted to offer solutions to the unique needs of the emerging nuclear industry, providing risk transfer to private and public operators in the sector and limiting the impact of potentially catastrophic losses to their balance sheet or to the taxpayers.

At that time nuclear energy was a revolutionary technology and the insurance industry was instrumental to enable its development, transferring financial risks and liabilities from private companies and governments to insurance companies, while offering statutory protection to the public.

Today, nuclear insurance continues to provide valuable and consistent support to the nuclear industry. Complex risks, which require insurance capacity beyond the individual means of the national insurers or co-insurance arrangements, are underwritten jointly through a mechanism which involve market-wide national pools. There are currently 26 national pools. However, the total aggregated capacity committed is still limited and not always sufficient to provide the full insurance cover demand. Some of the largest nuclear risks require the involvement of more than 20 national pools. If we assume that each pool represents circa 20 insurance companies on average, then such risk will be diversified across up to 400 carriers around the world, each taking a small manageable net share of the overall exposure.

Nuclear insurance remains a niche class if compared to other insurance classes such as general property, marine, general liability etc. Nuclear insurance is currently classified as a non-life, non-marine class and it can fall within the remit of a broader property book or energy book alongside with conventional upstream energy.

Nuclear insurance products are available to companies operating across all phases of the nuclear fuel cycle. These include conversion, enrichment, deconversion, fuel fabrication, power generation, storage, reprocessing, disposal and decommissioning.

Nuclear insurance is considered a highly volatile class of business with low frequency and high severity, essentially catastrophic in nature. The business case needs to be supported by strong fundamentals to be considered a viable business. This requires careful underwriting, claim management, capital allocation, reserving and pricing.

Because of the limited number and the complexity of the risks, nuclear insurance is a highly technical class. This means that engineering knowledge of the system design, construction, operations, legal framework and business model are required alongside the insurance expertise.

Disruptive technologies and the use of nuclear in non-traditional sectors may affect the availability of insurance products if not actively addressed. A proactive approach from all parties can guarantee continuity of offering.

Insurance can be also an enabler to the adoption of disruptive technologies as well as a key facilitator for the successful deployment of nuclear in non-traditional sectors.

Implications of disruptive technologies for insuring the nuclear industry

The implementation of disruptive technologies might affect the availability of insurance in several ways and the extent might be different whether material damage, third-party liability or other insurance products are involved.

Technologies of particular interest in that respect are AI, autonomous operations, novel materials and manufacturing, digital twins and augmented reality. All these technologies have the potential to disrupt the industry internal processes whether adopted by nuclear power plant operators or by the supporting nuclear upstream or downstream players.

One way for these technologies to impact the existing insurance products is in the perceived material change of the risk profile. Every insurance product is subject to continuous risk analysis by the underwriters to guarantee homogeneity within their portfolio and price adequacy. The challenges in estimating frequency and severity of loss events can be exacerbated by the unknown ramifications of the adoption of these technologies.

The increased asymmetry of information might prevent risk identification and risk assessment. In the extreme case of inability to perform such activities the insurance offering might be restricted or in the worst case withdrawn.

The narrower the information gap the more accurate the analysis is and the more valuable the insurance offering. Either under-estimating or over-estimating the additional risk might result in -under-performing or inadequate insurance products.

Disruptive technologies such as autonomous operations might introduce further vulnerabilities to existing perils, which need to be understood and addressed, or they might expose the insured asset and the client to new perils not envisaged before.

The insurance regulators are mandating insurance companies to avoid silent coverages whenever possible. This means that clarity and certainty of the insurance cover provided by the insurers and purchased by the clients is paramount for the correct performance of the insurance contract.

For example, the digitalisation of the nuclear industry, as new systems are introduced, offer improved efficiency, consolidation of functionalities or address obsolesce issues, which contribute to changing hardware and software assets and procedures. This represents an evolving and potentially expanding attack surface which is exposed to increasingly sophisticated attack vectors in an unpredictable threat landscape.

The insurance regulators had to address the lack of clarity due to dated policy language and legacy practices with the mandate to clearly state whether indemnity for damages caused by malicious cyber acts is provided or not. In the affirmative, the extent of the additional coverage needs to be specified, assuming a quantitative assessment of the risk is possible. It is reasonable to expect that other disruptive technologies, once adopted, will follow a similar course.

Another example is the insurance implication of the amended protocol to the Paris Convention on Nuclear Third-Party Liability. The legal changes to the international legal framework, specifically the extended reported period for compensation from 10 to 30 years and the extended liability covers, pose similar quantitative assessment challenges to the insurance industry once enacted in the national legislation. The lack of clear definitions, historical data, technical pricing, reserving and capital allocation methodologies have material implications for nuclear operators, insurers, regulators and governments.

The insurance companies have adopted different approaches from offering speculative insurance products, to not being able to provide coverage at all, with a few proposals between the two extremes, but still requiring the governments intervention and ultimately the taxpayers to fill the gaps.

On the other hand, disruptive technologies might contribute to reduce the overall insurance risk. For instance, digital twins have the potential to improve predictive maintenance. The adoption of augmented reality might improve the general maintenance, inspection and repair operations, thus reducing the operational risk during and as result of those activities.

It is also assumed that all the technologies above, once introduced, will comply with the regulatory requirements of the applicable nuclear safety framework. However, one point worth stressing is that the insurance risks might differ from regulatory, business, environmental and other types of risk, and they might include components from all the above to different extents.

The introduction of disruptive technologies may introduce several challenges when not communicated or understood adequately. However, once able to overcome the initial barriers, insurance can adapt and include the resulting risk change for the benefit of the nuclear operators and ultimately become an enabler to the adoption of such technology. Insurance can trigger a virtuous cycle where the overall industry moves to the next level of efficiency and performance.

Similar considerations can be extended to the use of nuclear technologies to disrupt new sectors. Other industries have experienced similar trends where existing products or services have been re-designed and re-purposed to new business cases and application domains.

The deployment of nuclear technologies such as fission, or even fusion in the next future, to smart grids and cities involves a broader insurance risk analysis to include different risks, which were previously not correlated or not relevant, but potentially becoming contributing or aggravating factors in new loss scenarios.

Insurance can play a major role in the success of small modular reactors (SMR), micro modular reactors (MMR) or advanced modular reactors (AMR). Modularity and scalability of insurance products have been already successfully implemented in other industries.
For traditional nuclear power plants, the nuclear liability insurance requirement starts at the arrival of nuclear fuel at the site. The construction plan of SMR and MMR requires further assessment and insurance cover should adapt to the case in which nuclear fuel is loaded at the manufacturing facility and shipped to the site before final integration.

The modularity of the design, the improved manufacturing to achieve scalability of production, the new testing procedures may impact the overall system reliability.

The extensive use of digital electronic components and software architectures might also introduce additional risks which requires specific expertise to be mitigated or retired. Components obsolescence is just one example of potential increased threats to the system life cycle if, for availability and cost implications, off-the-shelf components are extensively used in the design.

Depending on the application domains, such as smart grid, smart cities, data centres, etc., new safety cases might be introduced and depending on the final energy system, where the nuclear power generation part is closely associated with a battery or solar farm, broader insurance cover might be required or offered.

It can be foreseen that for SMR, MMR and AMR's to be developed at scale the traditional government supported utilities will be replaced to some extent by private sector. In turn the private sector will have differing risk appetites and if we introduce private finance into the mix then operators may become even more risk adverse in the future. This will inevitably lead to new insurance coverages being required including delay in start-up, during the construction phase, and business interruption when in operation.

The adoption of nuclear marine propulsion will also present new challenges to the insurance industry where nuclear perils are historically associated to fixed assets or transportation of nuclear fuel. Nuclear reactors used for propulsion are currently excluded from the scope of the legislation. Marine insurance is a well-established class able to provide cover to the vessel's structure and equipment including propulsion machinery as well as a range of liabilities for damage to third party property, loss of life or bodily injury. Currently, a merchant nuclear ship cannot be insured in the conventional market, and liability for damage caused by nuclear fuel or waste is generally excluded.

The international regulatory framework and its application at national level need to be fully understood. The nuclear liability regime and its interpretation are key elements in the provision of insurance cover, especially in complicated scenarios where different countries with different regulatory approaches are involved.

Nuclear insurers are also mindful of all other new emerging technologies which combined with the evolving nuclear industry might significantly change the risk landscape. The technologies which expose the insured assets to systemic losses are of particular concern. Systemic losses can affect several contracts covering assets or liabilities geographically uncorrelated. Unknown vulnerabilities might be introduced by the application of new technologies or new technologies might be used to exploit existing vulnerabilities.

For instance, more sophisticated cyber threats and the capability leap offered by quantum computing should be further understood and assessed at portfolio level, especially when they might affect several installations rather than just one. Existing capital provisions, made by insurers today, might not be enough to cope with the extent of such losses or the uncertainties of these scenarios might induce risk adverse reactions among capital providers.
Such scenarios should be also carefully considered by regulators and law makers when deciding the operational environment and the statutory controls and requirements.

Implementation considerations

There are several key contributors to the successful implementation of disruptive innovations in the nuclear industry. Commercial nuclear insurance is one of the pillars of a healthy nuclear industry ecosystem.

Innovation poses several challenges to the insurance industry modifying existing risks or adding new risks. Insurance risks are generally broader than the risks addressed by the regulators in the context of safe operations and public liability. An example is an innovative system breakdown that might not pose any threat to the overall nuclear safety, but it might still result in a loss under an insurance policy.

When faced with changing risk profiles the insurance companies react by adapting their assessment and proposition to preserve the value offered to all stakeholders. Ultimately the insurance products need to add value to the clients by addressing their specific needs while offering the expected profit return to the capital providers. On the contrary, an insurance commercial product is not available, leaving the clients either financially exposed, retaining the risks through their balance sheet, or requiring governments and taxpayers to fill the gap if of public interest.

Sharing and transfer of knowledge can facilitate the process. An early and constant engagement between insurers and nuclear operators would facilitate the adaptation of existing insurance products or the design of new propositions. For example, we can expect that the successful deployment of SMRs, MMRs and AMRs would require the insurance companies to design new products driven by the specific client needs and developed through close co-operation. Specifically, the availability of insurance can be instrumental for the funding and development of any 1st of a kind of the above.

Finally, it is worth noting that nuclear insurance has been historically characterised by a low volume of large nuclear installations. SMRs and MMRs, depending on the extent of the economy of scale that they can achieve, have a potentially disruptive impact on the traditional way in which nuclear insurance pools collaborate and diversify risk.

If capacity, in the order of magnitude of millions rather than billions is required to underwrite 100% of the risk, you could see nuclear pools competing for business in the future, instead of collaborating to build sufficient capacity. The insurance of SMRs and MMRs may need a different approach from the pooling system, while at the same time maintaining its “collaboration” for the traditional gigawatt scale risks.

Conclusions, further plans and recommendations

Referring to the start of the civil nuclear industry in the 1950s, insurers, governments and the newly forming industry came together to develop solutions for these newly emerging risks.

Insurers started insuring civil nuclear risks for third-party liability damage before the International Conventions were brought into place. The principle of “net capacity” was quickly adopted and “insurance channelling” of risk was established with the introduction of conventional insurance market nuclear exclusion. This channelling of insurance is in the spirit of the channelling of liability which is a key principle within the civil nuclear legislation. The insurance market has had a history of adapting and enabling changes to industry and new industries and the risks that they present. In the case of nuclear, given its highly engineered, regulatory and safety characteristics it is likely that a technical approach to underwriting will be applied and through a deep understanding of the risk coverages will continue and adapt.

A potential challenge for the future is that as nuclear technologies become designed to be safer with design-basis calculations in excess to ten to the power of seven, then at what point does the concept of walk-away safe really become a reality versus the perception in the minds of the public about nuclear safety and the concept of social licence?

If insurance for some of these future designs is still required and self-insurance solutions are not completely viable then the challenge for the industry and the insurers will focus upon value for money versus the insurer’s requirements for a return on capital in a much shorter time frame. Nuclear insurance capacity will compete with other risks and if insurers can make better returns on their capital elsewhere then they will do so.

A final point therefore is that since the formation of the nuclear pools in the mid-1950s there has been a tripartite relationship of sorts between nuclear operators, governments and insurers. Long may this relationship and acknowledgement of each other's roles in maintaining this unique risk transfer and insurance market continue, until of course there is a better, smarter alternative!

Regulatory implications

Federal Authority for Nuclear Regulation, United Arab Emirates - Nuclear innovation and newly emerging disruptive technologies

Abstract

Nuclear innovation and disruptive technologies are revolutionising the energy industry, providing solutions to climate change and meeting growing energy demands. Regulatory frameworks are essential for the safe and responsible deployment of nuclear technologies, balancing innovation with risk management. Key factors shaping the regulatory landscape include technological advancements, climate change mitigation, energy transition policies, geopolitical dynamics, and stakeholder engagement. Investing in these advancements can accelerate the transition to a cleaner, more efficient energy system. The nuclear sector offers opportunities for streamlining regulatory processes and promoting innovation through risk-informed regulation, modular designs, regulatory sandboxes, international collaboration, advanced simulation tools, stakeholder engagement, and regulatory reform. Disruptive technologies like big data, AI, autonomous operations, quantum technologies, and distributed ledger technology can enhance resource utilisation, reduce waste generation, and improve proliferation resistance. Adopting closed fuel cycles, smart grids, energy-as-a-service models, and a circular economy approach can further promote resource efficiency and reduce environmental impact.

Introduction

Research on nuclear innovation and disruptive technologies emphasises the need for ongoing development to ensure safety, efficiency, and cost-effectiveness. Regulatory frameworks and public acceptance are crucial for widespread adoption. Policymakers and industry leaders must collaborate to create supportive policies and incentives for these advancements. Investing in these advancements can accelerate the transition to a cleaner, more efficient energy system. Innovative technologies like advanced reactor designs, digitalisation of nuclear plants, and integration with renewable energy sources are playing a significant role in transforming the energy industry. These developments are driving a shift towards cleaner, more efficient energy systems.

The nuclear sector faces regulatory challenges and enablers in implementing nuclear innovation and emerging disruptive technologies. Key factors shaping the regulatory landscape include international co-operation, advancements in digitalisation, and the need for flexible and adaptive regulations.

It is crucial for regulators to navigate these challenges and ensure the safe and effective implementation of these technologies. The concept of VUCA (volatility, uncertainty, complexity, and ambiguity) will be crucial for leaders and regulators to navigate and ensure the safety and public acceptance of these technologies. By acknowledging and addressing the VUCA qualities inherent in a situation, leaders and regulators can enhance their strategic abilities and improve outcomes. Embracing uncertainty as an opportunity for learning and innovation, fostering agility and adaptability in decision-making, and promoting collaboration and communication are key strategies for navigating VUCA environments successfully.

Additionally, developing resilience, flexibility, and a growth mindset enables leaders and regulators to thrive in complex and dynamic conditions, ultimately leading to more effective and sustainable outcomes.

Key factors shaping the regulatory landscape include technological advancements, climate change mitigation, energy transition policies, geopolitical dynamics, and public engagement and trust. Adaptive regulation, collaborative governance, and continued investment in research and development are critical for navigating these dynamics and ensuring the safe and sustainable deployment of nuclear energy.

Discussion

Regulatory challenges in nuclear technology include safety assurance, licensing procedures, risk perception, public acceptance, international co-operation and harmonisation, and waste management and decommissioning. Regulatory agencies must assess and verify the safety features of emerging technologies while maintaining safety standards. Traditional licensing processes may not be well-suited for innovative designs, and addressing safety, security, and safeguards concerns, while ensuring transparency, is crucial for all parties involved.

International co-operation and harmonisation are essential for nuclear innovations, as divergent regulatory requirements can create barriers to technology deployment and hinder global co-operation. Waste management and decommissioning must adapt to accommodate new reactor designs and fuel cycles, and addressing long-term waste storage and disposal challenges is critical for the sustainability of nuclear energy.

Regulatory enablers include adaptive regulation, collaborative governance, regulatory sandboxes, continued research and development, and public engagement and education. Regulatory agencies need to adopt flexible approaches to accommodate technological innovations while maintaining safety standards, implementing risk-informed regulation, and using advanced modelling and simulation tools.

Multiple countries have successfully implemented advanced nuclear technologies, overcoming regulatory hurdles through strategic partnerships and government support. Companies like TerraPower and NuScale Power in the US have also navigated regulatory challenges, leading to widespread adoption of disruptive nuclear innovations. As more countries and companies invest in these technologies, the global energy landscape is poised for significant transformation, addressing environmental concerns and meeting growing energy needs in a cleaner and more efficient manner.

The nuclear sector is witnessing a surge in disruptive technologies, including big data and artificial intelligence (AI), autonomous operations, novel materials and manufacturing, next-generation communications networks, digital twins, and distributed ledger technology. These technologies can improve predictive maintenance, optimise reactor operations, enhance safety and security, and expedite regulatory reviews and design optimisation processes.

Autonomous systems can increase efficiency and safety in nuclear operations by reducing human error and enabling continuous monitoring and adaptive control. Quantum computing and sensing technologies have the potential to revolutionise nuclear reactor design, materials science, and computational chemistry. Novel materials with enhanced radiation resistance, thermal conductivity, and structural integrity can enable safer and more efficient nuclear reactors and fuel cycles. Advanced manufacturing techniques, such as additive manufacturing and nanotechnology, can reduce costs and lead times for producing nuclear components.

Next-generation communications networks, such as 5G and beyond, support real-time data exchange, remote monitoring, and teleoperation of nuclear facilities. Digital twins replicate physical assets and processes in a virtual environment, allowing for real-time monitoring, optimisation, and predictive maintenance. High-fidelity computing platforms enable complex simulations and modelling of nuclear phenomena, while distributed ledger technology, like blockchain, enhances transparency, traceability, and security in nuclear supply chains and regulatory compliance. Integrating these technologies into nuclear operations requires careful consideration of regulatory requirements, cybersecurity risks, and workforce training needs.

The adoption of a closed fuel cycle, including reprocessing and recycling of nuclear fuel, can enhance resource use, reduce waste generation, and improve proliferation resistance. Cybersecurity measures are essential for protecting nuclear facilities and systems from cyber threats. Nuclear power plants can integrate into smart cities infrastructure to support sustainable urban development and address growing energy demands. Smart grids provide base-load power, grid stability, and energy storage capabilities, enabling dynamic load management, demand response, and grid optimisation. Energy storage systems, such as battery storage and pumped hydroelectric storage, enhance grid flexibility and reliability. Nuclear power can also be used in non-traditional sectors, such as heat applications, mining, chemical industry, maritime propulsion, and space applications.

Energy-as-a-Service (EaaS) models allow customers to access reliable and clean energy services without the upfront costs of owning and operating nuclear facilities. Micro-grid and community energy projects empower local communities to generate, store, and distribute clean energy autonomously, promoting energy independence, resilience, and sustainability while fostering economic development and social equity. Blockchain-based energy trading enables transparent and decentralised transactions among energy producers and consumers, facilitating efficient allocation of nuclear-generated electricity and incentivising renewable energy integration. Subscription-based energy services offer predictable pricing, flexibility, and convenience for energy consumers while ensuring stable revenue streams for nuclear operators.

Decentralised energy production through distributed generation and renewable energy co-operatives promotes energy democracy and resilience, enabling local communities to harness nuclear and renewable energy resources for self-reliant and sustainable development. Embracing a circular economy approach in the nuclear sector promotes resource efficiency, waste minimisation, and material reuse. Adopting circular business models, such as fuel leasing and spent fuel reprocessing, maximises resource use and reduces environmental impact throughout the nuclear fuel cycle.

Considerations

The nuclear sector presents numerous opportunities for streamlining regulatory processes and promoting innovation. Key opportunities include risk-informed regulation, which focuses resources on areas of highest risk, modular and standardised designs, regulatory sandboxes, international collaboration, advanced simulation and modelling tools, stakeholder engagement and transparency, continuous improvement and learning, regulatory reform and modernisation, and fostering a culture of continuous improvement and learning within regulatory agencies.

Risk-informed regulation can streamline the licensing process by prioritising safety-critical aspects of new nuclear technologies while reducing regulatory burden on low-risk components. Modular and standardised reactor designs can simplify regulatory reviews and accelerate licensing processes. Establishing regulatory sandboxes or pilot programmes allows regulators to test new technologies in a controlled environment, facilitating early-stage innovation while ensuring safety and compliance with regulatory requirements. Therefore, the nuclear industry should engage regulators in the early stage of planning and designing promising technologies. International collaboration on regulatory harmonisation and mutual recognition agreements can streamline regulatory processes for nuclear innovations that span multiple authorities. Advanced simulation and modelling tools can enhance the efficiency and effectiveness of regulatory reviews, reducing the need for physical testing and expediting regulatory approvals.

Stakeholder engagement and transparency foster transparency, trust, and accountability, allowing regulators to address concerns proactively and build consensus around innovative nuclear projects. A culture of continuous improvement and learning within regulatory agencies promotes regulatory agility and responsiveness to technological advancements.

Regulatory reform and modernisation are essential for promoting innovation and ensuring regulatory effectiveness. Updating and modernising regulatory frameworks to reflect advancements in science, technology, and best practices can reduce regulatory burdens and incentivise investment in nuclear innovation. By capitalising on these opportunities, regulators can facilitate the safe and timely deployment of innovative nuclear technologies, drive cost reductions, enhance regulatory certainty, and contribute to the long-term sustainability and competitiveness of the nuclear sector.

Conclusion

In conclusion, the exploration of nuclear innovation and disruptive technologies underscores their pivotal role in reshaping the energy industry to address climate change and meet escalating energy demands. Regulatory frameworks emerge as essential for ensuring the safe and responsible integration of these technologies, necessitating a delicate balance between innovation and risk management. Key factors shaping regulatory landscapes include technological advancements, climate change mitigation efforts, energy transition policies, geopolitical dynamics, and stakeholder engagement. Investment in these advancements holds the potential to expedite the transition towards a cleaner, more efficient energy system.

Moreover, the nuclear sector presents countless opportunities for refining regulatory processes and fostering innovation. These opportunities encompass risk-informed regulation, modular designs, regulatory sandboxes, international collaboration, advanced simulation tools, stakeholder engagement, and regulatory reform.

These strategies, coupled with the incorporation of disruptive technologies like big data, AI, and quantum technologies, promise to enhance resource use, reduce waste generation, and bolster proliferation resistance within the nuclear domain. However, the journey towards widespread adoption of nuclear innovations is not without its challenges. Regulatory hurdles pertaining to safety assurance, licensing procedures, public acceptance, international co-operation, and waste management demand concerted efforts to navigate effectively. Adapting to these challenges necessitates regulatory agility, collaboration, and a forward-thinking approach guided by the principles of VUCA (volatility, uncertainty, complexity, and ambiguity). By embracing uncertainty as an opportunity for learning and innovation, nurturing a culture of adaptability, and fostering transparent communication, leaders and regulators can enhance their strategic capabilities and navigate the evolving landscape of nuclear energy effectively.

Through a combination of regulatory reform, technological integration, and stakeholder engagement, the nuclear sector can chart a course towards sustainable, resilient, and competitive energy solutions, thus paving the way for a cleaner and brighter future.

Idaho National Laboratory - Changes to the United States regulatory framework enabling the safe and near-term deployment of disruptive and innovative reactor technologies

Jason Christensen, Chris Chwasz, Scott Ferrara, and Jim Kinsey

Abstract

The near-term and widespread demonstration, deployment, and use of disruptive innovative technologies within the commercial nuclear power industry will require a regulatory framework that readily accommodates those innovations, where appropriate.

This paper provides an overview of United States regulatory development activities and accomplishments in eliminating stakeholder regulatory uncertainty, while creating these deployment pathways. This includes the comprehensive assessment of nuclear safety for a broad range of nuclear technologies, as well as methods for integrating safeguards and security into these state-of-the-art systems and facility designs.

Introduction

Disruptive innovation in any industry provides a step change and lasting effect, through technological advancement that gains market share, and directly affects the fundamental way in which business is performed. These disruptive technologies, such as the smartphone, the cloud, and artificial intelligence applications, provide opportunities for efficiency and further innovation when embraced and managed appropriately.

In the nuclear continuum, disruptive technology advancements must be evaluated for appropriate application and demonstrated as safe and secure through the regulatory processes both domestically and internationally.

The regulatory process must be agile and provide an efficient and robust pathway with regulatory certainty. The regulatory process must afford developers and operators the pathway to propose and obtain regulatory acceptance of disruptive technology use within the existing nuclear fleet at a component level, in the developing advanced-reactor technologies, and as the disruptive technology in emerging industrial applications, while ensuring clean, efficient nuclear technology deployments are safe and secure.

In the US, the regulatory framework consists of four major components, namely:

- addressing unresolved and high-impact commission policy issues
- developing adaptations of LWR-based regulations & regulatory guidance
- performing R&D necessary to establish licensing technical requirement
- establishing clear expectations for licence application content and review criteria.

This paper will expand these major elements of the current US regulatory framework, and discuss identification of real or perceived barriers, potential opportunities for resolving those barriers, and recommendations for continual check and adapt processes within the regulatory environment.

The discussion is intended to be a paradigm shift, just as disruptive technologies have proven to be, and to evoke broad policy, regulatory, and research actions to enable these innovations within the nuclear industry. Idaho National Laboratory (INL) is currently working in multiple areas, such as the National Reactor Innovation Centre (NRIC), to bring disruptive innovations to the industry.

Addressing unresolved and high-impact commission policy issues

Commission policy drives regulatory acceptance and licensing of nuclear facilities and has a major impact on technological advancement in the United States and abroad. Unresolved and high-impact commission policy issues hinder the development and licensing of new nuclear due to uncertainty in licensing processes. For example, lack of completion and resolution of a technology-inclusive, risk-informed, and performance-based licensing process such as 10 CFR Part 53 has hindered nuclear design development and applications for design certifications in the United States.

Rather than have a flexible, secure regulatory process, developers are currently forced to adapt to decades-old regulatory processes intended for light-water reactors (LWRs) such as 10 CFR Part 50 or Part 52. This has cost significant time and funding to both the NRC and the developers, as these old regulatory processes must be adapted to non-LWR technologies. Other unresolved, high-impact issues and rules have included, but are not limited to, emergency planning, generic environmental impact statements and physical security.

Developing adaptations of LWR-based regulations & regulatory guidance

Due to unresolved, high-impact commission policy issues and regulatory uncertainty, many developers have been forced to adopt older, more deterministic strategies for their more advanced, non-LWR reactors. Most developers have been forced to prepare their designs to the more deterministic 10 CFR Part 50 or Part 52 regulations.

The Nuclear Regulatory Commission has been forced to develop guidance for the licensing and regulation of these new, non-LWR reactors to be licensed under existing, more LWR centric regulations. This has resulted in the use of significant NRC staff resources in the development of this guidance, thus re-focusing their efforts on other, more fruitful and advanced regulatory development. INL has supported this by hosting the Light-Water Reactor Sustainability Program (LWRS), which drives disruptive technologies into the LWR fleet and helps prepare industry for the future of advanced reactors. The use of such significant resources to develop and approve adaptations to LWR-based regulations and regulatory guidance has used significant hours of NRC staff and have slowed the progression of non-LWR-based policy development.

Performing R&D necessary to establish licensing technical requirements

Research and development activities performed in the regulatory space seek to identify and resolve technical gaps to licensing and resulting outcomes of that research can provide technical justification of a material, processes, or novel technology. These efforts inherently aim to provide regulatory certainty and can inform through technical reports or developed codes, standards, or guidance. As disruptive technologies are developed and emerge for broad application, regulatory pathways must exist to efficiently analyse the application of that technology in the nuclear environment, its fundamental benefits, and the limitations either inherent or necessitated to ensure nuclear safety and security.

Research activities in support of disruptive technologies should address these factors through research of the disruptive technology's application using prototype application, modelling and simulation, in situ-controlled testing, or a combination thereof. Some of the disruptive technologies include artificial intelligence (AI) to support inspection planning and licence development, new modelling and simulation platforms such as NRC's BlueCRAB, and the advanced fuel campaigns, which drives R&D in areas such as Tri-structural Isotropic (TRISO) fuels.

Currently, applicants use-cases are often singular and need based, driven for novel technology use in nuclear and can come at significant financial cost to a developer. Offsetting these initial R&D costs to developers individually and in the licensing space is critical to motivate usage of novel disruptive technologies.

Developing industry led and government-funded programmes to identify these disruptive technologies at an early state is critical to staying in front of emerging technologies and understanding their potential impacts to the nuclear industry and regulatory landscape. Early identification will allow for timely versus reactionary performance of nuclear application use and safety and reliability studies that will foster the creation research and development test environments and provide necessary baseline data needed for use in licensing.

Establishing clear expectations for licence application content and review criteria

Establishing clear criteria for the application of disruptive technology use in nuclear is critical to removing regulatory uncertainty for developers and operators. Actions that set the rules for use of these technologies lessen both regulatory uncertainty and provide for efficiencies within the regulatory authority and its internal processes. Clearly defining what is required for impacts analysis of these emerging tools, including design criteria, nuclear safety (such as probabilistic risk assessment), security, and cross-cutting factors will enable developers to embrace, analyse, and incorporate these innovative technologies in their designs, fully capitalising on their benefits. Providing regulatory guidance documents in combination with policy and regulatory changes is key to lowering regulatory uncertainty and lessens the potential for stranded asset projects and capital losses to developers.

In this effort, key regulatory guidance documents must be developed that look broader than just component level application or standard electrical production applications of nuclear disruptive technologies and remove unnecessary regulatory costs inherent when guidance is non-existent or ambiguous. Analysis from industry experts with government support, and endorsement from the regulatory agency, for application of disruptive nuclear in novel industrial and emerging markets must be developed. These novel deployments will certainly have unique aspects of safety and security that must be understood and have guidance that enables efficient deployment.

Conclusions

In the nuclear continuum, disruptive technology advancements must be evaluated for appropriate application and demonstrated as safe and secure through the regulatory processes both domestically and internationally. The regulatory process must be agile and provide an efficient and robust pathway with regulatory certainty. The regulatory process must afford developers and operators the pathway to propose and obtain regulatory acceptance of disruptive technology use within the existing nuclear fleet at a component level, in the developing advanced-reactor technologies, and as the disruptive technology in emerging industrial applications, while ensuring clean, efficient nuclear technology deployments are safe and secure. Delays and regulatory uncertainty have hindered the licensing and development of advanced non-LWR reactors and continues to hinder development today. The further development of technology-inclusive, risk-informed, performance-based licensing pathways will help improve the pathways available to the regulatory development and licensing of advanced, non-LWR concepts in the future.

UK Regulators - Nuclear innovation and newly emerging disruptive technologies: Implementation challenges & enablers

Dr Jake Surman (Environment Agency) and Dr Tom Eagleton (ONR)

Abstract

The Office for Nuclear Regulation (ONR) and the Environment Agency are two of the principal nuclear regulatory bodies in the UK and regulate under a largely non-prescriptive, goal-based regulatory regime which is inherently open to innovative technologies and approaches. Both regulators have, for many years, employed an enabling approach and have used this to support the deployment of a range of innovations in the nuclear sector, while ensuring that high standards of safety, security and environmental protection are maintained. ONR and the Environment Agency are jointly exploring new approaches – innovative advice, expert panels and regulatory sandboxing – and are using these to help progress regulation of disruptive innovations such as blockchain and artificial intelligence. This brief provides a description of this work, as well as a summary of key implementation challenges and enablers from a nuclear regulatory perspective.

Introduction

The Office for Nuclear Regulation (ONR) and the Environment Agency are two of the principal nuclear regulatory bodies in the UK. ONR is responsible for regulating nuclear safety, civil nuclear security and safeguards, the transport of nuclear material, and conventional health and safety on nuclear sites in Great Britain. The Environment Agency regulates the disposal of radioactive waste and broader environmental protection on nuclear sites in England to contribute to sustainable development.

The UK's nuclear regulatory regime is largely non-prescriptive and can be characterised as goal setting, meaning that it is largely technology-neutral and outcome-focused. This provides nuclear operators with flexibility around technological advancements and the use of new methods and approaches, so long as operators can demonstrate that they have suitable arrangements to meet high regulatory standards of safety, security, environmental protection and waste management. As independent regulatory bodies, ONR and the Environment Agency assess and form regulatory decisions on whether innovations are demonstrably in line with these standards.

An enabling approach to regulation, adopted by UK nuclear regulators (ONR, 2020; Environment Agency, 2022), emphasises the value of early engagement for nuclear site operators to receive regulatory advice related to the design of innovative solutions. The aim is to provide site operators with a better understanding of how the regulators require them to demonstrate safety, security and environmental protection, reducing uncertainties and costs, and increasing the chances of successfully deploying new approaches. Both ONR (ONR, 2020b) and the Environment Agency (Environment Agency, 2022) have made specific commitments to help support the implementation of innovative technologies and approaches, where it is safe, secure and sustainable to do so.

Finding new ways forward

UK nuclear permit and licence conditions require operators to demonstrate that they have suitable arrangements to meet regulatory requirements. Many requirements are based on optimisation of radiological protection, for example, demonstrating that risks from ionising radiation are reduced as low as reasonably practicable (ALARP) (ONR, 2020c) or as low as reasonably achievable (ALARA), considering environmental, social and economic factors (Environment Agency, 2021).

It can be difficult for site operators to understand how to safely deploy an innovation and how to adequately demonstrate that an innovation meets regulatory requirements, even more so if it is particularly novel or there is limited relevant good practice and experience of deployment. ONR and the Environment Agency are working to strengthen how we support innovation, by developing and exploring approaches that go beyond established ways for working.

Innovation advice

ONR has developed innovation advice as a tool to support innovators, which builds on the work ONR has already undertaken on enabling regulation. An early example of how this can be applied to disruptive technology is ONR's advice on key considerations for the application of blockchain technology in the nuclear sector (ONR, 2023b). This will support industry to further develop and progress blockchain applications, helping to reduce regulatory uncertainty.

Expert panels

An expert panel comprises a diverse group of experts collaborating to establish a roadmap for effective and enabling regulation of an innovation. The panel will typically consider the innovation at a high level and bring in learning and experience from elsewhere.

Together with the Advanced Nuclear Skills and Innovation Campus, ONR and the Environment Agency contributed to a series of ONR-convened expert panel meetings on artificial intelligence (AI) and nuclear regulation (ONR, 2022a, 2022b, 2023a). The expert panels drew together stakeholders from the nuclear industry, academia, other industries, other regulators, national laboratories and government representatives and suggested three broad opportunities for deployment of AI in the nuclear sector:

- advisory (e.g. inspections, modelling to assist design)
- supervisory (e.g. analysis of data and operational efficiency/optimisation)
- control (e.g. automation).

These three opportunities present an increasing level of challenge, associated with increasing levels of autonomy, in demonstrating that safety, security and environmental protection requirements are met.

The expert panel also derived five aspects that should be considered in the development of a framework for nuclear AI regulation.

Regulatory sandboxing

UK regulators of different industries have been developing regulatory sandboxing approaches as experimental tools to support innovation (e.g. financial [FCA, 2022], energy market [Ofgem, 2020] and aviation safety [CAA, 2023]) regulation.

A regulatory sandbox can be defined as:

> *"A controlled real-life or realistic environment (digital, physical or table-top exercise) whereby regulators and industry collaborate to test innovations, e.g. new products, services, business models or technologies. The intent of a regulatory sandbox is to explore how the sandboxed innovation can be regulated and safely deployed"* (UK Department of Science, n.d.).

In a nuclear regulatory context, ONR and the Environment Agency have established sandboxing as a tool for regulators and industry to collaborate in a non-regulatory environment. Sandboxing has provided stakeholders with a safe space to explore how innovations could be deployed and regulated.

In November 2023, ONR and Environment Agency published a joint report (ONR, 2023c) on our pilot of regulatory sandboxing, which focused on two nuclear site applications of AI. ONR and Environment Agency resourcing was funded by the UK Government's Regulators' Pioneer Fund and industry provided funds via the UK Control and Instrumentation Nuclear Industry Forum.

The findings of this work are being fed into existing work on AI within Great Britain's nuclear sector and internationally, including various IAEA initiatives (IAEA, 2024). This will contribute towards progressing a regulatory framework for AI in the nuclear sector, reducing industry and investment uncertainty and ensuring safety and environmental considerations are included at an early stage.

Regulatory research

The use of innovative approaches to progress the regulation of AI has been supported and informed by regulatory research commissioned by ONR (Adelard, 2021). Further, ONR-commissioned research is being carried out on technical and regulatory approaches that enable the safe and secure deployment of AI technologies on UK nuclear licensed sites.

The Environment Agency is currently finalising research reviewing digital and robotic innovations (including AI) relevant to its nuclear regulatory function. The overall objective of the project is to help ensure nuclear specialists are ready to regulate new digital and robotic innovations, using a gathered evidence base to review regulatory principles (Environment Agency, 2021) and standard permit conditions. The key aims are to explore whether more detailed guidance is needed to help industry comply, and whether there are any unnecessary regulatory barriers. Importantly, the evidence base is being used to inform future training needs of regulatory staff so the Environment Agency can build the necessary capability and capacity.

Conclusions

Key challenges for implementing innovations, particularly the most novel or disruptive approaches, include the lack of shared understanding between regulators and industry on the relevant safety, security and environmental considerations. It can be especially difficult for industry to adequately demonstrate that an innovation can be safely deployed if there is limited relevant good practice or experience of deployment. It is important for industry and regulators to build this shared understanding. Early and continual collaborative engagement is vital for this, as is the need for regulators to take an enabling, outcome-focused, technology-neutral approach. Pulling in diverse expertise, for example from expert panels, can be particularly valuable.

There are many benefits to experimental regulation approaches such as the regulatory sandboxing piloted by ONR and the Environment Agency. Bringing innovations out of the abstract and into practical terms means that a whole system approach can be taken. This enables existing regulatory benchmarks to be applied, ways of delivering and demonstrating safety and environmental protection to be considered, and gaps and future areas of focus to be identified.

Nuclear regulators should adopt an 'anticipatory regulation' perspective to look ahead and prepare for how the nuclear sector may change and take steps to ensure that they will be ready to regulate new technologies and approaches. As part of this, regulators should consider their guidance, capability and capacity needs, enabling them to mature in line with the rate of deployment of innovations on nuclear sites and the need to make regulatory decisions.

It should be recognised that what regulators can do to support innovations is only one aspect to their successful deployment. The wider assurance landscape and the maturity of industry to develop, deploy and demonstrate the safety of innovations are of prime importance. Proactive work by regulators, such as that indicated in this briefing, can provide vital support.

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UK Department for Science, Innovation and Technology (DSIT), facilitated Regulators’ Innovation Network.

United States Nuclear Regulatory Commission - Implementing innovation as a nuclear regulator

Milton Valentin and Adam Govia, US NRC Office of Nuclear Regulatory Research

Abstract

The implementation of new technologies for nuclear applications involves all segments of the nuclear industry. Each segment is facing a different set of challenges and questions, some of which may require new process and greater co-ordination with other parts of the industry. As the regulator for the use and handling of nuclear materials for civilian purposes in the United States, the US Nuclear Regulatory Commission (NRC) has consistently assessed and implemented innovative technologies in its processes and through licensees and licence applicants in the US This article examines how the NRC has handled innovation internally and external to our regulatory body by describing challenges and enablers to help sustain innovation while considering regulatory implications. A summarised history and description of current activities of the Innovate NRC Program is provided to explain the NRC's efforts to support the agency's transformational aspirations in becoming a modern risk-informed regulator and drive change from within.

Introduction

The implementation of new technologies for nuclear applications involves all segments of the nuclear industry. Each segment is facing a different set of challenges and questions, some of which may require new process and greater co-ordination with other parts of the industry. As regulator for the safe use and handling of nuclear materials for civilian purposes in the United States, the US Nuclear Regulatory Commission (NRC) has consistently assessed and implemented innovative technologies in its processes. Also, the NRC continuously assesses how technological innovations are used by licensees and licence applicants in the US to protect the American people and the environment. This article examines how the NRC has approached innovation both internally and external to our regulatory body by describing examples of challenges and enablers to help sustain innovation while considering regulatory implications.

Programme history

Historically, each technical area has led efforts to assess the application of new principles and methods that have the potential to increase process efficiencies while still meeting regulatory requirements. Examples include new technologies pursued by nuclear licensees, results from research and development activities, or new principles and/or methodologies proposed by professional organisations to be included in codes and standards. From a regulatory perspective, the NRC engages with experts in the specific technical field(s) as early as possible to understand the implications of these new technologies to capture diverse perspectives and a solid technical justification to ensure technologies meet applicable regulations.

The NRC has a long history of engaging with entities that are either developing or implementing disruptive innovations. However, there is ongoing work to assist the NRC become more transformative and innovative, and that might be news for some. These efforts are described in the NRC's public website under NRC's Transformational Journey.

As explained in link provided above, the NRC's journey to become a modern, risk-informed regulatory agency is ongoing. This article provides insights regarding the creation and sustainability of a formal innovation programme within the NRC, which is one of the focus areas supporting NRC's transformation.

The challenge being addressed was that the agency did not have an agency-wide best practice to monitor and promote the progressive evolution of internal processes.

In 2017, the NRC created and implemented innovation panels both at the local and agency level, with representation from across the agency to evaluate various innovative suggestions. Then in 2018, the NRC committed to developing and began putting in place the infrastructure for an agency-level innovation programme to support the pursuit of new and better ways to work while maintaining the highest safety standards. Also, the InnovateNRC programme strives towards a culture that encourages, supports, and expects everyone to identify, research, prototype and implement better ways to work.

Since then, the NRC has evaluated best practices and resources to establish an innovation programme that allows the aspirational cultural shift for innovators to enhance agency processes. As a direct result of the request from management, the InnovateNRC Program was established.

The InnovateNRC Program saw great potential in deploying and managing a platform where innovators could interact, crowd source solutions to common issues, and exchange ideas. The platform identified for this purpose, called IdeaScale, offers capabilities for crowdsourcing within the agency, which has allowed for teamwork, networking, and the gathering of platform data. This data helps the NRC understand where the agency is actively looking for process improvements and how often different segments of the organisation are considering new ways of working. The platform contributes to the holistic view the agency has adopted to assess progress towards our transformational aspirations.

InnovateNRC benefits from a network of volunteers across the agency. These volunteers serve in different capacities but share a common goal to assist and promote innovation activities. These volunteers also serve as liaisons with InnovateNRC to communicate progress and to help evaluate innovative opportunities. Innovation volunteers include both staff and management at all levels to consider diverse perspectives and leverage different influence levels.

Management support and participation has been instrumental to motivate staff in contributing towards innovation. InnovateNRC engages with volunteers on a regular basis to maintain awareness and communication within its network.

Another enabling element has been educating the whole agency about services offered by InnovateNRC. The programme initiated a series of podcasts where innovation related topics were discussed between a diverse group, to offer alternative views and share relevant details to spark interest on innovation. Simultaneously, a series of workshops were developed to help different segments of the organisation realise their contribution towards supporting innovative initiatives. Each workshop was designed to train volunteers and other interested parties on the innovation platform, to provide recommendations for socialising ideas within their organisation, and to support others in presenting ideas to increase the potential for implementation. Innovation education has allowed greater involvement and increased use of our platform. Also, it has helped others see the potential an innovative environment has on improving internal processes.

Innovators at the NRC are recognised for their contributions. Since 2021, the agency has presented an annual innovation award, where successful innovations are evaluated to select the innovation of the year. This ceremony provides visibility and perspective to the greater audience regarding examples of what can be achieved with an innovative mindset.

A key element to sustaining a culture of innovation is the sharing of success stories of innovations that have been implemented across the agency. The NRC leverages the IdeaScale platform to serve this purpose and actively promotes these successes throughout the year through various mechanisms. Another key element to sustaining a culture of innovation within the NRC has been to seek out and collaborate with agency innovators leading in key technical areas. For example, the InnovateNRC programme proactively engaged with those leading agency efforts to prepare for the application of artificial intelligence. By doing so, the programme gains insights regarding how these initiatives are shaping the landscape of technology across the agency. Also, these insights provide the programme with an advantageous point of view for recognising opportunities to co-ordinate and collaborate among groups that might not typically collaborate.

Networking and benchmarking opportunities within the NRC and with our external stakeholders are critical to know what is happening, to understand priorities of other like-minded programmes, to compare best practices and lessons learnt, while exploring opportunities for collaboration.

As regulators, a significant enabler of understanding innovation and process changes come from data. As such, the NRC has dedicated resources within its innovation efforts to assist with data collection and visualisation to support decision-making. EMBARK serves as the agency centre of expertise for data collection analytics and visualisation to support risk-informed decision-making and is a focal point for leading multi-office transformational initiatives.

Dashboards and other services provided by EMBARK are adding great value to the way the NRC is meeting its goals. Some of these products (like MAP-X) serve both NRC and external stakeholders. Their mission is to serve as the NRC's catalyst for change and is responsible for being an innovation and transformation accelerator across NRC programme and corporate offices. EMBARK is a great example of how the NRC is enabling innovation by making data visualisation available to support process improvement.

These efforts are promoting the cultural shift needed within the NRC to support our transformational goals. It is imperative to embrace this mentality so that our processes can adapt and grow with the progress happening outside the NRC. As the InnovateNRC programme continues to support the agency's goals, early communication and alignment between all interested parties may help us to cope with the nation's increasing energy demands.