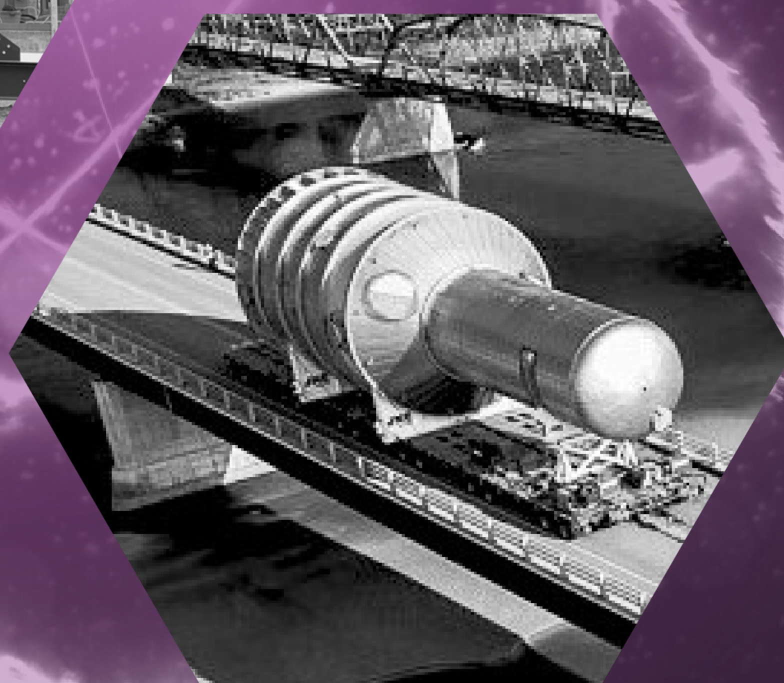
Advanced Manufacturing for Small Modular Reactors: Implications for the Saskatchewan Supply Chain



NGen SIMSA March Consulting Associates Inc.

Forward

Message from SIMSA:

The Saskatchewan Industrial Mining Suppliers Association is pleased to present this report to its members and other interested parties. SIMSA would like to acknowledge and thank NGen for providing the funding for the project. The primary goal of this study was to provide information to SIMSA members to help understand the opportunities that investing in advanced manufacturing techniques could provide in service to small modular reactor markets. This work is important to SIMSA members as they assess business opportunities in nuclear and look to differentiate themselves as providers to the nuclear sector. While this is the intended audience of this study and the primary focus of SIMSA's scope of activities, we hope this study is useful to a broader audience and will foster improved awareness of the value of advanced manufacturing across multiple sectors. We also hope this report will help to provide a little awareness of Saskatchewan's unique skills and capabilities that have yet to be tapped by the growing SMR sector.

Statement from March Consulting Associates Inc.:
March is pleased to provide this report to both SIMSA members as well as the broader audience of current or potential SMR supply chain participants from Saskatchewan and the rest of Canada. The report shares an overview of the factors influencing the development and adoption of SMR technologies and how advanced manufacturing techniques can help accelerate and optimize the delivery of SMR projects. It shares insights into the existing nuclear industry supply chain and discusses the anticipated changes and developments as SMRs become a key focus of the nuclear industry. Opportunities for members of the Saskatchewan industrial supply chain to adopt advanced manufacturing techniques to serve this market are discussed. March would like to acknowledge that this work was supported in part by Mitacs through the Mitacs Business Strategy Internship program.

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Cover Art: M. Olson, Image credits (left to right): Graham Construction Inc., Saskatchewan Polytechnic, and JNE Welding Limited Partnership.

Abbreviations

ABSA – Alberta Boilers Safety Association

AECL – Atomic Energy of Canada

AMT – Advanced Manufacturing Techniques

ASME – the American Society of Mechanical Engineers

ASME BP&V – ASME Boiler & Pressure Vessel Code

ASTM –ASTM International (formerly known as the American Society for Testing and Materials)

BWR – Boiling Water Reactor

CAMiNA – Canadian Advanced Manufacturing in Nuclear Alliance

CANDU – Canada Deuterium Uranium reactor

CIC – Crown Investments Corporation of Saskatchewan

CME – Canadian Manufacturers & Exporters

CNL – Canadian Nuclear Laboratories

CNSC – Canadian Nuclear Safety Commission

COP 28 – the 28th United Nations Climate Change Conference (2023)

CSA – Canadian Standards Association

DED – Direct Energy Deposition

DLC – Diode Laser Cladding

EBW – Electron beam Welding

EPRI – Electric Power Research Institute

ESG – Environmental, Social and Corporate Governance

FOAK – First of a kind

HALEU – High-Assay Low Enriched Uranium

HTGR – High Temperature Gas-Cooled Reactor

IAEA – International Atomic Energy Agency

IEA – International Energy Agency

IIoT – Industrial Internet of Things

IMCN – Indigenous Manufacturing & Contracting Network (IMCN)

INL – Idaho National Laboratory

IPWR – Integral Pressurized Water Reactor

LMFR – Liquid Metal Fast Reactor

L-PBF – Laser Powder Bed Fusion

MSR – Molten Salt Reactor

MWe – Megawatt Electric

MWth – Megawatt Thermal

NAMRC – Nuclear Advanced Manufacturing Research Centre, UK

NDE – Non-destructive Examination

NEI – Nuclear Energy Institute

NGen – Next Generation Manufacturing Canada

NPPs – Nuclear Power Plants

NRC-IRAP – National Research Council – Industrial Research Assistance Program

OCNI – Organization of Canadian Nuclear Industries

ORNL – Oak Ridge National Laboratory

PHWR - Pressurized Heavy Water Reactor

PM-HIP – Powder Metallurgy – Hot Isostatic Pressing

RPV – Reactor Pressure Vessel

SDO – Standards Developing Organization

SIMSA – Saskatchewan Industrial and Mining Suppliers Association

SMR – Small Modular Reactor

SR – Salt Reactor

SRC – Saskatchewan Research Council

TRISO – Tri-structural Isotropic particle fuel

TSASK – Technical Safety Authority of Saskatchewan

TSSA – Technical Standards and Safety Authority

US DOE – U.S. Department of Energy

US NRC – U.S. Nuclear Regulatory Commission

VDR – Vendor Design Review

Executive Summary

Supply chains are complex systems based on capabilities, expertise, infrastructure, logistics, contracts, trust, and relationships. The supply chain is critical to achieving project schedule, cost, and quality, particularly for large projects. Growth of supply for a particular good or service is typically driven by actual or anticipated market demand. For a relatively simple product operating in an open market system, supply chains can grow quickly and organically, such as the face mask industry that developed during the COVID-19 pandemic. However, for industries with highly specialized skill sets, long lead times and stringent codes, regulatory or security requirements, supply chain growth is significantly more restricted. Understanding the business case to enter these markets and where and/or how a competitive niche can be established can be challenging for newcomers. Nuclear supply chains embody these challenges in spades. And yet, to achieve the energy transition that the world needs, it is of paramount importance to add considerably more nuclear power generation as expeditiously as possible. Given the huge investment involved in this energy transition, it is vitally important that these projects are delivered in a cost-effective manner. All of this must be achieved while also maintaining the stringent level of quality needed to ensure the safe construction and operation of these facilities, which in addition to human and asset insurance is also paramount to retaining broader public trust. To achieve these goals, we must foster the expansion of skills and capabilities well beyond the current nuclear supply chain channels. And we must adopt new technologies such as advanced manufacturing techniques to enhance quality, reduce costs and minimize schedules. These challenges will require education, training, and investment, as well as building trust within the supplier community, as the steps needed to join this ecosystem involve considerable risks for individual businesses.

This report presents market drivers for the adoption of small modular reactors within the energy transition landscape to provide a backdrop to a business case to join the nuclear supply chain. Advanced manufacturing techniques and how they can be applied to the SMR sector are explored to help suppliers assess the potential of leveraging these technologies to establish a market niche to focus on as they enter the nuclear supply chain. The current nuclear supply chain structure is presented to illustrate both its complexity and to identify the significant supply gap that needs to be filled.

The third element of this study, after small modular reactors and advanced manufacturing are discussed, is the Saskatchewan supply chain. The capabilities of Saskatchewan's existing industrial and mining supply chain were explored to understand it's current capabilities, existing potential, the industry appetite to enter the nuclear supply chain, as well as levels of interest in adopting advanced manufacturing techniques. The broader business case for the latter was also touched on, recognizing suppliers need to build a strong business case to justify investment in these techniques.

The project identified four emerging thematic areas with the strongest potential for new entrants from Saskatchewan to leverage advanced manufacturing techniques for the support of small modular reactor

development projects: welding and joining, additive manufacturing and advanced materials, automation, sensors and smart systems and data management and logistics.

In addition to exploring the landscape, this project also sought to foster the relationships needed to make things happen. Meetings and workshops were held to connect members of the nuclear supply chain with local suppliers, as well as with members of academia, government, and Indigenous representatives, to understand one another's needs, capabilities, and interests. A framework is presented illustrating the pathway to continue to advance specific areas of interest toward joint development programs.

Supply chains rely on an interplay between technical and soft skills. While global supply chains can seem impersonal, the human element that facilitates contractual relationships is crucial, even in massive systems. The connections needed here go beyond technical capabilities, infrastructure, and capacity to deliver; they also encompass nuclear safety culture, quality programs, sensitive information, and above all, a commitment to invest in one another. Supporting new entrants into the nuclear sector requires upfront investment, from both buyer and supplier, and given the strategic importance, also from government. The more effective Canada is at building a strong domestic nuclear supply chain, the more successful the nation will be in achieving an economic energy transition that will enable Canada's energy-intensive industrial sectors to remain globally competitive.

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1.0 Nuclear Resurgence Catalyzed by Small Modular Reactors

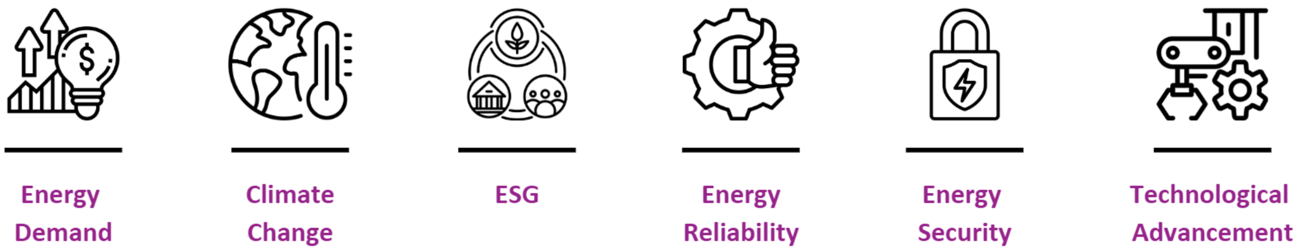


Figure 1: Drivers accelerating nuclear resurgence.

Nuclear energy has been experiencing unprecedented interest and support in recent years. This shift toward nuclear energy is being driven, in part, by the entrance of small modular reactor technologies and these 6 inter-related key drivers:

- Energy Demand
- Climate Change
- Environmental, Social and Corporate Governance
- Energy Reliability
- Energy Security
- Technological Advancement

Energy Demand

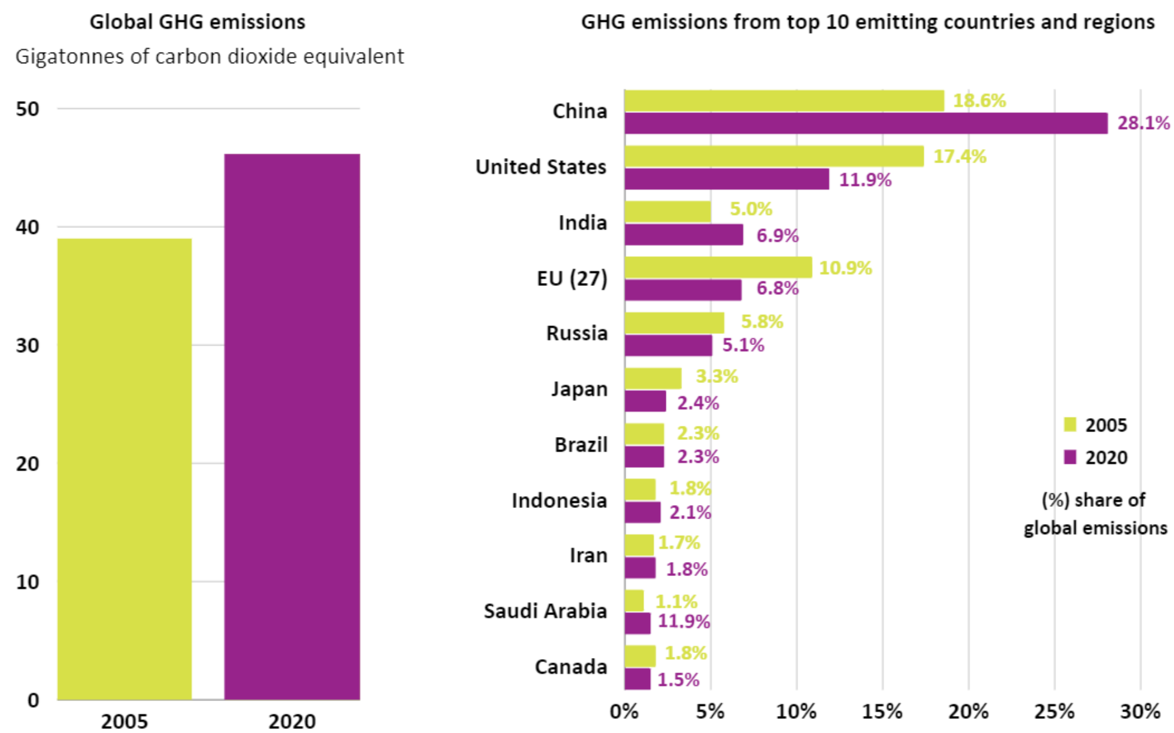
Despite widespread concern regarding the significant impacts human advancement has on our environment, and significant corresponding efforts to reduce those impacts, energy demand continues to grow. Driven by the rising global population, ever-increasing global industrialization, improved quality of life, and the continual invention of new ways to use energy, global energy use has continued an upward trajectory. The latest projections indicate this trend will continue, with forecasts putting global energy use in 2050 at 34% over 2022 levels [1].

Climate Change

The impact on the global climate from industrialization fueled predominantly by fossil fuels has become not only an environmental concern but also a significant global policy issue (Figure 2). Governments and industries worldwide seek to curb global temperature increases, primarily by reducing greenhouse gas emissions from the burning of coal, oil, and natural gas. The Paris Agreement, signed in 2015 and adopted by 196 countries, represents a pledge to take action to this effect. The role of nuclear to address this challenge was amplified at COP 28 in 2023 by the commitment of world leaders from 22 countries (including Canada) to triple nuclear generation capacity by 2050 [2]. In Canada, this manifests as a commitment to reduce GHG emissions by 30% below 2005 levels. In 2021, Canada had achieved GHG emission reductions of 8.4% thus far [3].

Environmental, Social and Corporate Governance

Growing awareness of the effects and impacts of industrial operations has led companies dependent on the markets for capital to become increasingly focused on Environmental, Social and Corporate Governance. ESG encompasses a broad set of ethical factors tied to business operations, including environmental factors like GHG emissions, water use, land use and waste management, social impacts, including affected communities and Indigenous peoples and effective ethical corporate governance. In addition to financial performance, the investment community has become increasingly focused on the ESG performance metrics of corporate entities. The importance of ESG has evolved to a point in recent years where it has become difficult for companies to raise market capital for new projects unless they can demonstrate strong ESG performance. A corporate plan to reach net zero emissions for a business is among the strongest factors investors demand from corporations.



Source: Canada.ca/environmental-indicators [4]

Figure 2: Global greenhouse gas emissions and the top 10 emitting countries and regions, 2005 and 2020.

Energy Reliability

In the modern world, access to energy is paramount to our daily lives and businesses – from transportation to communication, mining to manufacturing, food production to consumer goods, and so on. Access to reliable energy in many parts of the world is an expectation of society. As the world looks to reduce GHG emissions, we have become more aware of the convenience of fossil fuels as an energy source. Fossil fuels are relatively easy to transport and produce on demand, energy reliability. In contrast, renewable options, including hydro, geothermal, wind and solar, have geographical factors influencing where this energy can be generated, creating transportation challenges or limitations depending on energy demand requirements. Additionally, in the case of wind and solar, these sources produce energy intermittently, a challenge that the present energy storage technologies are not yet capable of mitigating sufficiently to be economic at scale. Industrialized society has become accustomed to reliable energy, available 24/7, and an energy system that does not provide this would require adaptation on the demand side, that at present is not tenable. Therefore, adopting wide-scale renewable energy requires baseload power options to be implemented alongside these technologies to maintain grid stability and reliability.

Energy Security

Ensuring a reliable and resilient supply of energy is interlinked with the stability of the global political landscape. Most recently, many countries are seeking to attain energy independence following disruptions to global energy markets caused by the war in Ukraine, conflict in the Middle East and the Red Sea/Gulf of Aden shipping crisis. This goal has tended to hasten the drive toward energy transition. New energy sources also have geopolitical considerations, though the structure may be different than fossil fuels.

Another aspect of energy security is the need to develop new energy systems, including the supply chain for fuel, fabrication of equipment and components, raw material supplies, transportation networks, etc., to support new generation sources. A resilient energy system has a robust supply chain for all aspects of materials, goods and services needed to support it. For nuclear as well as other sources of energy, building the supply chain to support the scale of development needed for energy transition will require significant investment in new mines, mills, factories, machine shops, skilled workforce, etc. In addition to the global political considerations surrounding fuel supply, access to key components needed for these new energy systems, such as metallic alloys containing critical minerals, will be a key factor in ensuring a secure and resilient energy system.

Technological Advancement

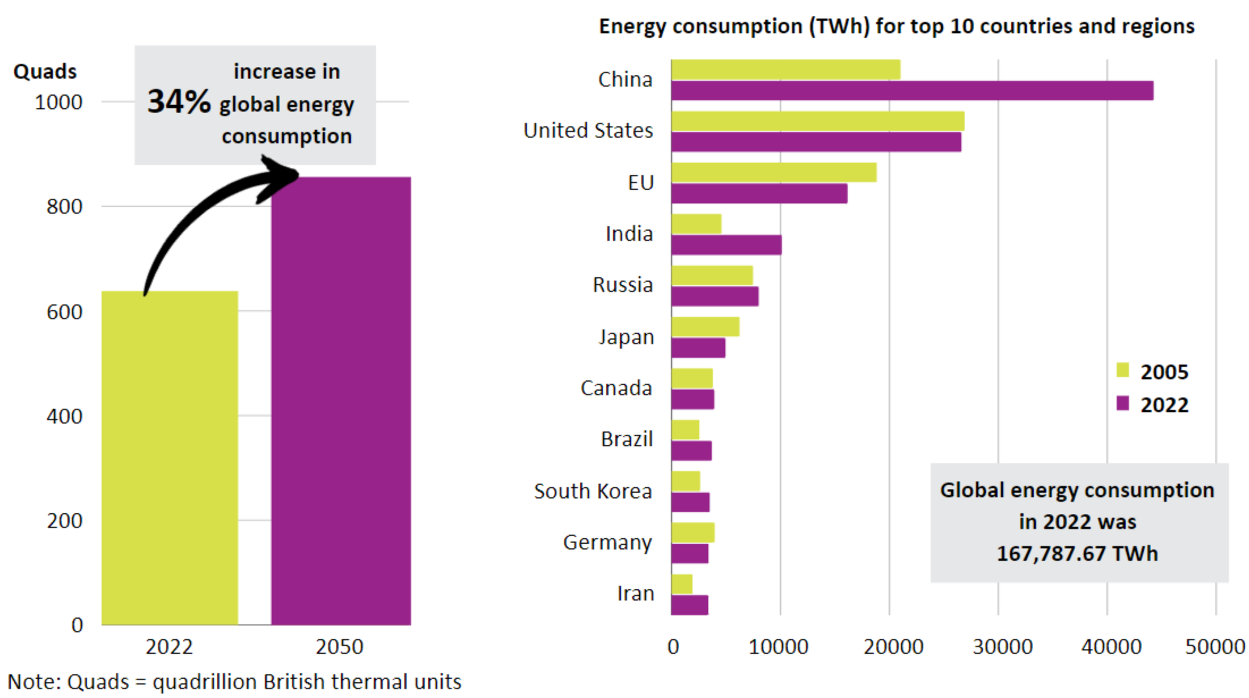
The development of small modular reactors (SMRs) is enabled in part by a myriad of related technological advancements. Improvements in digital technologies, such as simulation software, enhancements in advanced materials, additive manufacturing techniques, etc., are enabling the design and development of new reactor technologies. SMRs represent a new generation of technologies which will leverage technological advances, including safety enhancements developed from decades of experience operating larger reactors. While many of these technologies have been considered for some time, multiple designs are nearing technology readiness levels that support commercial deployment, and thus garnering interest and orders. In addition, technologies to support construction, finance, advanced manufacturing techniques, etc., have been improving concurrently. There are significant opportunities to leverage these tools to further address the cost and schedule challenges which are associated with large capital projects that demand a high level of quality, such as nuclear projects.

2.0 Energy Transition and the Role of Nuclear

In 2021, Canada's GHG emissions from power and heat usage accounted for 7.8% and 13% of the nation's total emissions, respectively. Globally, these figures stood at 39.4% and 21%, respectively [3]. According to IEA projections, global energy demand and electricity consumption are expected to increase as electrification efforts continue, until such a time when improved energy efficiency reduces electricity consumption [5]. This demand is mainly driven by growing economic development and industrialization in developing nations, particularly China and India. Presently, fossil fuels account for 80% of the global energy supply, presenting a daunting decarbonization challenge.

Since the Paris Agreement signed in 2015, many nations have focused on transitioning to clean energy, particularly in areas linked to clean electrification, including solar PVs and electric vehicles. A few countries worldwide are considering accelerating transition timelines beyond this agreement. Canada has declared 2035 as the final year for the sale of internal combustion engine vehicles (ICEVs) and has released a draft plan for Clean Electricity Regulations (CER) proposing 2035 as the new deadline to sunset fossil fuel use for electricity generation in Canada [6].

The focus on EV adoption is forecasted to put greater strain on the electrical grid. Considering the ongoing energy transition activities globally, selecting the right energy mix to achieve net zero emissions is crucial. The low-carbon technology options that are adoptable in the desired timeline include biomass, wind, solar, hydroelectric, and nuclear. Aided by the emergence of SMRs, nuclear stands to play a significant role in achieving decarbonization goals worldwide



Source: U.S. Energy Information Administration [1]; Our World in Data [7]

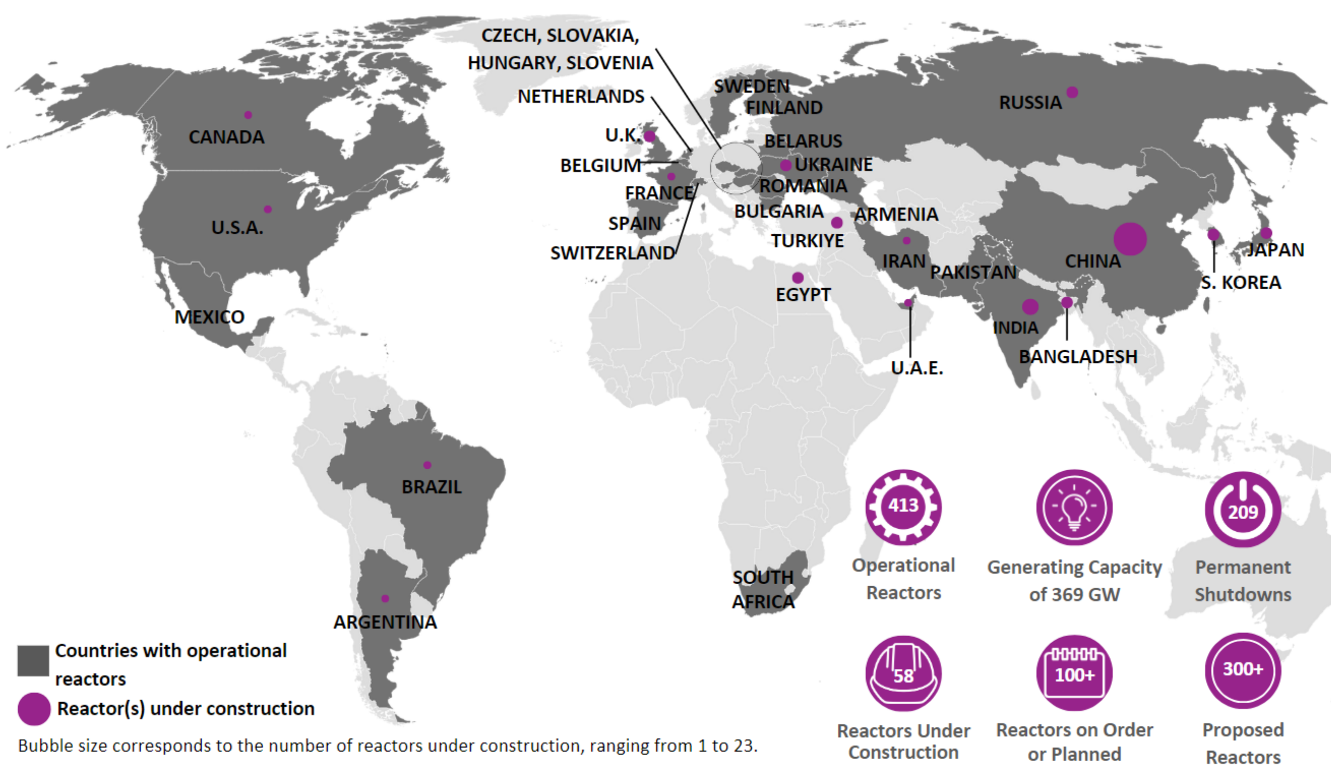
Figure 3: Global energy consumption projections and consumption for the top 10 countries and regions.

2.1 Nuclear Overview

Nuclear power is a form of energy generated from the controlled nuclear fission reactions of uranium. The heat from the fission reaction is used to generate steam, which drives turbines to produce electricity. Today, nuclear energy is used almost exclusively for electricity generation, with only some limited combined heat and power applications where residual heat is captured and distributed for localized heating.

In 2022, nuclear energy produced approximately 10% of the world's electricity, with 413 operational nuclear power reactors operating in 31 countries. While 2022 saw the retirement of a few reactors, primarily in Europe, nuclear capacity grew, with 8 GW of new nuclear capacity coming onstream, primarily originating from China, Finland, Pakistan, and Korea. This growth is estimated to continue, with projections pointing to over 900 GW of nuclear capacity by 2050 [5]. Of the total 58 reactors currently under construction in 17 countries worldwide, the largest concentration of activity is focused in emerging economies such as China (23) and India (8) [8]. More reactors are also either on order or planned, especially in Asian countries with fast-growing economies and rapidly rising electricity demand [9].

Recognizing the critical role of nuclear energy in reaching net zero, over 20 countries, including Canada, pledged to triple nuclear energy capacity by 2050 at COP 28 [2]. This goal can be achieved by extending the lifetimes of existing reactors, large-scale Gen III+ nuclear new builds, and SMRs for both power and non-power applications [10].

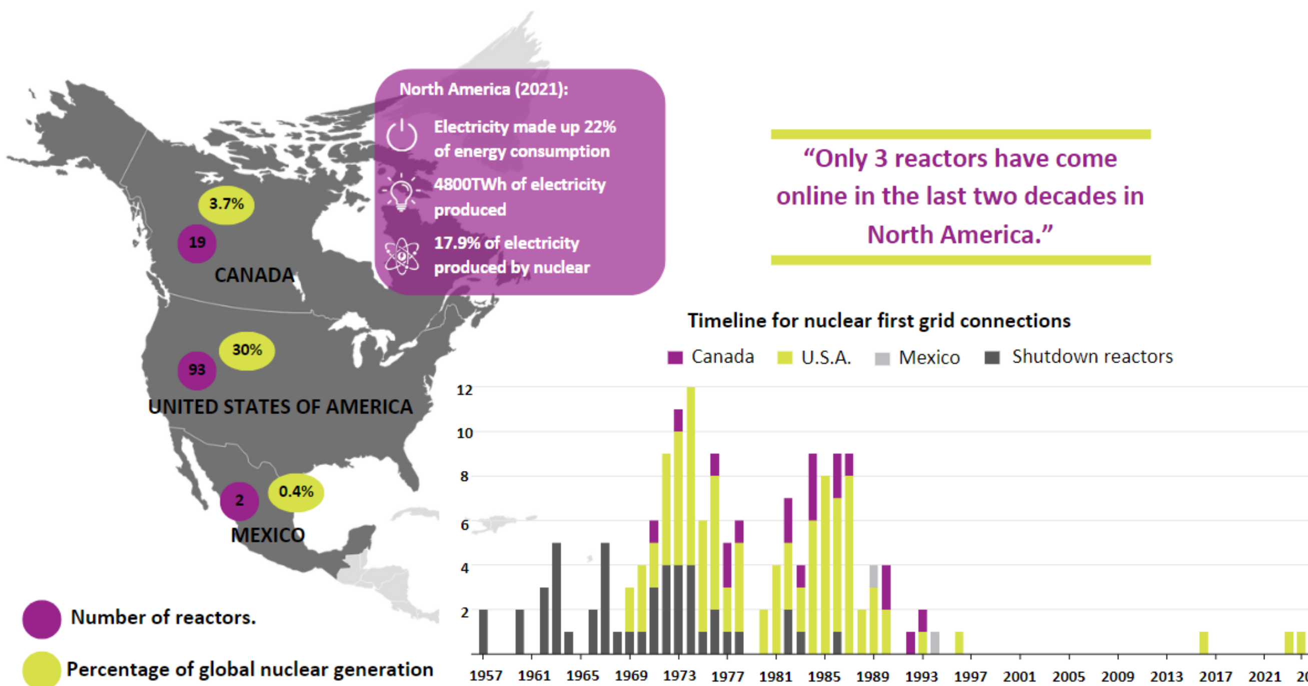


Source: IAEA Power Reactor Information System (PRIS) [11]; World Nuclear Association [9]

Figure 4: Global nuclear power.

2.1.1 Nuclear Power in North America

Canada, Mexico, and the United States all operate nuclear reactors, with Canada and the USA having a long-term active presence in the industry. Nuclear power is the largest low-carbon source in North America, accounting for approximately 18% of electricity produced in 2021. Its share nearly doubled from 1980 to 1990 and has remained stable at 18% since 1990. For several reasons, there have been almost no new nuclear constructions in North America for more than 30 years. Beyond the Watts Bar-2 and the Vogtle 3 & 4 Units in the US, no new construction has started since 2013. However, despite the slowdown in new construction, the reliance on nuclear energy has grown. There have been power uprates, life extensions and refurbishments of existing plants and planned new constructions in the North American region. For instance, in the US, the NRC has authorized 171 power uprates between 1977-2021, yielding a cumulative capacity increase of 8,029.4 MWe [12]. The NRC is also now considering applications for extending operating licences beyond 60 to 80 years and has approved 6 such applications as of October 2021 [13]. Canada has also extended the life of some of its reactors at Darlington, Bruce and Point Lepreau nuclear-generating stations. Similar developments can also be seen in Mexico, where the two reactors in its Laguna Verde nuclear plant have been granted extensions, taking their lifetime to the 2050s.

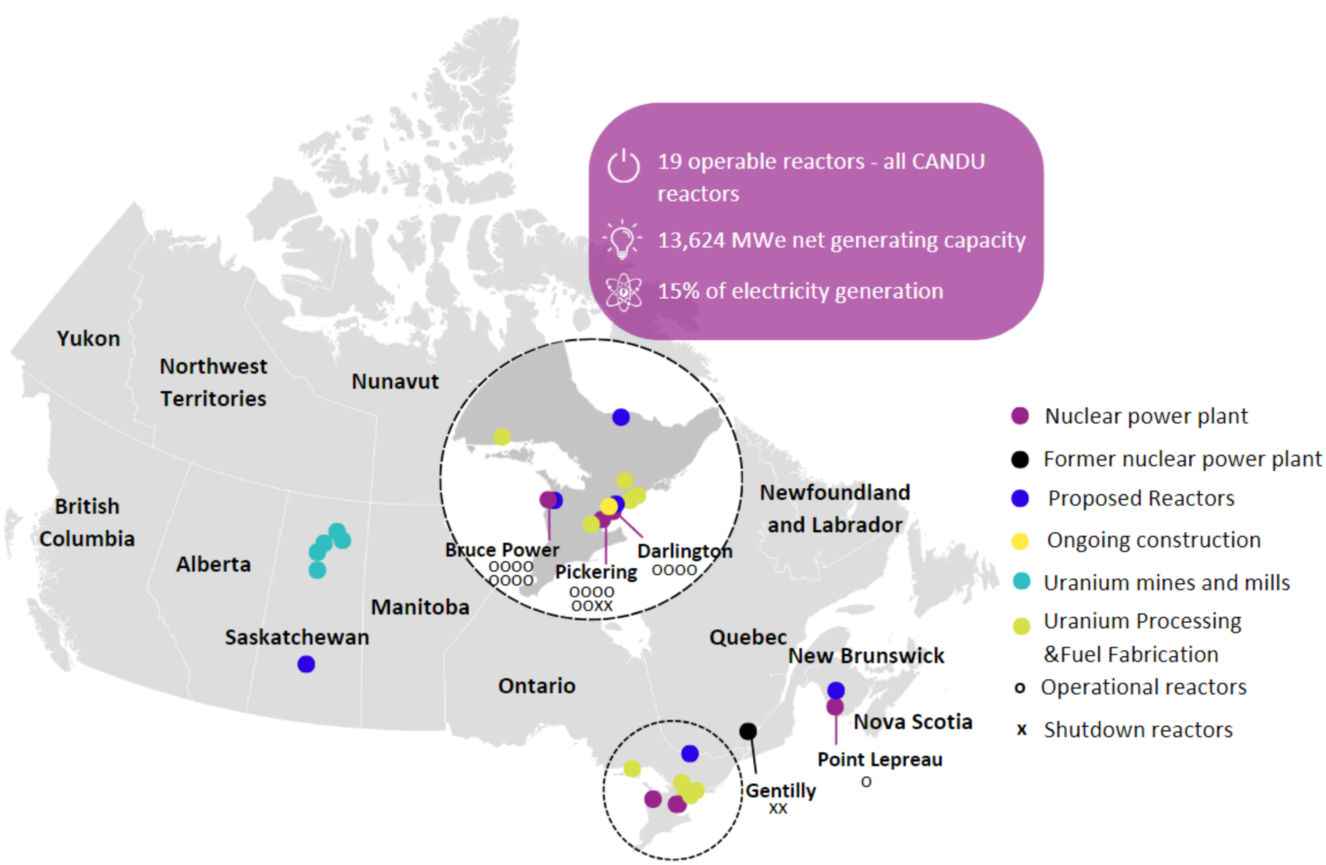


Source: IAEA Power Reactor Information System (PRIS) [11]; World Nuclear Association [9]

Figure 5: Nuclear power and first grid connection timeline for nuclear reactors in North America.

2.1.2 Nuclear Power in Canada

Canada is a Tier-1 nuclear nation. Since the 1940's, Canada has been a leader in nuclear research and technology, and in the late 1950's it started developing its own line of nuclear power reactors – the Canada Deuterium Uranium (CANDU) reactor. The CANDU reactors are products of innovative Canadian engineering that utilize heavy water as moderator and coolant, natural (non-enriched) uranium as fuel, and can be refuelled online. Today, nuclear energy is Canada's second-largest source of non-emitting electricity, with 19 operable CANDU reactors at four plants in Ontario and New Brunswick that produce approximately 15% of Canada's electricity supply. Canada also operates several research reactors and has contributed a high proportion of the world's supply of radioisotopes used in medical diagnosis and cancer therapy. Canada is the second largest producer of uranium in the world, with 514,000 tonnes of known uranium reserves, mainly in Northern Saskatchewan. Saskatchewan's nearly $1 billion-a-year uranium industry is key as the world plans to transition to sustainable power generation. The Canadian nuclear industry contributes to the Canadian economy through GDP, government revenue, and employment. This industry generates revenues of over $6 billion per annum; a value expected to increase considering the planned and ongoing expansion of the nation's uranium, nuclear generation, and isotope industries.



Source: Canada.ca [14]; IAEA Power Reactor Information System (PRIS) [11]

Figure 6: Nuclear power in Canada.

3.0 Small Modular Reactors: A New Energy Solution

Small	SMRs are a fraction of the physical size and power output of a conventional nuclear power reactor.
Modular	Systems and components to be factory-manufactured in modules and installed module by module on-site.
Reactors	Harnessing nuclear fission to generate heat that can be used directly or to produce energy.

Figure 7: Small Modular Reactors.

SMRs represent a new generation of nuclear reactor designs. The smaller size of up to 300 MWe per unit, about one-third of the generation capacity of traditional nuclear power reactors [15], is intended to provide a more versatile range of applications. In addition to fundamental research on new concepts, over 80 SMR designs are under development in 19 countries, and the first electricity-generating SMR units are already in operation in China (1) and Russia (1) [16].

SMR designs span a number of technology types, ranging from Gen III+ reactors that build on existing water-cooled reactor technology to a suite of Gen IV advanced reactor technologies, including high-temperature gas-cooled reactors, liquid-metal, sodium and gas-cooled reactors with fast neutron spectrum, and molten salt reactors.

3.1 The SMR Advantage

Compared to conventional reactors, SMRs offer the following advantages:

Modularization & Factory build: SMRs are intended to be partially or entirely built in a factory setting and installed module by module on-site. Modularization enables factory manufacturing which, by providing a more controlled environment for fabrication, has potential to enable improved quality and efficiency. It also simplifies construction, intending to reduce schedule and risk.

Safety: SMRs incorporate safety lessons learned from over 60 years of experience in the nuclear energy sector. Compared to existing reactors, the safety concept for SMRs relies more on passive systems and inherent safety characteristics, such as low operating pressures and inherently safe fuel design. The intent is to reduce reliance on human intervention for shut down and to prevent accidents by relying on physical phenomena that drive negative reactivity, such as natural circulation, convection, gravity, and self-pressurization. Passive safety systems and other design attributes such as accident tolerant fuel hold the potential to reduce overall operational risk and simplify emergency response requirements as well.

Flexibility: SMRs are designed with load-following capabilities which can integrate into energy systems with other energy sources to enable high shares of variable renewable energy. SMRs also allow more site options to host reactors, including proximal to industrial operations and potential for the remote edge of grid or off-grid locations. The designs also present multiple use-case opportunities, including grid-scale power, process heat applications for industry, hydrogen generation, desalination and combined heat and power for communities (IAEA, SMR Book_2016).

Cost and Competitiveness: Historically, economies of scale have led the nuclear sector to increase the size of reactors. However, SMRs aim to follow a different approach based on serial construction. Several technical features, such as design simplification, standardization, and modularization, play a crucial role in SMRs' cost analysis. SMRs will benefit from lessons learned from other sectors that have successfully implemented serial construction and will benefit from a progressive increase in learning rate as more SMRs of the same type are built, ultimately leading to a reduction in costs. SMR projects are on a notably smaller scale than large nuclear installations, reducing both capital outlay and related project risk, which reduces adoption hurdles and expands the market potential for nuclear to grids with smaller energy demand profiles.

3.2 SMRs in Canada

SMRs are a clean source of safe and affordable energy, opening opportunities for a resilient, low-carbon future, providing benefits for Canada and Canadians. Canada is among the world leaders in big nuclear and has now a window of opportunity to also lead in SMR deployment. It has all the necessary elements required to support the emerging SMR market: extensive nuclear operating experience, a competent and performance-based regulator, world-class nuclear laboratories and demonstration sites, a mature supply chain and domestic uranium mining, milling, refining and conversion, including natural uranium fuel manufacturing, and strong science and technology in related areas (materials science, medicine, irradiation/sterilization). Many countries across the globe are beginning to recognize nuclear power as a clean energy source as illustrated in the inclusion of nuclear energy in Green Bond programs. Developing domestic SMR expertise provides an opportunity to subsequently export Canadian technology to these growing markets. Table 1 summarizes publicly available information on SMR designs that are presently being developed or considered for deployment in Canada.

In 2019, based on an inter-provincial memorandum of understanding (MOU) between Ontario, New Brunswick, Saskatchewan, and Alberta (AB subsequently joined in 2021), the provinces issued an SMR Action Plan, which outlined a path forward for the advancement of SMRs in Canada. In 2021 OPG selected GE Hitachi's BWRX-300 for its Darlington new nuclear site and in 2023, announced plans to build three additional BWRX-300 SMRs. SaskPower also selected the BWRX-300 for potential deployment in Saskatchewan, subject to a decision to build expected in 2029. Notwithstanding, project development, licensing and regulatory work, environmental assessments and community and Indigenous engagement, are on track to enable deployment of the first BWRX-300 SMR in Saskatchewan by the mid-2030s.

Funding from the federal and provincial governments and industry stakeholders is crucial to bringing first of a kind SMRs online. The Canadian government has committed over $40 billion in new federal measures to help provinces advance new non-emitting technologies, including SMRs [17]. In August 2023, $74 million in federal funding was announced to support SaskPower's SMR development in Saskatchewan. The Saskatchewan provincial government also announced $80 million in funding for the Saskatchewan Research Council (SRC) to pursue a project to deploy and demonstrate a Westinghouse eVinci microreactor in the province.

Table 1: SMR designs and technologies being designed, constructed, or licensed in Canada.

Reactor	Type	Developer	Country of Origin	Capacity, MWe/MWth	Targeted 1st Deployment	Canadian Connections and Considerations
MMR	HTGR	USNC	USA	3.5-15/10-45	As early as 2028	Global First Power (GFP), ON
BWRX-300	BWR	GE - Hitachi	USA	300/870	2029	OPG, ON SaskPower, SK
eVinci	Heat pipe	Westinghouse	USA	5/13	2029	SRC, SK
Xe-100	HTGR	X-Energy	USA	80/200$^{(1)}$	2028/29 in USA	MOU with OPG
ARC-100	LMFR	ARC Nuclear	Canada	100/286	2029	NB Power, NB Belledune Port Authority, NB
SSR-W	SR	Moltex Energy	Canada	300/750	Early 2030's	NB Power, NB
IMSR	MSR	Terrestrial Energy	Canada	195/442$^{(1)}$	TBD	CAD Technology
CANDU-300	PHWR	Atkins Realis	Canada	300/960	TBD	CAD Technology

**(1) single unit; PHWR - Pressurized Heavy Water Reactor; BWR – Boiling Water Reactor; HTGR – High Temperature Gas-Cooled Reactor; MSR – Molten Salt Reactor; LMFR – Liquid Metal Fast Reactor; SR – Salt Reactor; IPWR – Integral Pressurized Water Reactor*

3.2.1 Benefits of SMRs to Canada

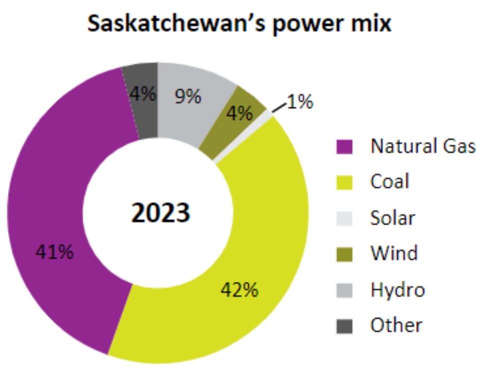
Economic Development: SMRs are estimated to yield up to $19B in total annual economic impact between 2030 and 2040 in Canada and up to $150B globally between 2025 and 2040 [18]. The Conference Board of Canada estimates that deploying a fleet of four 300 MWe reactors in Saskatchewan could yield $8.8 billion in GDP, $5.6 Billion in wages, and $2.9 Billion in taxes for the province [19].

Addressing climate change beyond the grid: In addition to addressing clean electricity, there are opportunities for Canada to leverage SMRs to address decarbonization in different applications, such as off-grid power, district heating, and desalination, in remote communities (currently relying on diesel). SMRs can also help decarbonize Canada's industrial sector, which contributes to more than 30% of Canada's GHG emissions [3]. A recent study estimates that between 2035 and 2050, SMRs could reduce GHG emissions in the Canadian heavy industrial sector by 216 Mt, equivalent to taking more than three million cars off the road each year in Canada [20].

Meeting Electricity and Energy Demands: As stated earlier, nuclear energy has an important role to play in Canada's future energy mix as we strive to reach a net-zero emissions grid before 2050 and expand clean electricity supply. While large nuclear plants are a great solution to address electricity demands in some regions, they are not ideal for all situations. SMR technologies are better a match for energy applications involving smaller electrical grid loads, remote locations, or industrial heat requirements.

SMRs and the Saskatchewan electricity grid

In 2020, the Saskatchewan electricity sector produced Canada's second highest GHG emissions after Alberta in 2020. Saskatchewan's grid still relies on about 42% coal generation (Figure 8) [21].



Source: SaskPower [21]
Figure 8: Saskatchewan electricity mix.

In addition to the pressure from the Federal Government to bring the electricity grid to net zero by 2035, the provincial utility, SaskPower, must also prepare for an increase in demand, which they estimate will double from 5,400 MW to 10,000 MW by 2050 [22]. Considering the low-emitting options available to the province, SMRs offer the following advantages.

- Most SMRs are designed to be load-following, making them ideal partners for intermittent renewables.
- SMR projects are a more manageable size and investment for the region. SMRs are the right size for the Saskatchewan electricity grid, offering different power outputs (10 - 300 MWe) to support both on-grid and off-grid applications, including decarbonization beyond the power sector.

SRC's micro-reactor (eVinci) demonstration and SaskPower's grid-scale SMR project (BWRX-300) mentioned earlier are expected to be the first of a series of SMR deployments in the province to address net zero emissions targets by 2050.

4.0 Advanced Manufacturing: Innovation in Action

Advanced manufacturing refers to using innovative technologies and methods to improve and enhance competitiveness in the manufacturing sector. Manufacturers stand to reap numerous benefits to enable them to stay at the forefront of their industries by incorporating cutting-edge advancements in manufacturing. Compared to traditional manufacturing, which effectively transforms raw materials into products through established methods, advanced manufacturing focuses on rapidly transferring science and technology into manufacturing products and processes. Advanced manufacturing is an important factor in enabling industry to keep pace with today's fast-paced and constantly evolving market demands.

Although advanced manufacturing is sometimes viewed as limited to manufacturing processes, it can and should encompass every aspect of the value chain, from conception to end-of-life considerations. It relies on information, computation, automation, software, sensors, and networking to integrate manufacturing and business activities into one seamless, efficient operation. The spectrum of advanced manufacturing technologies (AMTs) encompasses three distinct categories:

- **Efficient production:** Emphasizes simultaneous rather than sequential engineering. It involves design, simulation, advanced production technologies and control techniques.
- **Intelligent production:** Defined by real-time communication between connected devices. Uses ICT, embedded sensors, IoT, and other related technologies coupled with machine learning and data analytics to optimize production facilities through effective monitoring and regular maintenance/repair.
- **Effective organization**: Involves the efficient coordination and exploitation of physical and knowledge-based manufacturing resources. Relevant topics include virtual bidding, smart contracts, shared facilities, and resources, blockchain technologies, incubation units and e-commerce.

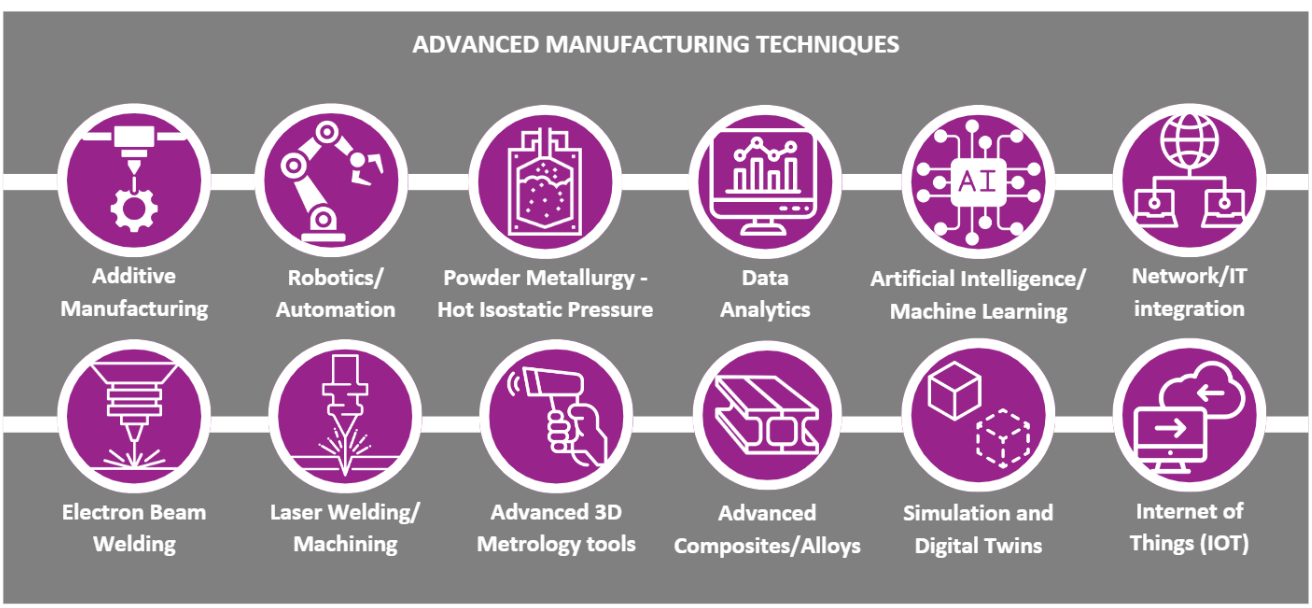


Figure 9: Examples of advanced manufacturing techniques.

Advanced manufacturing offers the following benefits to manufacturers:

- **Innovation:** AMTs allow manufacturers to edge their competition by creating innovative products.
- **Increased quality:** By applying AMTs in the entire manufacturing cycle, manufacturers can improve their productivity and product quality.
- **Reduced costs:** AMTs can reduce materials required for production, improving both production and inventory costs and can reduce labor requirements as well. They can reduce labor requirements as well.
- **Reduced time to market:** AMTs offer faster production cycles, leading to increased responsiveness to market needs and customer demands.
- **Reduced environmental impact:** Improved production efficiency leads to the reduction of waste generated during production.

4.1 Adoption of AMTs

The adoption of advanced manufacturing is revolutionizing how products and processes are created and implemented across various industries, ushering in a new era of innovation, efficiency, and precision. Organizations across sectors, such as automotive, aerospace, mining, and healthcare, are embracing AMTs such as additive manufacturing, automation, and artificial intelligence, to streamline production processes, enhance product quality, and facilitate customization. However, the adoption rate isn't quite the same across all industries.

The comparatively slow adoption of AMTs in the nuclear industry can be attributed to a number of factors; among them, low activity levels for new builds and the adherence to known, safety-proven approaches which is driven by stringent regulation and licensing restrictions. The nuclear industry's low activity levels (until recently), also served to inhibit new entrants into the workforce, resulting in reduced cross-industry hiring, as well a minimal entry of new graduates who bring new ideas and approaches from other sectors and academia.

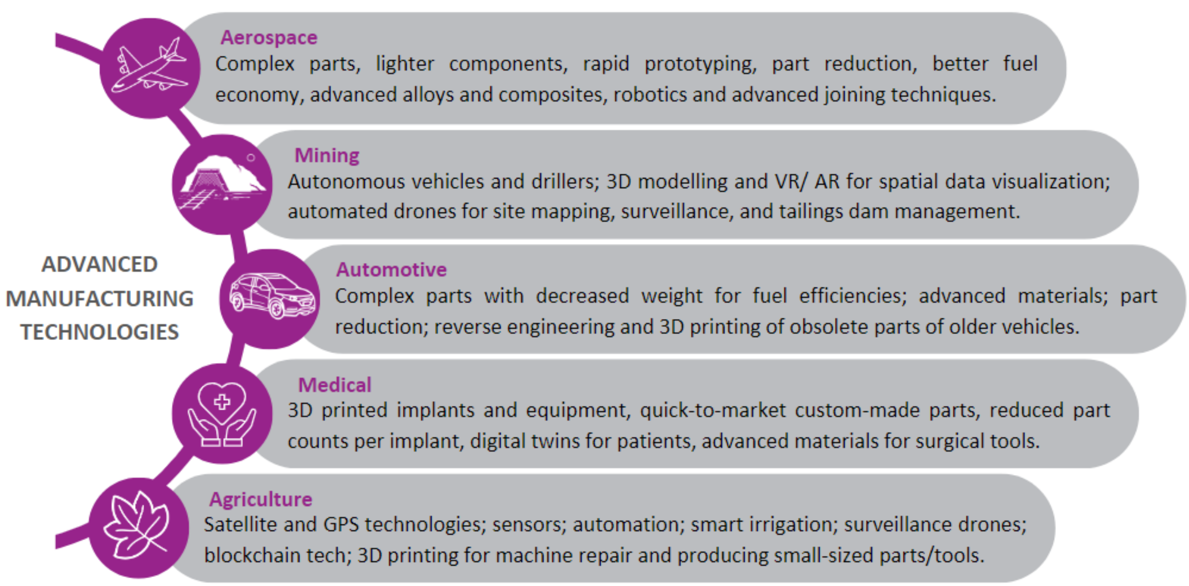


Figure 10: Adoption of AMTs in different industries.

The hazards associated with high energy density and radiation must be factored into the design of nuclear power plants (NPPs), requiring component manufacturing processes and materials to undergo rigorous testing and proof of performance to comply with the requirements of stringent nuclear codes & standards before they can be incorporated into a nuclear system. The recent resurgence of global interest in nuclear power and the need to build safe, nuclear power plants in shorter periods of time are significant drivers promoting interest in the product quality advantages typically offered by AMTs. In addition, early adoption in other industries has seen significant progress in technology advancement and standards development for various processes and components, which can provide some of the demonstration and testing needed prior to adoption by the nuclear industry.

4.2 AMTs Considered for Nuclear

AMTs have the potential to bring significant efficiency gains to the nuclear industry by producing high-quality components faster, cheaper, and with better material properties. This could improve the performance of existing operating plants and the ability to manufacture SMRs, advanced reactors, and microreactors. AMTs can also strengthen nuclear supply chains against obsolescence and reduce the need for large inventories. While the adoption of AMTs in the nuclear industry is still at an early stage, there are notable efforts to demonstrate the viability of these techniques and develop the action plans necessary for their implementation.

The discussions around AMTs in the nuclear industry have mostly been centered around direct manufacturing processes rather than the entire value chain. Many nuclear organizations and bodies like the NEI [23] and USNRC [24] have published roadmaps and documents on AMTs, identifying and evaluating various AMTs that may be of most interest to the nuclear industry; most focusing on additive manufacturing, near-net shape manufacturing, joining or surface modification techniques [23]. This study takes a more holistic approach to evaluating advanced manufacturing technologies for nuclear applications by including technologies not restricted to the manufacturing floor. The following fourteen techniques in Table 2 have been selected after literature reviews of technical reports, input gathered from conferences, and direct engagements with various key nuclear vendors. Appendix A provides a description of each of the AMTs listed in Table 2.

Figure 11: Additive manufacturing equipment at Saskatchewan Polytechnic. Credit: Saskatchewan Polytechnic.

Table 2: AMTs considered for nuclear applications.

Category	AMTs	Drivers for adoption
Joining techniques	Electron beam welding Laser welding/machining	• Reduced welding cost and time • Highly repeatable quality welds • Thick-section welding • Minimal heat affected zone (HAZ)
Near-net shape manufacturing	Powder Metallurgy - Hot Isostatic Pressing (PM-HIP)	• Reduced lead time – elimination of welds, no tooling development required • Reduced cost – reduced material wastage, reduced machining costs • Material quality improvement – homogenous, isotropic components • NDE improvement – Homogenous structure allows for easy inspection
Additive manufacturing	Direct Energy Deposition Laser powder bed fusion (L-PBF) Cold spray	• Reduced lead time – rapid prototyping, reduced inventory, obsolete & replacement components, urgent parts (plant outage demand) • Design Flexibility – complex parts, advancement of new materials, embedded sensors for real-time monitoring • Reduced costs – decreased part count, reduced environmental footprint
Surface modification	Thermal spray Diode laser cladding	• Improved surface or near-surface properties of nuclear components, especially those exposed to radioactive and corrosive environments in the reactor
Automation, sensors & smart systems	Robotics/Automation Simulation & Digital twins Artificial Intelligence & Machine Learning Big data/ Data Analytics Virtual Reality/Artificial Reality	• Components/Systems health and performance monitoring – mitigate equipment failures, boost plant health, predictive maintenance, remote monitoring • Improved plant reliability, efficiency, and productivity • Data-driven diagnosis/predictions • Improved worker training and productivity
Metrology	Advanced 3D metrology tools	• High-precision measurements • Reverse engineering • Quality control – Part inspection and testing • Imaging nuclear reactors

4.3 Development of AMTs for use in the nuclear industry

Research and development efforts for the application of AMTs in the nuclear industry have ramped up in recent years owing to the technical advancements that promise to either modernize the manufacturing of replacement components in existing reactors or streamline the fabrication of SMRs and advanced reactors. These efforts have been backed by significant public and private investments in programs that model insights from prior successful deployments of AMTs in other industries. Most of these efforts are concentrated in Europe and North America.

Europe

Engie Group, **Tractebel** and **Laborelec** have been involved in the development of additive manufacturing for several years, principally using powder bed fusion (PBF) technology. In 2019, Engie installed its first additively manufactured valve body (a non-safety classified component) in an NPP [25]. Tractebel and Laborelec are now working with the European Union's Sustainable Nuclear Energy Technology Platform (SNETP) under its Nuclear Components Based on Additive Manufacturing (NUCOBAM) program. They contributed to the production of L-PBF test coupons and NDE testing on the additively-manufactured components [26].

NUCOBAM is a 4-year EU-funded project involving a consortium of 13 European organizations from 6 countries and is coordinated by the CEA (the French Alternative Energies and Atomic Energy Commission). NUCOBAM aims to develop a qualification methodology and evaluate the in-service behavior of nuclear-grade components produced via additive manufacturing (Laser-Power Bed Fusion (PBF)) [26].

Framatome, a French nuclear reactor business owned by EDF (Électricité de France), has also been developing different AMTs for the nuclear industry, such as Powder Metallurgy- Hot Isostatic Pressing (PM-HIP), additive manufacturing, robotics, and simulation. Framatome has been at the forefront of introducing additively manufactured fuel components into operating nuclear power plants, such as fuel elements for the Gösgen NPP in Germany [27] or fuel channel fasteners in the Tennessee Valley Authority's (TVA) Browns Ferry NPP [28]. Framatome was the first industrial company to produce uranium fuel using the L-PBF process [29], [30] and is also an active contributor to the NUCOBAM project. Besides the additive manufacturing technique, Framatome is also set to commercialize a digital twin-based diagnostic technology for nuclear plant auxiliary systems [31].

Figure 12: Channel fasteners installed in TVA Browns Ferry nuclear plant. Credit: Framatome [32]

Rolls-Royce is a major player in AMTs, with involvement in seven advanced manufacturing research centres that link companies, industrial sectors, and universities in collaborative research to accelerate the development and commercialization of innovative techniques [33].

Rolls-Royce's recent HIP development work, project FAST (Future Advanced Structural Integrity), involved the world's first complete HIPed low alloy steel (LAS 508 Gr 4N) electron beam welded pressure vessel [34]. The project's main objective was to explore additive rather than subtractive processes for nuclear-quality vessel manufacture.

Figure 13: Small Vessel Demonstrator (SVD) – Upper and lower sections after HIPing. Image provided courtesy of Rolls-Royce © 2020 [35].

The **Nuclear AMRC, UK,** is a partnership between the University of Sheffield and Manchester and a consortium of industry partners, including Rolls-Royce, EDF, Areva, Westinghouse, Sheffield Forgemasters and Tata Steel, focused on developing the UK manufacturing supply chain for nuclear new builds and other nuclear market subsectors. Outside the UK, NAMRC recently partnered with EPRI and **NuScale Power** on a US DOE-sponsored SMR program to demonstrate the feasibility of manufacturing the NuScale SMR RPV under 12 months while reducing the manufacturing cost. The project demonstrated that EBW could be applied to thick-section circumferential welds. In 47 minutes, the team joined two shells with a diameter of 70 in (1.77m) and a thickness of 3 in (76.2 mm), a process that could take up to two weeks to complete using conventional techniques [36].

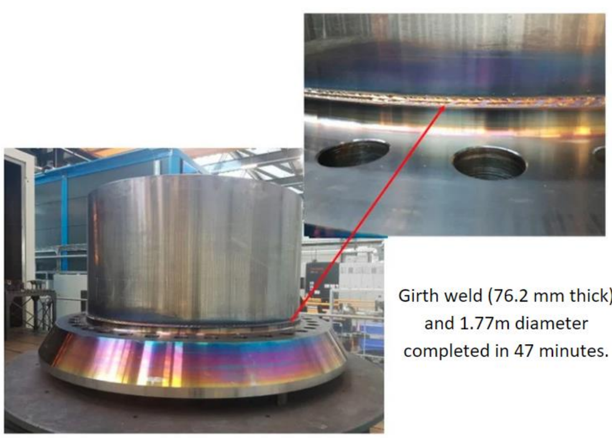


Figure 14: Electron beam welding of SA508 Gr3.Cl 2 steel. Image provided courtesy of EPRI [36].

North America

U.S.A.

In the US, the Department of Energy (**US DOE**) works with different national laboratories and research institutes to develop transformative science and technology solutions to energy, environmental and nuclear challenges. The US DOE, **EPRI**, and some industry partners are working together to demonstrate powder metallurgy-hot isostatic pressing (PM-HIP), electron beam welding, diode laser cladding, bulk additive manufacturing, and advanced machining fabrication methods at 2/3-scale to produce major component assemblies of the NuScale Power SMR design. EPRI has also developed different advanced manufacturing roadmaps for the nuclear energy industry [37], [38].

The US DOE is also working with Oak Ridge National Laboratory (**ORNL**), Idaho National Laboratory (**INL**), and Argonne National Laboratory on the Transformational Challenge Reactor (TCR) program, which is a federal R&D effort to enable technologies for advanced nuclear reactors through additive manufacturing and artificial intelligence. The program will manufacture and operationally test a fueled microreactor fabricated using additive manufacturing techniques [39].

Figure 15: 3D-printed prototype nuclear reactor core. Credit: Brittany Cramer, ORNL, US Dept. of Energy [40].

A key priority at TCR is to target a method to quickly certify the quality of components that will go into nuclear reactors [41].

The US NRC's workshops on "AMTs for nuclear applications" also contribute significantly to developing AMTs for nuclear. These workshops bring major industry players and stakeholders together to discuss practical experience and plans for implementing AMT components/technology, AMT process/part qualification and certification approaches, ongoing research, and the latest developments in codes and standards pertaining to AMT adoption [42].

Canada

AMT development in Canada has focused on additive manufacturing because it has been identified as a potential solution to address the obsolescence of some CANDU components as well as to reduce fabrication costs of SMR components. In January 2022, the Organization of Canadian Nuclear Industries (**OCNI**), along with **KSB** and Kinectrics, released an "Advanced Manufacturing Roadmap for the Canadian Nuclear Industry," with a high-level plan and 10-year vision on how to develop AMT capacity in the Canadian nuclear supply chain. To ensure progress along the roadmap, the OCNI announced the establishment of **CAMiNA** (Canadian Advanced Manufacturing in Nuclear Alliance) on March 11, 2022.

The Canadian Nuclear Laboratories (**CNL**) also develops nuclear technology for innovative applications. Recently, CNL fuel researchers successfully 3D-printed nuclear fuel using uranium dioxide (UO_2) [43]. CNL and AECL are also building an Advanced Nuclear Materials Research Centre (ANMRC), slated to be one of the largest nuclear research facilities ever constructed in Canada. This initiative is part of a broader Chalk River Campus revitalization project, backed by a substantial $1.2B investment from the Canadian government. Upon completion, the ANMRC will serve as the backbone of CNL's research and development infrastructure [44].

Industry-led initiatives and collaborations have also facilitated the adoption of AMTs for nuclear applications. For example, **Kinectrics** is collaborating with the Nuclear Innovation Institute (NII) and Bruce Power to create a standard framework and qualification process for an additively manufactured (PBF) hydraulic manifold, an essential component in an inspection tool deployed during station outages to assess reactor component condition. Design review for manufacturability is ongoing with Burloak Technologies, with subsequent phases focusing on manufacturing and material qualification, including pressure boundary integrity assessments. Next Generation Manufacturing Canada (**NGen**) is building world-class advanced manufacturing capabilities in Canada by spurring innovation and collaborations and providing funding for different advanced manufacturing projects across various industries, including nuclear.

Similar to the NRC workshops, the annual CNS International Conference on Disruptive, Innovative and Emerging Technologies in the Nuclear Industry (**DIET**) facilitates AMT adoption by providing a forum for nuclear industry professionals, academics and regulators to exchange views, ideas and information relating to innovative technologies that are available or currently having an impact in the nuclear industry.

Presently, the international nuclear industry's adoption of AM technology consists of control room parts such as control knobs and electrical casings, some quality level 4 or equivalent components and a few pilot cases within reactor environment [45].

4.4 Regulatory framework for adopting AMTs in the nuclear industry

Regulatory framework considerations are discussed here in a Canadian context; however, even within Canada, other US or international regulations or standards will have applicability to the extent that they may be referenced by or influence the content of prescribed Canadian requirements. It is essential to recognize that even SMR technologies destined for a Canadian application may be designed by a vendor to meet the additional requirements of other jurisdictions and support sales into these jurisdictions. Thus, even though a reactor in Canada will be designed and licensed to meet Canadian regulations fully, additional manufacturing requirements may be embedded in the equipment supply specifications, which originate from non-Canadian sources. A supplier's business case for investing in AMTs for the nuclear market in Canada may also include the subsequent supply of similar equipment or services to non-Canadian markets. Thus, non-Canadian regulations and standards may be of consequence to a Canadian manufacturer.

As mentioned earlier, advanced manufacturing discussions for nuclear often focus on the implementation of direct manufacturing processes, such as EBW or PM-HIP technologies, where the focus of relevant regulations will be on the resulting properties of the materials in the manufactured component – properties which are critical to meeting the structural and environmental design requirements for the equipment throughout its lifetime. However, other types of AMTs, such as the application of data capturing, advanced analytics, artificial intelligence, digital transformation, or virtual reality, may not be directly affected by regulatory frameworks. There is, thus, sufficient room to explore some AMTs without adhering to rigorous nuclear regulatory constraints.

For 'nuclear' supply, there will always be quality assurance requirements, which will apply to all facets of the supply chain, so any process implemented must be demonstrated to function reliably, no matter what role it plays in the supply cycle. However, the extent of these requirements will depend on the system in the facility for which the product is destined, because not all equipment at a nuclear facility is directly employed in operating the nuclear elements of reactor operation. The requirements for some non-nuclear island, or 'balance of plant' equipment at a nuclear facility may look and very much feel like a commercial supply to any other industry.

Where there is a regulatory framework integral to the supply of goods or services provided by a manufacturer, most of the requirements will be determined by others upstream of the issuance of an actual supply contract. Thus, although regulatory compliance is important, detailed knowledge of all regulations that dictate manufacturing requirements by the manufacturer may not be essential.

No codes or standards are mandatory unless and until they are invoked, directly or indirectly, by the conditions of a reactor license, which in Canada will be issued by the CNSC. As nuclear facilities are federal sites, even provincial regulations are not applicable unless invoked directly or indirectly by the CNSC. The heart of the regulatory structure in Canada for nuclear reactors is illustrated in Figure 16.

Although it is the reactor 'Operator' who must hold the license to construct or operate a nuclear reactor, an important additional element to the process is the availability of a Pre-Licensing Vendor Design Review (VDR) process which the reactor vendor can undertake in advance of a license application by the Operator, for a preliminary assessment of a design to CNSC regulatory requirements and early identification of any fundamental barriers to licensing.

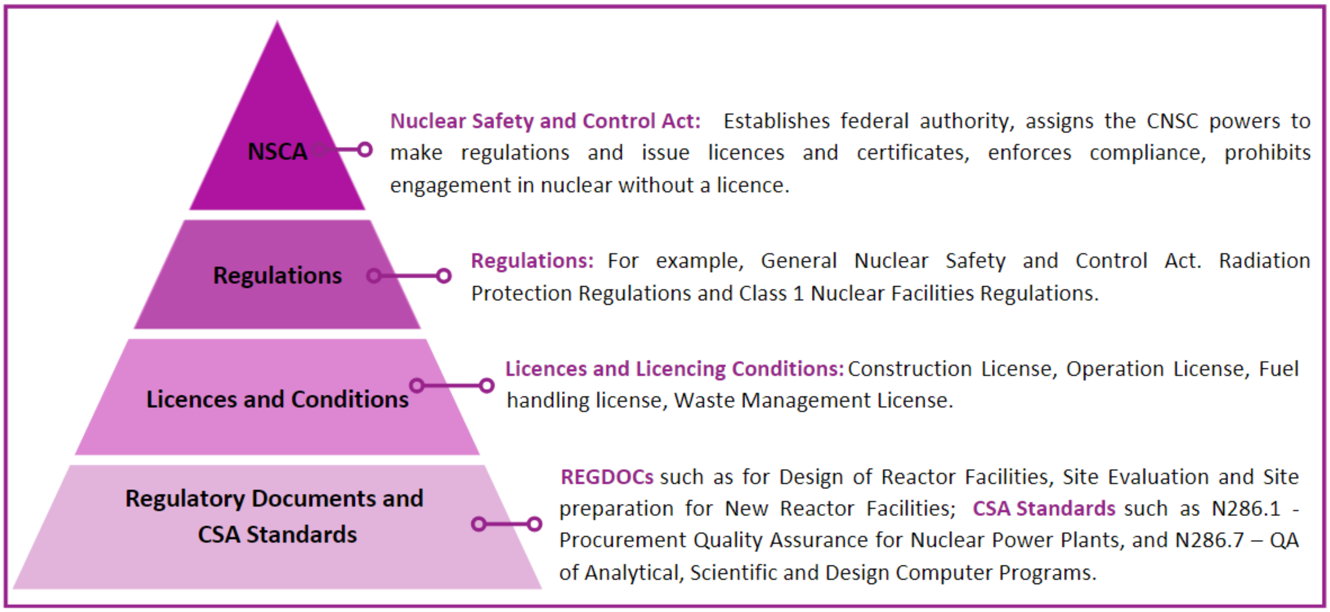


Figure 16: Nuclear reactor regulatory framework in Canada.

An element of the CNSC regulatory involvement that will be important to introducing AMTs to nuclear is that the CNSC requirements are largely a 'non-prescriptive', performance-based approach, which allows a nuclear vendor to propose a method to achieve a desired safety outcome. This approach is specifically intended to provide flexibility to enable, and more easily adjust to, the introduction of new technologies, processes, and procedures.

How might these regulations affect the supply of materials for nuclear?

At the heart of any equipment supply is the material of which it is constructed. Globally, there are numerous voluntary consensus technical standards which provide material specifications. These standards strive primarily to control a material's chemical and physical properties, although not exclusively.

An important classification for the supply of a product is whether it is considered a 'pressure boundary' item. If it is, then the materials, the fabrication, and the examination processes will likely need to be in accordance with the requirements of the ASME Boiler & Pressure Vessel Code. This is an example of a US standard invoked by a Canadian standard (CSA N285) for the supply of 'nuclear' pressure vessels and components. CSA N285 itself is a non-mandatory standard, but it becomes mandatory when embedded in, wholly or partially, by the Canadian regulator conditions of the reactor license.

An ASME material specification may be equivalent to an ASTM or other material standard, or it may invoke additional requirements for a nuclear application. Even the ASME material specification itself, however, may be insufficient to detail all of the material supply requirements. For example, there might be an additional restriction on cobalt content for a specific application in nuclear due to its propensity to become radioactive when subjected to neutron bombardment in reactor environments.

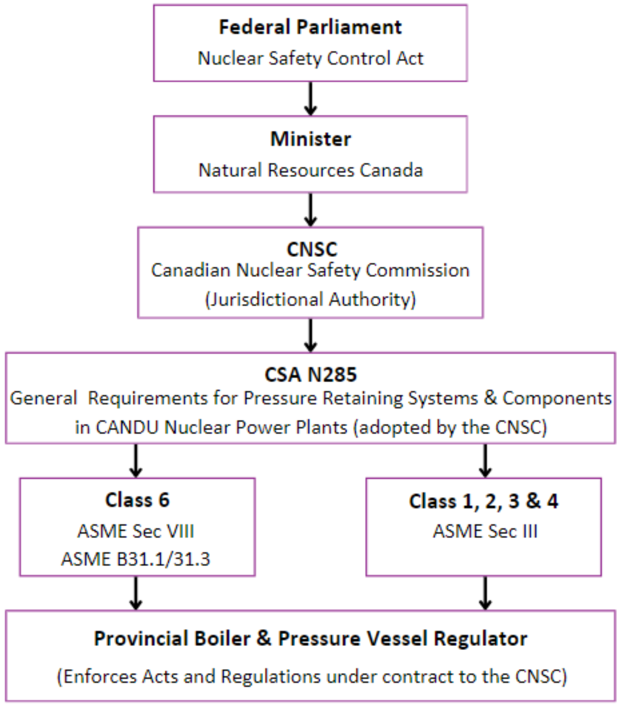


Figure 17: Nuclear pressure boundary equipment regulatory structure in Canada.

Not 'all' materials that make up the pressure boundary of a nuclear pressure vessel will have an ASME material specification. For example, a sight-glass window may be required in a flowmeter. As there are no ASME material specifications for glass, the integrity of the glass for this particular nuclear application can be adequately demonstrated by conducting burst tests at pressures sufficiently above the design/operating pressures of the particular application, using samples of glass from each batch supplied. This could be an important concept for possibly introducing advanced manufactured components.

The integrity of the material, no matter what specification it is purchased to, is only as good as the quality program under which it has been supplied. Where a material does not have the nuclear pedigree, i.e. if, for example, a nuclear pressure boundary part does not come with a certified material test report from an ASME-qualified nuclear supplier, then an accredited nuclear manufacturer may upgrade the material to the required nuclear standard by performing physical and chemical testing of the material to confirm its specified properties. This is another potentially important concept for the supply of advanced manufactured materials.

The NRC has specific Code of Federal Regulation criteria, which, if complied with, can exempt a 'pressure boundary' part from the ASME code entirely. In Canada as well, it is up to the licensee to make a case to the CNSC as to why a given component might be deemed exempt from any particular code or standard; thus, early consideration by a reactor vendor as to the adoption of an AMT for particular reactor components may be important.

4.5 Challenges and opportunities with adopting AMTs in the nuclear industry

Integrating advanced manufacturing techniques into the nuclear industry faces many challenges that must be addressed before they can be widely adopted, but there are opportunities to help overcome these challenges as well.

Reactor Design

Although there are numerous challenges in adopting AMTs for SMRs, one distinct advantage that SMR technologies have is that they are new. With larger reactors using well established technologies, there may be some reluctance to stray from tried-and-true part designs. With SMRs however, equipment and components are being designed from the ground up, and thus the designs can take advantages of AMTs which today can be employed and have their capabilities embedded right into the parts basic form, potentially giving them desirable features such as reduced weight or complexity, that were simply not attainable previously.

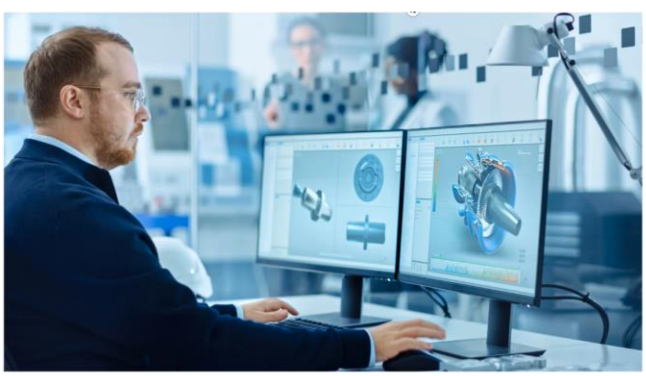


Figure 18: 3D visualizations enhance design.

Standards Considerations – ASME code cases/CSA

Developing and validating AMTs for nuclear use is essential in ensuring that the fabricated component will meet nuclear quality expectations and serve its intended function over its design life. The lack of established codes and standards for the nuclear applications of AMTs makes it difficult for manufacturers or the operator to identify which criteria must be met and what could be deemed acceptable to the safety authorities to maintain the same level of quality and reliability offered by a component manufactured by conventional methods.

While standard developing organizations (SDOs) are developing qualification methodologies to overcome these issues and enable the codification of AMTs in nuclear applications, the overall process is lengthy and usually limited to select technology variants and qualified materials. For instance, ASME recently approved PM-HIP use in Section III based on approved Code Case N-834, but the code only covers applications using alloy 316L SS (UNS S31603) [46].

Indeed, current standards and regulations are not equipped to deal with the entirety of AMTs being considered for nuclear. Still, the opportunity here is that there have always been paths for unique materials and processes to be used in nuclear applications. It becomes a question, of course, as to whether the importance of an AMT warrants the time and expense involved to qualify its use and/or whether or not sufficient flexibility is included in the licensing of the SMR reactor technology to allow for it.

Our study did identify however that some AMTs (e.g. EBW, PM-HIP) have been codified in non-nuclear codes and standards, and lessons learned from these should be maximized to translate them into a nuclear context to accelerate the qualification process. Additionally, innovations made in other industries can inspire solutions to challenges in the nuclear industry, leading to more rapid advancement and adoption of AMTs.

Addressing these challenges require collaborations between vendors, suppliers, academia and R&D organizations, standards developers, nuclear operators, and governments. SDOs and research institutions can also collaborate on international qualification projects to develop harmonized AMT codes and standards for the nuclear industry. The timeline involved requires planning and investment in advance.

Once a full suite of codes and standards have been developed or revised to fully address the implementation of the AMTs of interest to the industry, there will be better defined and hopefully more streamlined processes for the adoption of advanced manufacturing technologies to support the development and supply of Small Modular Reactor technologies. Market conditions for nuclear energy today are driving these developments.

Regulatory and Licensing

As is evident from the regulatory discussions above, one of the biggest challenges with adopting AMTs for nuclear applications is that most of these technologies are unproven for service in the nuclear industry. Before new manufacturing methods can be adopted in the nuclear industry, certainly for reactor critical components, there must be proof of their viability in service in a nuclear environment, and evidence of compliance with at least the intent of mandated codes and standards.

The integration of AMT in nuclear is still in its infancy, and understandably, most operators and technology vendors are treading with caution. The absence of AMT specific considerations in many established codes and standards, the lack of associated demonstration test work, as well as the risks typically associated with being first movers, can slow down or even ultimately discourage the adoption of these techniques. Additionally, some AMTs are being considered for large-scale applications (e.g. large-scale additive manufacturing and PM-HIP), which have not yet been explored even in adjacent industries. Therefore, more research and process development are necessary to push the adoption of these technologies further.

Regulatory acceptance can also be a bottleneck when exporting reactor designs to new markets due to differences in national regulatory requirements. These challenges are magnified when it comes to SMRs, as their factory-based manufacturing approach will be difficult if the standards to which they must be manufactured are not aligned.

Figure 19: Quality control inspection.

In Canada however, nuclear technology vendors can undergo a process called Vendor Design Review where the reactor technology is evaluated and the Canadian regulator for nuclear plans, the Canadian Nuclear Safety Commission (CNSC) provides feedback on whether the submitted documents appear to cover the requirements of CNSC regulations and where there may be gaps or areas requiring additional information. This process is meant to streamline the licensing process when an entity seeks to deploy a particular reactor technology, but it does not provide a 'license' for the technology.

This process is also an opportunity to demonstrate through design, that new AMT driven material or structural characteristics can meet operational safety expectations, without reliance on the directives from

Codes and Standards invoked for conventional methods. Providing the proof is up to the vendor.

Material Development and Supply

Material sourcing involves carefully selecting and procuring high-quality, compliant, reliable materials. It is a crucial part of ensuring the safety, reliability, performance, and economic viability of SMRs. This stage identifies critical reactor components and long lead time items and ensures timely sourcing of these materials to avoid delays in the manufacturing schedule. It also helps to identify and mitigate potential risks in the supply chain by considering alternative suppliers and sources to build a resilient and reliable supply chain.

Many of the alloys found within nuclear applications have been manufactured using traditional methods such as forgings and have been subjected to applications at reasonably low temperatures (<400 ^{o}C). However, as the industry moves towards the higher temperatures (550 – 750 ^{o}C) involved with advanced reactor applications, additional alloy qualifications will be required. Presently only six materials have been approved for high-temperature nuclear applications in the ASME B&PV code [47]:

- Type 304 and 316 stainless steels
- Alloy 800H
- Grade 91 (9Cr-1Mo-V)
- 2-1/4Cr-1Mo
- SA508 Grade 3 Class 1 and SA533B Class 1
- Alloy 617 – most recent addition in 30 years. Allows designs of up to 950 ^{o}C unlike other approved materials that could not be used above 750 ^{o}C [48].

Additional alloys are being considered for nuclear applications, and qualification work is currently underway for some of them. EPRI developed an Advanced Reactor Materials Development Roadmap highlighting many of these alloys, which is a great resource for further detail [49].

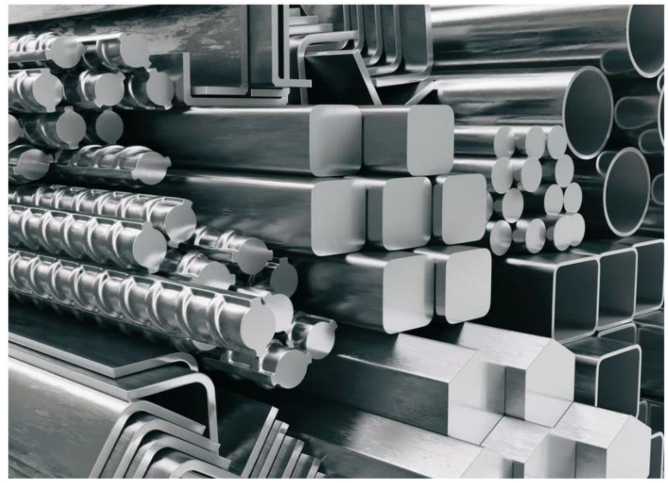


Figure 20: Stainless steel products.

Additionally, **material qualification** for components made by AMTs for nuclear use poses another challenge to their adoption. For components produced using traditional methods, their final properties can be predicted due to established processing conditions and the abundance of data accumulated over time. However, this is not always the case with some AMTs. For instance, the inhomogeneous nature of additively manufactured components can lead to greater variability and uncertainties in material performance. Components produced with a similar additive manufacturing process and feedstock material can have different properties, defects, and performance, which can vary between machines and batches of production. Qualifying such methods and understanding the long-term behavior of such components when exposed to high temperatures, stresses, radiation, and corrosive environments will be time-consuming, costly, and require a large statistical database, especially when varying microstructures and properties are considered throughout the part volume.

This translates to long-term testing and data gathering. Sometimes, the challenge lies in developing testing methods for the components manufactured using these techniques. For example, traditional NDT methods designed for homogenous materials might not always be appropriate and sometimes require specific adaptations to account for the inherent anisotropic nature of additively manufactured parts. Testing methods may also vary for similar parts produced using different additive manufacturing processes.

There are however also opportunities that are unique in nuclear, to the SMR industry. These opportunities lie in the quantity and diversity of SMR development projects around the world. The level of activity by scientists and engineers around the globe, in so many countries, directed to the challenging of establishing qualified materials for these new applications, presents an opportunity that with enough international collaboration, the process of qualifying materials could be accelerated.

Figure 21: Magnetic particle inspection (NDE).

Innovation/Development Risks

The investment required to get through the innovation step of designing and producing parts with AMT can be challenging for both the vendors and the suppliers. Getting over the innovation hurdle is one thing; the challenge of the 'newness' of SMR designs is another. There's a cost factor, too. Continuing to innovate and improve the design, is counter to standardizing SMR manufacturing enough to see capital cost gains from the nth unit.

Additionally, talent gaps can slow the innovation and adoption of AMTs. Vendors seek specialized skills and expertise to fast-track innovation and finalize designs. At the same time, suppliers require experts to operate complex AMT equipment/systems – experts not readily available in today's job market. Hence, there is a need for investment to upskill the existing workforce and create a career pathway into the industry.

The advantage that the nuclear industry has however, which is applicable to nuclear, is that it has a long planning cycle. Suppliers will know facility construction intentions many years before the first shovel hits the ground, giving them a lead time to plan on how to develop necessary skills and manpower resources etc. This is not the case in every industry.

Cybersecurity

Safeguarding critical data and ensuring system resilience against cyber threats are top priorities for critical infrastructure like nuclear power plants (NPPs), thus despite all the benefits that AMTs offer, the nuclear industry faces a significant challenge in adopting digital AMTs due to the ever present and growing threat of cyber-attacks. These cyber-attacks can come in the form of information theft like in the Gori NPP, South Korea (2014) or sophisticated attacks targeting specific process control systems like the Stuxnet attack at the Iranian uranium enrichment facility at Natanz. The important question is thus how can AMTs be developed and implemented in a manner that does not increase the risk of any kind of postulated cyber-attack.

Cyber security in nuclear programs is a global issue, with different national nuclear bodies requiring adherence to strict rules and standards before AMTs like robotics, automation, and IoT can be implemented. For instance, in the US, the NRC issued the 10 CFR 73.54 Cyber Security Rule, requiring nuclear plant operators to submit a cyber security plan for Commission review and approval. In Canada, nuclear operators must comply with the requirements of CSA N290.7:21 – Cyber security for nuclear facilities.

Figure 22: Cyber protection measures are essential for SMRs.

Even in this context, there are some opportunities that the SMR industry offers over conventional nuclear plants. Nuclear facilities for years have been backfitting safeguards into established processes, procedures, and technologies, to stay ahead of cyber security threats. The advantage that AMTs for SMRs will have here is in their newness. Processes, procedures, and technologies are being developed from the ground up, with cyber security threats front and center in how everything is structured.

Limited supply chain availability and interest

For new innovative technologies to be adopted, there of course must be sufficient appetite within the supply chain to do so. New equipment and technologies like EBW and PM-HIP require significant initial investment, and without concrete agreements/contracts to demonstrate ROI for early adopters, some suppliers may have difficulty justifying investment in AMTs.

Suppliers can justify investment in AMTs by diversifying the scope of application beyond nuclear. Not only does this help spread risks across various industries, but it also offers the possibility of increasing the suppliers' technical know-how and transferring lessons learned in other industries to the nuclear industry. Diversification can also lead to an increase in production volumes, reduced costs, and economies of scale, making AMTs more financially attractive. By broadening the business case, suppliers can create a more resilient and sustainable foundation for adopting AMTs.

5.0 Nuclear Supply Chain

5.1 Existing Nuclear Supply Chain

5.1.1 Canada

Canada has been a player in the nuclear industry essentially from its beginnings in the 1940's. Canada developed its own power reactor technology, the CANDU, and all Canadian power reactor deployments have been CANDU technology reactors. As a result, the Canadian nuclear supply chain evolved to be very focused on supporting these technologies. Most of Canada's reactors are situated in Ontario, which resulted in the majority of the traditional supply chain developing in this geographic region as well.

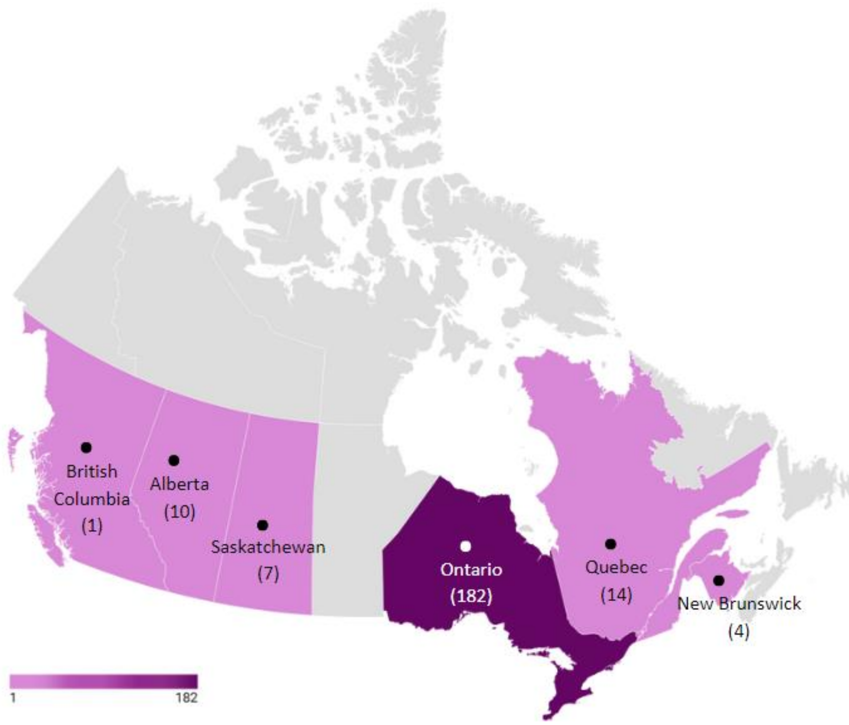
While the last CANDU reactor in Canada came on stream in 1993, refurbishment of CANDU reactor units at Bruce Power and Point Lepreau in the late 2000's through 2013 kept the Canadian nuclear supply chain active. After a seven-year break or so, refurbishment ramped up significantly at both Bruce and Darlington in 2020, which led to a significant increase in activity in the Canadian nuclear supply chain. Work to refurbish 10 of Canada's 18 reactors carries a price tag of $25 Billion. Refurbishment projects involve upgrades and replacements of components such as instrumentation, pressure tubes, etc. A single refurbishment project is estimated to provide 6,500 direct years of employment.

In January 2024, the Ontario government announced plans to fully refurbish Pickering as well and there are rumblings of potential studies looking to restart the Gentilly site in Quebec. The activity these projects have generated has allowed the existing CANDU-focused Canadian nuclear supply chain to begin fostering the training and development of a new generation of talent in the industry. While some aspects of CANDU technology are unique, nuclear services honed on CANDU projects can relatively easily be shifted to support the deployment of new SMR technologies. Undoubtably, the recent refurbishment activity in Canada has helped to positively position and prepare the local supply chain for upcoming SMR projects.

The structure of the CANDU related nuclear supply chain is largely Canadian-centric, due in part to the fact that while the United States is a strong player in nuclear, they have not deployed any CANDU units, thus, the American supply chain has shown limited interest in the direct supply to the CANDU market. However, the low level of American supplier presence supporting in the Canadian nuclear projects is unlikely to continue with the adoption of SMRs, many of which are based on American-sourced technology. Instead, an evolution to a more integrated North American supply chain for SMR nuclear projects seems likely.

Canadian projects will continue to involve significant local supply chain content, and, in some cases, there will be intentional efforts to ensure this takes place. For example, in the development of the Darlington New Nuclear Project which is deploying the first of four planned BWRX-300 reactors (a grid scale SMR technology produced by GE Hitachi), Ontario Power Generation has pledged to utilize large percentages of Ontario supply chain content on the project. The Conference Board of Canada has estimated that the four BWRX-300 projects will increase Ontario's GDP by 13.7 Billion and sustain on average 2,000 jobs per year [50]. New Brunswick Power is also seeking to utilize a strong local content for the deployment of an ARC-100 reactor and has been evaluating local capabilities in an effort to right-size these targets. While SaskPower has yet to set local participation goals (or formally commit to building their first unit – a decision which is targeted for 2029), it is expected that some targets will be identified here as well.

While some aspects of localization relate to policy and government interests in economic activity, there are additional reasons to engage localized suppliers. Factors such as minimizing transport costs, reducing lead times, ensuring rapid response and flexibility, all favor localization. Some aspects of nuclear projects rely on, or benefit from local knowledge of the area and, for some services geographic proximity is a necessity, both for construction and during operation. Components requiring highly specialized knowledge and equipment, however, are sourced from where these capabilities are available, with locality only entering the mix if other important quality, safety, and expertise criteria have been met.



Source: OCNI member directory 2023 [51]

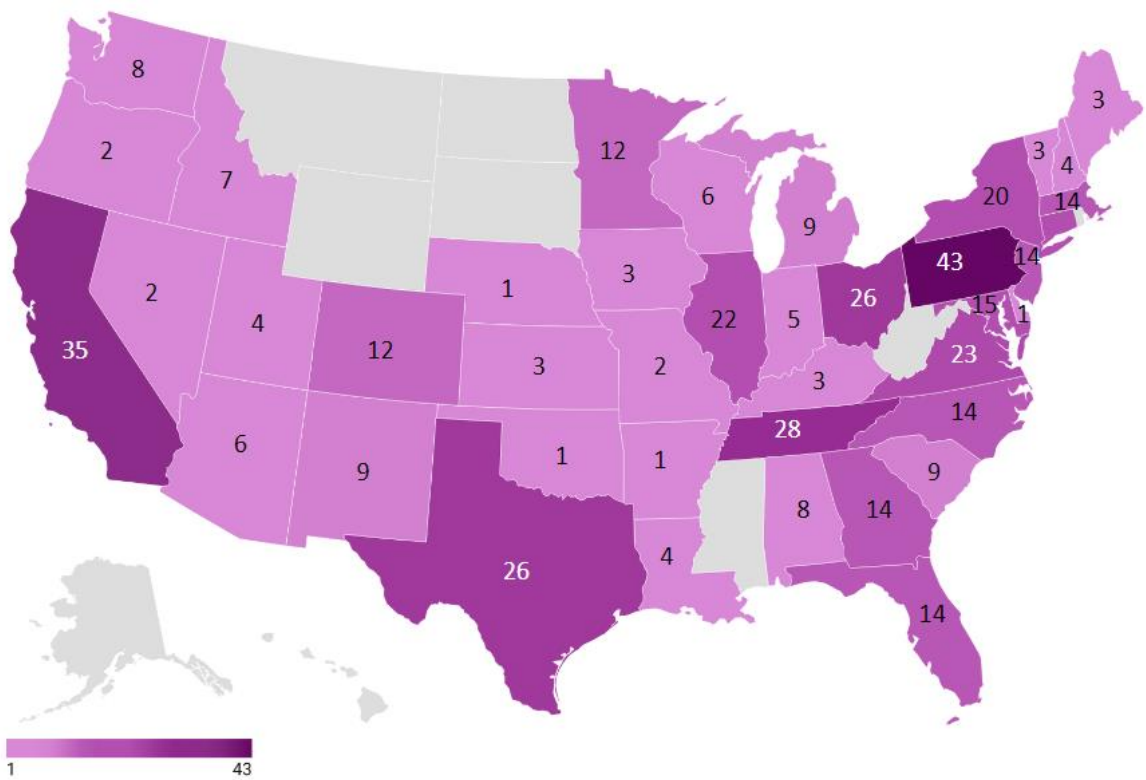
Figure 23: Map showing locations of existing nuclear suppliers.

5.1.2 North America

The United States is among the largest active players in the nuclear industry. Similar to Canada though, there was a significant lull in new reactor projects in the US from 1996 until the 2010's. This gap in activity caused the gradual degradation of the strength of the nuclear supply chain, as companies elected to discontinue the quality programs required due to lack of activity and orders. In the 2010's the US experienced new nuclear build activity spanning 3 projects: Unit 2 at Watts Bar was completed (based on a conventional Westinghouse PWR design) and two major projects to install sets of two Westinghouse AP 1000 reactors (a Gen III+ technology) at Vogtle and Virgil C. Summer respectively. These projects were fraught with challenges including delays and cost overruns. The VCS project was ultimately cancelled in 2017 and the Vogtle project has had a protracted construction path but is now fully constructed, with unit 3 fully operational and unit 4 projected to be producing power in Q2 2024 2024 [52], [53]. While these projects were tumultuous, they helped to rejuvenate the American nuclear supply chain. Refurbishment work in the US has been less active than Canada to date, but there have been a number of recent announcements of decisions to extend the life of older nuclear units in the U.S., many of which had been slated for retirement. These projects will provide further incentive for the nuclear supply chain in the US to step up capacity and given the level of activity that may be involved, signal another concern about upcoming supply chain shortages to service the many upcoming concurrent projects.

In recent years the US has announced significant funding for several nuclear related initiatives, spanning refurbishment projects, nuclear fuel infrastructure development, SMR technology development and financing tools for SMR deployments. Once source estimates as much as over $40 Billion of new federal investment over the coming decade – a figure that is likely already conservative, as new initiatives continue to be announced [54]. This funding is needed, and a lot more like it will be required to achieve energy transition goals in North America and globally.

While there are several SMR design projects underway worldwide, the U.S. hosts some of the most promising technologies in terms of orders and commitments to construct. Some of these projects are receiving funding support within the US from the DOE. A summary of the key SMR technologies with Canadian connections was provided in Table 1 in section 3. Many of the American designs listed in this table have either received direct funding support from the DOE or are in some way benefiting from previous DOE funded R&D. The concentration of US-based SMR vendors provides a potential advantage to North American based suppliers, particularly those in the U.S., but potentially to Canada and Mexico as well.

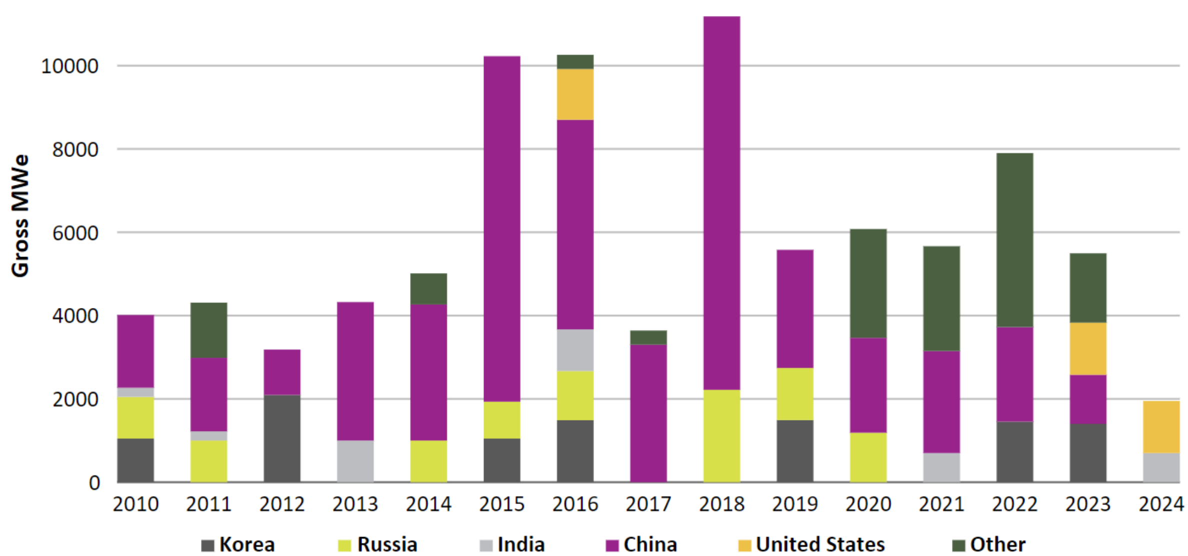


Source: American Nuclear Society Buyers Guide 2023 [55]
Figure 24: Map of American Nuclear Suppliers.

5.1.3 Global

While new nuclear power plant construction and refurbishment work experienced a notable period of lower activity in North America in the 1995-2020 time-frame, nuclear builds in other nations did not slow to the same degree. From 2010-2019 almost all new builds in the world occurred in China, Russia, India, and Korea. China has added 40 reactors since 2010 and is currently constructing 15 more. These new reactor builds include some of the earliest deployments for Gen III+ technologies and among the first SMRs. Naturally, international regions with significant recent activity on nuclear builds will also have established strong nuclear supply chains.

SMR developments are underway around the globe and the first to come on stream are all located outside North America. Some of these technologies may be less likely to come to North America than designs based in the region, but these projects are undoubtably fueling the development of skill sets and capabilities for the nuclear supply chain worldwide. They are also capturing resources within the supply chain that might compete with North American SMR projects. Given activity levels, the opportunity for qualified Canadian nuclear supply chain companies to participate in global projects is growing alongside North American opportunities.



Source: IAEA Power Reactor Information System (PRIS) [11]

Figure 25: Global Nuclear Additions, 2010-2024.

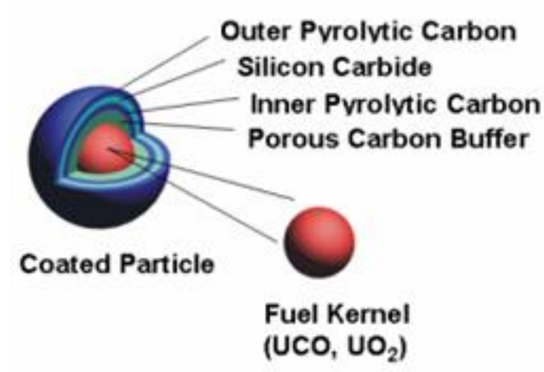
5.2 Supply Chain Development for SMRs

As the SMR market matures from the first of a kind types of projects, it is anticipated that the builds will shift from custom to factory fabrication processes. Presently, no 'factory-style' nuclear fabrication facilities exist. As sufficient orders for new reactors are confirmed, centralized fabrication infrastructure will become established, with the potential for supply chain clusters to form around these facilities. Which locations are selected to host the facilities may be based on existing nuclear supply chain maturity and/or proximity to market (future deployment locales) or to key transportation corridors. Most SMR designs leverage new technology, aspects of which are new to existing nuclear suppliers as well as new entrants, with regional or supplier-specific capabilities still developing. However, after some of the early projects are executed, the specialized skillsets involved in specific advanced reactor technologies will be concentrated amongst the early supplier group involved in the respective first deployments. This may result in clustering of supply chain development around the expertise from these early projects.

Among the services and requirements of a future SMR supply chain, it is anticipated that factory fabrication will necessitate transportation logistics for moving large or heavy components [56]. Some SMR designs will require additional new infrastructure such as in the case of micro-reactors, fueling/defueling centers. The nuclear supply chain is often discussed as split into two main segments: plant equipment components and the fuel cycle.

For plant equipment components, first of a kind projects will necessitate 'one-off' fabrication. As orders for multiple reactor units come to fruition, orders for multiple components will as well. This will allow the supply chain to establish standard processes for manufacture that begin to create production cost efficiencies. While AMTs have several drivers, among them will be component production systems that can produce equipment with reliable repeatability in terms of quality while concurrently optimizing cost.

The nuclear fuel cycle will also require significant investment and development to support the significant increase in nuclear power worldwide. As discussed earlier, many advanced reactor designs require new types of fuel, and higher enrichment. Increasing the availability of high-assay low enriched uranium (HALEU) is one required for multiple reactors. Several advanced designs use TRISO fuel (tri-structural isotropic particle fuel), a fuel type that involves a kernel of uranium coated by layers of carbon and ceramic-based materials which are designed to contain fission products, making the fuel inherently lower risk [57]. Manufacturing of TRISO fuel kernels (which are about the size of a poppy seed), and the subsequent fabrication of fuel pellets or pebbles, that consist of multiple TRISO kernels also represent steps in the global nuclear fuel supply chain that must be developed and built at scale. While some of this infrastructure will likely be centralized, some reactor designs will require fuel fabrication facilities to be located in relative proximity to reactor deployments, due to continual refueling requirements.



Source: Neutronbytes.com [58]
Figure 26: TRISO fuel particle layers.

Assembly factories for nuclear modules and nuclear fuel fabrication facilities will both require supply chains to support them. Some of these activities will likely be clustered around the fabrication facilities, though there is still potential to supply from farther afield.

The nuclear industry is heavily regulated and is impacted by geopolitics and restrictions around preventing the proliferation of nuclear technology. There are aspects of the fuel supply chain, such as enrichment, that are heavily restricted and other aspects of nuclear technology can be similarly tightly held. These concerns affect supply chain development in that it is not a completely open system – there are a restricted number of countries which can supply key components for Western nuclear projects. In addition to these challenges, the nuclear sector requires exacting levels of quality and faces significant regulatory scrutiny – both with the goal of maintaining high levels of safety. These factors further restrict supply chain development as they represent hurdles for new suppliers trying to enter the market. There is a risk that the global goals to vastly increase the adoption and use of nuclear power will be stalled by an inadequate supply chain. It is therefore, of significant importance to global decarbonization efforts to consider how to develop adequate supply chains to support the level of activity and the development of the specialized skills and knowledge to ensure the high level of quality, safety, and security the nuclear industry requires are addressed.

Some nuclear power producing nations have recognized the importance of the supply chain to achieving their goals for growth and have initiatives in place to support development of new suppliers. For example, in 2009 the United Kingdom government established a Nuclear Advanced Manufacturing Research Centre at the University of Sheffield (Nuclear AMRC). This group has since developed a project called Fit for Nuclear that helps UK manufacturing companies get ready to bid for work in the nuclear supply chain, which includes training and grants to support the development of quality programs [59]. Canada’s Organization of Nuclear Industries (OCNI) has launched a Ready4SMR program to address some of the same goals. OCNI also established CAMiNA, the Canadian Advanced Manufacturing in Nuclear Alliance and prepared an Advanced Manufacturing Roadmap for the Canadian Nuclear Industry in 2022 [60].

6.0 SMR Manufacturing

SMRs are a promising advancement in nuclear technology, offering scalable, flexible, and cost-effective solutions for clean energy generation. With the SMR appeal growing globally, the development of new, efficient, and cost-effective manufacturing processes to support this growth becomes even more crucial. In this section, we explore how AMTs can be leveraged to improve various stages of the manufacturing process, and examine the challenges and opportunities associated with their implementation. The section also highlights emerging technologies and innovative approaches shaping the future of SMR manufacturing.

The information presented in this section leverages survey responses from five active SMR vendors operating in Canada regarding their interest and plans to leverage AMTs.

6.1 Advanced Manufacturing of SMRs

AMTs present significant potential for addressing several of the challenges inherent in conventional manufacturing processes. Recently, nuclear vendors have become more familiar with the different advanced techniques available to them and how they can be leveraged to improve SMR manufacturability, with cost and schedule reductions being the top-ranked drivers for applying these technologies.

With AMTs, SMR vendors can explore new possibilities in designing reactor components, optimizing structures, and improving overall efficiency. A cohesive corporate strategy is indispensable for leveraging the full benefits of these innovative technologies while ensuring alignment with organizational goals and objectives. Survey results indicated only a few vendors have an existing corporate strategy for AMTs. Presently, the focus is on achieving FOAK constructions primarily with proven technologies, without burdening these projects with the risks associated with adopting relatively new techniques. There is an indication that the adoption of AMTs are likely to be more pronounced in NOAK installations than in FOAKs.

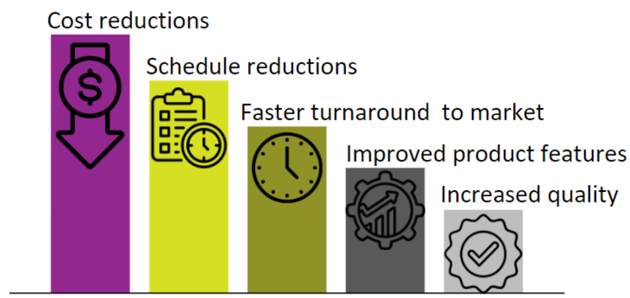


Figure 27: Nuclear Vendors' drivers for considering AMTs.

However, there is still definite interest in adopting AMTs. All survey respondents plan to adopt AMTs within the next decade (see Figure 28). Some vendors have started developing these techniques for different applications and have indicated they will adopt some AMTs in current designs and deployments, as shown in Figure 29. The techniques considered essential by the vendors encompass the entire manufacturing cycle and are not restricted to direct manufacturing processes on the manufacturing floor. This is important to capture the all-round benefits AMTs have to offer.

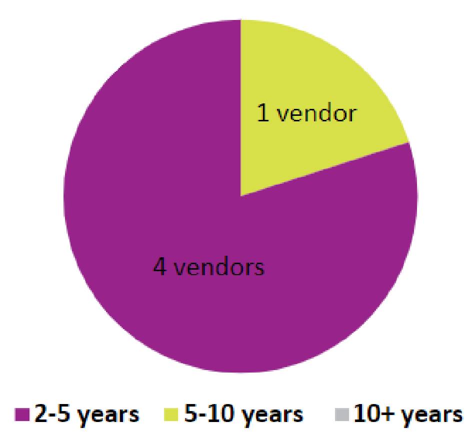


Figure 28: AMT Adoption Timeline for Nuclear Vendors.

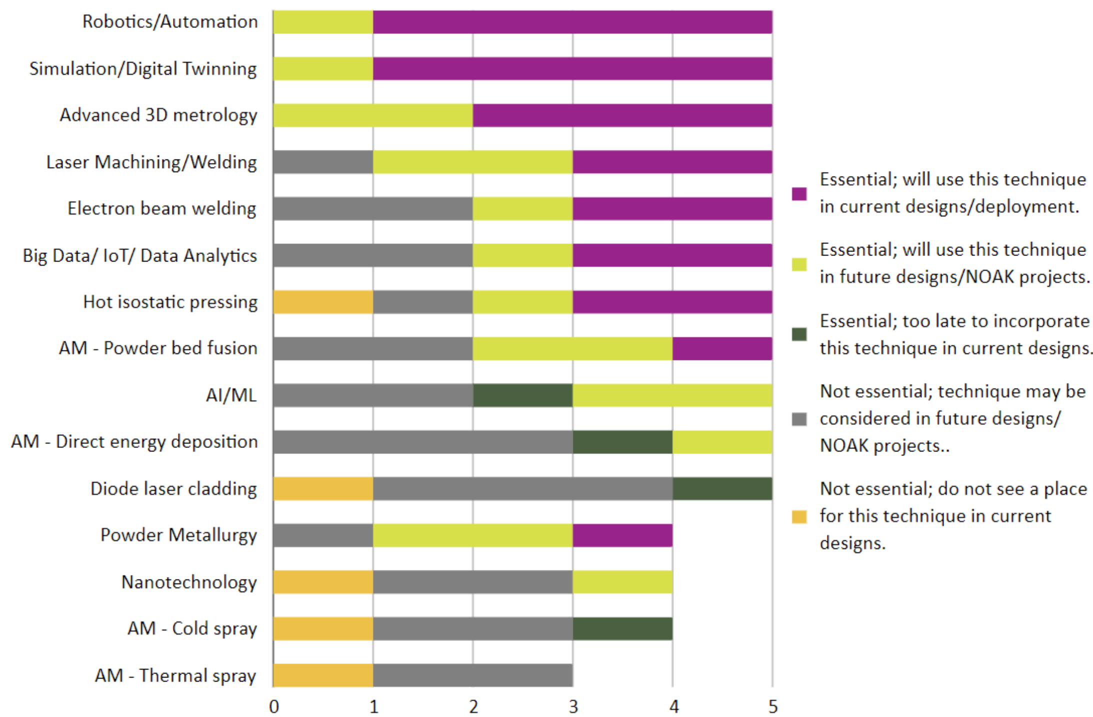


Figure 29: Vendors Level of Interest in AMTs.

6.1.1 Pain points in SMR manufacturing

When evaluating the best opportunities to incorporate AMTs, it is helpful to look for the challenges or pain points that can negatively impact various aspects of the manufacturing operation, including schedule, cost, quality, and overall success. The following are the top pain points identified by this study:

1. **Long lead materials and components:** Establishing a robust supply chain for advanced materials and complex components can be challenging because until the demand volume is up, there may be a constrained market for some specialty materials needed. Project schedules can be delayed if material sourcing isn't properly planned to cope with this, and costs can overrun as a result. Certain components, such as reactor pressure vessels and steam generators, have long lead times for manufacturing and delivery. For instance, considering that the "very heavy" forging capacity in operation today is concentrated in a few countries (Japan, China, South Korea, France, and Russia), nuclear projects worldwide must build in significant lead times for key components in order for delivery to meet deployment schedule targets.

2. **Costs and funding availability**: Securing financing for SMR projects can be challenging for several reasons, including market uncertainties, long payback periods for investors, and rising or fluctuating interest rates and inflation. Cost control and predictability is needed to maintain investor confidence in the project's viability, which ensures owners can access the capital needed to see projects through to completion. Financial market factors also affect suppliers of long-lead items, and consideration is needed on how to share risk and still ensure an attractive business proposition across the supply chain while managing project costs.

3. **Codes and standards:** The safety and regulatory rigor required for nuclear projects necessitates the use of stringent codes and standards. Code packages and material testing data are lacking for many new/advanced materials and components, particularly for high-temperature SMRs, which presents difficulty for design and reliable manufacture of components.

4. **Quality and inspection of components:** Proper quality and inspection practices are crucial in SMR manufacturing to avoid rework and ensure that manufactured items meet design requirements. The availability and adherence to appropriate testing techniques for different components requires a lot of effort to track, particularly where the work product involves a chain of different suppliers.

5. **Data management**: SMR manufacturing involves different stakeholders, including nuclear vendors, manufacturers, suppliers, regulators, and customers. Cataloguing, verifying, and tracking communications, drawings, designs, specs, codes, etc., from all these parties can become problematic if not properly managed, leading to severe costs and schedule implications. For example, according to some reports about the schedule delays and cost overruns at Vogtle, resolving inconsistent quality documents between Westinghouse and its contractor, Shaw Modular, sometimes took longer than fabricating the actual modules [61].

6.1.2 Addressing SMR Manufacturing Challenges with AMTs

Delving deeper into the challenges highlighted earlier, it becomes evident that certain manufacturing techniques are contributing to these obstacles. This is not to discredit the efficacy of traditional methods; rather, it underscores the evolving demands of modern industry, which often surpass the capabilities and efficiency of conventional approaches. AMTs have the potential to offer accelerated, safer, and higher-quality production outputs compared to conventional methods. Recognizing this potential, nuclear vendors are increasingly turning to AMTs to address manufacturing challenges. Some key processes earmarked for AMT intervention include fabrication and assembly, inspection, and testing, as well as data management. These targeted interventions aim to harness the transformative power of advanced manufacturing to overcome existing limitations and drive progress in SMR manufacturing.

Fabrication & Assembly

Given that fabrication and assembly of components represent a significant portion of the total cost and schedule of an SMR construction, addressing challenges within these processes becomes important. The issue of **extended lead times** for certain components can be mitigated by exploring alternative methods of production and establishing a robust supply chain for those critical components. Take for instance, RPVs and steam generators, which are long-lead items that are currently produced by forging – a manufacturing technique requiring engineering plants equipped with heavy forging presses, which have limited throughput. Nuclear vendors usually prefer large forgings to be integral, as single products, although they can also be split and welded together. Both options result in long-lead times, either by joining a queue of forgings orders that take time to complete or extensive hours spent on thick-section welding using conventional techniques like TIG welding, and subsequent non-destructive examination (NDE).

Addressing these challenges could involve exploring near-net shaped manufacturing with **PM-HIP** and adopting faster, high-quality precision automated welding with **EBW** or **laser welding**. PM-HIP enables manufacture of near-net shaped complex components, eliminates the need for welds, and produces components with improved material properties. Alternatively, EBW and laser welding offer significant advantages in single pass, thick-section welding with small heat-affected zones. These techniques eliminate the need for conventional layer-by-layer build-up welding, streamlining the welding process and reducing the need for inspections following each completed pass. Some nuclear vendors recognize the potential of these AMTs and are actively considering their integration into SMR manufacturing processes, including for nuclear island components. Nuclear vendors like NuScale and Rolls-Royce are at the forefront of developing these techniques for nuclear applications (see Section 4.4), with some already utilizing PM-HIP in upstream manufacturing processes.

Various other techniques offer unique solutions to different challenges and are under consideration by the nuclear vendors (refer to Figure 30). **Additive manufacturing** is attractive for fast production of components with complex shapes or internal features. **Robotics and automation** offer consistency and repeatability during fabrication and assembly processes – one of the main issues raised by manufacturers in this study, particularly concerning welding. Inconsistencies in weld quality between different welders or even the same welder at different times, pose significant uncertainties for project schedules and product quality. Automating these processes helps mitigate these challenges and offers the opportunity to refine process parameters for achieving optimal results more efficiently.

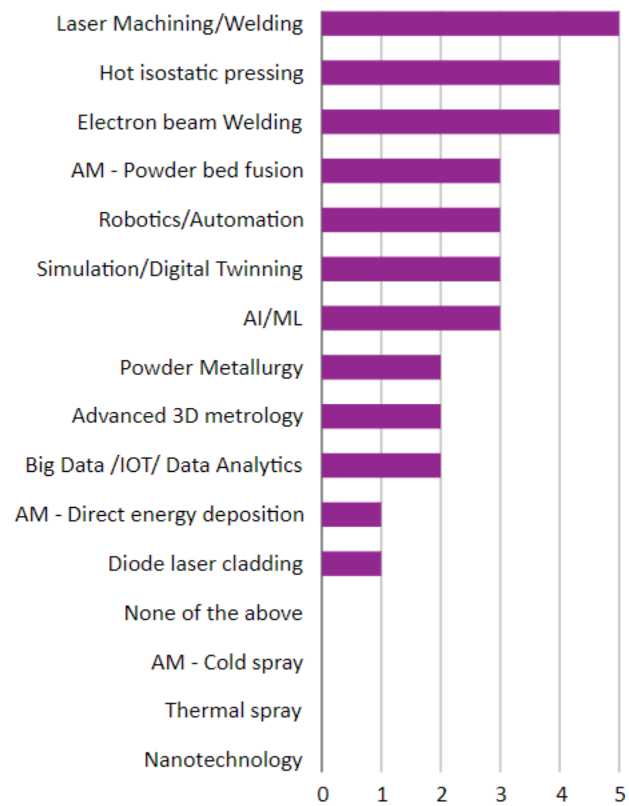


Figure 30: AMTs vendors plan to leverage to address pain points and improve SMR manufacturing.

Inspection and Testing

AMTs offer a comprehensive suite of tools and techniques that can significantly enhance the quality, inspection and testing of materials and components in SMR manufacturing. Utilizing certain AMTs like **additive manufacturing**, offers real-time monitoring of manufacturing processes, allowing operators to detect and address issues as they arise. This is a proactive approach to quality control that helps prevent defects and deviation before impacting component quality or production schedules. AMTs like artificial intelligence **(AI)** and **3D scanning** can be integrated with other advanced inspection and non-destructive testing techniques to ensure the quality and integrity of manufactured components. Industry examples, such as the International Thermonuclear Experimental Reactor Vacuum Vessel (ITER VV) fusion project, demonstrate the successful combination of AI with various welding processes (EBW, TIG welding) to predict welding success rates with up to 100% accuracy [62]. This predictive capability significantly reduces recalls by enabling the assessment of welding success before execution. Additionally, **AI** can process data from NDEs, such as, Phased-Array Ultrasonic Testing (PAUT), for predictive analysis. Automation of inspection and testing processes has the potential to enhance efficiency and accuracy, enabling faster output and improved quality assurance standards in SMR manufacturing.

Data Management

Effective data management practices can play a pivotal role in optimizing processes, enhancing decision-making, and ensuring quality throughout the manufacturing lifecycle of SMRs. Challenges associated with data management in SMR manufacturing can be effectively addressed through the integration of AMTs and advanced data management systems, such as, data analytics, AI, sensors, automation, and blockchain technology. AMTs typically generate manufacturing data that can be seamlessly accessed through interconnected systems (IoT), providing real-time visibility into manufacturing operations. Data analytics, AI and ML can then be leveraged to analyze this data and draw meaningful insights, enabling stakeholders to make informed decisions and identify areas for improvement.

Additionally, blockchain technology offers the potential to provide a secure, immutable ledger for recording manufacturing data, ensuring end-to-end traceability of components throughout the supply chain. This type of system could allow authorized parties to access and verify manufacturing data in real-time, enabling seamless communication, coordination, and decision-making across diverse teams and organizations. Blockchain could also enable real-time auditing and compliance monitoring of SMR manufacturing processes and activities. Moreover, AMTs support the implementation of smart contracts. These contracts could automate various aspects of SMR manufacturing, streamlining business processes, reducing administrative overhead, and improving operational efficiency, by eliminating intermediaries and manual interventions.

Overall, incorporating AMTs into SMR manufacturing processes can help address various challenges associated with SMR production. By leveraging AMTs, SMR manufacturers can effectively reduce extended lead times, expedite the construction period of SMRs, and significantly lower construction costs. The ability to streamline manufacturing processes and enhance efficiency enables SMRs to come online more quickly and affordably. This potential for accelerated deployment of SMRs would help to meet the growing demand for clean energy and enhance the attractiveness of SMR projects to potential investors. As SMRs become cheaper and faster to construct, they become increasingly viable and appealing investment opportunities, driving further growth and innovation in the nuclear energy sector.

6.2 Key Opportunities: Emerging Themes

Considering that there are numerous different types of opportunities for AMTs in SMR manufacturing, the nuclear vendors involved in the survey were asked to identify their top ‘low-hanging fruit’ opportunities to leverage advanced manufacturing in SMR production. The key opportunities identified, in no order, include:

- PM-HIP technology
- Additive Manufacturing
- Automated welding
- Robotics/Automation and digital twinning
- ASME code cases and case studies

To further explore these opportunities and their potential implementation in SMR manufacturing, the project's Technical Advisory Committee and industry stakeholders were consulted for their insights. These discussions centered around identifying SMR components that could benefit from these techniques, addressing hurdles to adoption, and exploring how suppliers and academic institutions can play a role in leveraging these opportunities. The findings and recommendations from these sessions are summarized in Table 3. These opportunities have significant potential benefits these AMTs could offer SMR manufacturing. Strategic insights regarding adoption challenges for each of these opportunities are summarized in the table as well.

Table 3: Summary of discussions on key opportunities.

Key Opportunities	Components considered	Strategic Factors to Address for Adoption
Automated welding and joining Electron beam welding Submerged arc welding (narrow gap and tandem) Cold metal transfer Diode laser cladding	Fine motor control rod drives, control rod blades, reactor pressure vessels, etc.	• Life span of AMT; risk of obsolescence • Clarity on exact components to be manufactured with AMTs • Potential work volume (hours, space) • Clarity on revenue potential and ROI is needed.
PM-HIP	Pumps, valves, reactor pressure vessels, etc.	• Limited large-scale capacity • Limited supplier capability
Additive Manufacturing Direct Energy Deposition Laser-Powder Bed Fusion	Heat exchangers, pumps, fuel assembly components, some components in shutdown rod systems, etc.	• Limited large-scale capacity • Limited material qualification testing for SMR applications • Codes & standard development • Regulatory acceptance
Digital AMTs Automation AI/ML, IIOT, VR/AR Digital Twins 3D Scanning	Instrumentation and controls, worker training, remote monitoring, predictive analysis, spatial visualization, etc.	• Safety and security concerns for cyber-attacks, embedded counterfeit/ suspect items must be addressed. • Risk of sensor malfunction can be safety issue. • Balance of digital training advantages with need for traditional field training.

7.0 Saskatchewan Supplier Potential

Given the significant commercial activity surrounding Small Modular Reactors (SMRs) worldwide, and with plans for some of these technologies to be constructed in Canada, including Saskatchewan, the province stands to benefit from numerous opportunities within the nuclear industry. As outlined in Section 5, certain SMR components necessitating highly specialized expertise and equipment will most likely be procured from established nuclear suppliers outside Saskatchewan. However, many other components can be sourced from the existing supply chain that serves adjacent industries such as agriculture, mining, oil and gas, and power generation. Leveraging the expertise and infrastructure from these sectors presents a strategic opportunity for Saskatchewan to capitalize on its participation in the emerging SMR market.

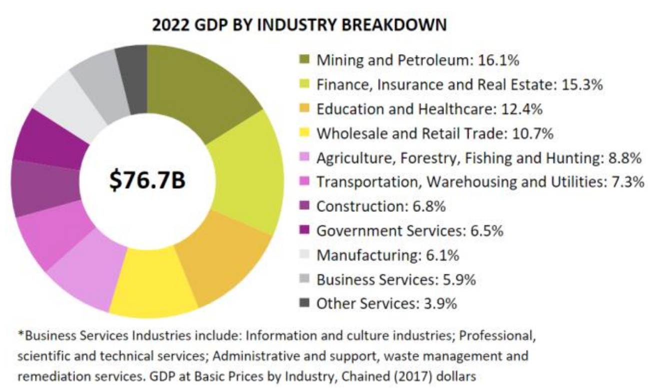
The information presented under subsequent headings in this section leverages responses from a survey sent to various suppliers in Saskatchewan, as well as information compiled from further one-on-one dialogues with these manufacturers, and other industry stakeholders.

7.1 Existing Capabilities, Infrastructure and Labour Force

Saskatchewan has a strong industrial economy centered around agriculture, construction, mining, and oil and gas, collectively contributing 31.7% of the province's real GDP in 2022. These industries are supported by solid professional, scientific, and technical services, transportation, warehousing, and business services – all of which are critical to an SMR supply chain. Existing suppliers serving these industries have robust, diversified construction and manufacturing experience and can execute mega projects, including project management, engineering, procurement, and construction. In fact, Saskatchewan had Canada's second most productive manufacturing workforce in 2021 [63]. Other relevant experience and capabilities include but are not limited to:

- Automation, instrumentation & control systems, electrical infrastructure design and supply.
- Steel structures and modular fabrication.
- Construction – civil and earthworks.
- Professional and specialized services, including inspections, engineering, operational support, asset management, etc.
- Supply and maintenance of heavy equipment.

The skills cultivated within the aforementioned industries are highly transferable to the nuclear SMR supply chain with appropriate training. Skilled and craft labour in these sectors can readily undergo reskilling to perform tasks within the SMR supply chain. However, the emergence of the nuclear power industry in Saskatchewan may necessitate additional labour to support deployments, as existing projects in adjacent industries may compete with SMR supply chain demands. This is further discussed in sections to follow.



Source: Government of Saskatchewan [64]

Figure 31: Saskatchewan's GDP by industry 2022.

Manufacturing Establishments

Saskatchewan boasts a robust manufacturing industry, with about 345 manufacturers and suppliers holding memberships with SIMSA across the province. The majority of these establishments are concentrated in Saskatoon (61%) and Regina (17%), both of which have been identified as potential locations for a future SMR manufacturing cluster in Saskatchewan. These cities are equipped with well-established fabrication and assembly facilities capable of supporting modularization and shipment of SMR modules. Saskatoon and Regina based suppliers can leverage the interconnections between various primary and supporting industries, including research and development, construction, and professional services, to offer comprehensive new build and operational support for SMRs. Situated in the heart of the Canadian Prairies, Saskatchewan manufacturers and suppliers benefit from access to markets encompassing 270 million people within a two-day drive. Established transportation networks can be leveraged to efficiently transport manufactured SMR modules both within and beyond the province's borders.

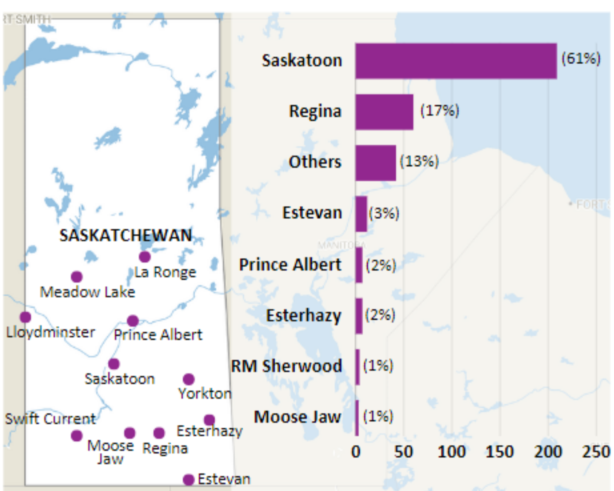


Figure 32: Distribution of manufacturers and suppliers across the province [65].

Innovation, Applied Research and Technology Development

Saskatchewan holds a leadership role in innovation, applied R&D, and technology commercialization in several sectors. The province is home to a dynamic research cluster comprising the following prestigious institutions that touch aspects relevant to the nuclear industry.

- University of Saskatchewan
- University of Regina
- Saskatchewan Polytechnic Inc.
- The Saskatchewan Research Council

The University of Saskatchewan and the University of Regina are members of the University Network of Excellence in Nuclear Engineering (UNENE), which includes 13 Canadian Institutions. SaskPoly has a number of initiatives underway relating to advanced manufacturing. The role of these three academic institutions is discussed further in Figure 33. The Saskatchewan Research Council (SRC) is an applied research and technology organization owned by the provincial government. SRC is a former operator of a slowpoke research reactor (decommissioned in 2019) and operates CNSC licensed laboratories for analytical services. In addition to the micro-reactor deployment project announced in 2023 and mentioned previously in section 3, SRC has recently formed an Applied Nuclear division.

Given the critical role of innovation and R&D in supporting SMR deployment and supply chain deployment, the expertise and resources within the Saskatchewan research cluster are poised to play a pivotal role in shaping the future of the nuclear industry. A collaborative R&D ecosystem provides fertile ground for major collaborations to advance nuclear technology and revolutionize construction practices.

Exploring the Role of Saskatchewan Post-Secondary Institutions in SMR Manufacturing

University of Saskatchewan

USask is a member of the U15 Group of Canadian Research Universities and home to world-leading research facilities, including:

- The Canadian Light Source (CLS) Synchrotron
- The Sylvia Fedoruk Canadian Centre for Nuclear Innovation Inc. (Fedoruk Centre)
- Saskatchewan Structural Science Centre (SSSC)
- Saskatchewan Centre for Cyclotron Science (SCCS)

USask actively supports SMR development through diverse research initiatives, involving faculty members investigating various facets of SMRs. This engagement can be extended to include engineering design, materials development, and testing of AMT-manufactured components. Faculty expertise span diverse fields such as engineering physics, mechanical engineering, and materials science.

University of Regina

U of R is renowned for its research excellence. It boasts extensive resources for cutting-edge research endeavors in various relevant fields, including physics, industrial engineering systems, energy systems, and others.

Noteworthy is the Clean Energy Technologies Research Institute (CETRI), a center for innovative research in sustainable energy technologies. U of R also hosts the Canada Research Chair in SMR Safety and Licensing, showcasing its commitment to advancing SMRs. Researchers at U of R are dedicated to addressing various challenges in SMR development, including investigations into the corrosiveness of nuclear fuel for different SMR designs.

Saskatchewan Polytechnic

SaskPoly stands as Saskatchewan's sole polytechnic institution, offering applied education and research opportunities. It is renowned for its comprehensive design and manufacturing program and boasts state-of-the-art facilities, including:

- Innovative Manufacturing Centre (IMC)
- Research, Additive Manufacturing and Prototyping (RAMP) facility
- Digital Integration Centre of Excellence (DICE)
- Sustainability-Led Integrated Centres of Excellence (SLICE)

Leveraging these advanced manufacturing facilities, such as the IMC and RAMP, SaskPoly can actively design, develop and analyze AMT-manufactured components for SMRs. The DICE TAC offers valuable resources for educating Saskatchewan suppliers on integrating IOT solutions, data analytics, and other relevant technologies.

Figure 33: Roles of Saskatchewan post-secondary institutions in SMR manufacturing.

Provincial support – Funding & Tax Incentives

The Saskatchewan government encourages innovation and investments in the manufacturing sector by providing a number of business incentives and tax credits to manufacturers. Examples of such incentives include, but are not limited to [66]:

- A 6% investment tax credit for equipment purchased for manufacturing and processing operations in the province.
- The corporate income tax rate for manufacturers in Saskatchewan can be as low as 10% through manufacturing and processing profits tax reduction.
- **Research and Development Tax Credit** – A 10% refundable provincial income tax credit for scientific research and development expenditures. For Saskatchewan Canadian-controlled private corporations, the credit is refundable on the first $1 million of qualifying annual expenditures. In all other cases, it is non-refundable.
- **The Saskatchewan Commercial Innovation Incentive (SCII)** - offers eligible corporations that commercialize their qualifying intellectual property a reduction of their provincial corporate income tax rate to 6% for a period of 10 years or 15 years (the longer time-frame applies when at least 50% of R&D takes place in the province).

7.2 Current Nuclear Supply Chain in SK

According to our survey results, the majority of Saskatchewan suppliers are currently non-nuclear suppliers, with approximately 22% of those who responded to the survey servicing the uranium mining industry and supplying industrial parts for balance of plant (BOP) components in nuclear power plants. Notably, there were no suppliers for nuclear island components within the province. Notwithstanding, respondents expressed interest in becoming nuclear suppliers, with about 25% expressing interest in nuclear island components, while the remainder showed interest supplying balance of plant components. Many of these suppliers are uncertain about the process of becoming a nuclear supplier and are not aware of applicable funding mechanisms to support this transition. Furthermore, less than 10% of respondents have a nuclear quality assurance (QA) system in place to support the nuclear supply chain.

The CSA N299 series is an essential standard for any supplier working in the nuclear industry. The series outlines QA program requirements for supplying items and services for nuclear power plants. However, there is a common misconception regarding the N299 series, with many suppliers believing it to be a one-size-fits-all standard. N299 offers a graded approach, allowing suppliers to tailor their requirements based on the scope of their work. This graded approach is addressed through four categories of the standard, ranging from CSA N299.4 for suppliers with low impact on the plant's operations to CSA N299.1, which covers requirements for suppliers of critical components.

Recognizing these challenges, the province has taken steps to address them. In August 2023, the Crown Investments Corporation of Saskatchewan (CIC) announced funding for the Saskatchewan Industrial and Mining Suppliers Association (SIMSA) and its partners to prepare local companies for their future participation in provincial, national, and global SMR development. Later in the year, Prairies Economic Development Canada (PrairiesCan) announced co-funding support for the same initiative. The funding supports the appointment of an SMR supply chain specialist within SIMSA. Additionally, it facilitates engagement with the First Nations Power Authority (FNPA) to explore indigenous economic opportunities and enables the OCNI to deliver its Ready4SMR program, aimed at developing local suppliers, including indigenous-owned companies.

7.3 Saskatchewan Potential Nuclear Supplier Risks & Opportunities

Supplier and Workforce Availability: A notable risk associated with SMR deployments in Saskatchewan is the potential competition for labor between existing industries and the emerging nuclear energy sector.

Many Saskatchewan suppliers have long-standing relationships with these industries and receive consistent orders from them. Therefore, for suppliers to consider investing in becoming nuclear suppliers, the scale and frequency of nuclear projects must offer favorable prospects to invest and expand to serve markets beyond the activity and stability provided by existing industries.

The Saskatchewan supply chain will require some degree of market certainty to capitalize on opportunities effectively. A strategic plan for industrial participation and engagement of the local supply chain is needed. Early engagement of local suppliers by future owners and nuclear vendors of SMR technologies selected for deployment, and transparency with them about future tender opportunities and the supplier qualification process, will help suppliers to make informed decisions about their involvement in the nuclear sector, while balancing support for adjacent industries.

Early coordination between nuclear vendors and suppliers could also help alleviate a shortage of certain skilled workers, such as qualified welders and pipe fitters, in the province, which is already a concern without active nuclear construction projects underway.

Nuclear Experience: Most Saskatchewan suppliers are not experienced nuclear suppliers, except for a few who have in-house nuclear experience within their general franchise, although not specifically at their Saskatchewan location. The reality is that Saskatchewan suppliers will have to compete with established nuclear suppliers with extensive experience and qualifications. They will need to vie for contracts against well-established Canadian suppliers from Ontario and New Brunswick, as well as international suppliers for both domestic and global deployments.

Additionally, there is the issue of scale, particularly as projects become large. Many SK suppliers are small-sized companies and may not have the balance sheets to shoulder project risks to compete with larger companies. Collaboration through partnerships or joint ventures with larger established nuclear companies may be a desirable option for some of these smaller firms. However, to engage at any level, suppliers will need to gain relevant experience.

A possible way for SK suppliers to gain experience ahead of future Saskatchewan opportunities is by actively participating in earlier deployments, such as the new nuclear project or refurbishments planned at sites like Darlington NPP. Existing resources such as the federal government, OCNI, or SIMSA, could potentially be leveraged to develop a plan to help enable potential SK nuclear suppliers to partner with or be mentored by experienced suppliers on ongoing nuclear projects. This approach could allow for the transfer of lessons learned and valuable insights, to help meet any localization objectives for work related to Saskatchewan projects in the future.

Certification and Licensing capacity: Saskatchewan could benefit from the enhancement of its certification and licensing capacity to support the nuclear industry. Due to specific missing capacity, some suppliers are currently seeking support for certifications from Alberta (ABSA) or Ontario (TSSA), which can add logistical challenges and delays. Streamlining the process and making certifications more readily accessible to SK suppliers will help the advancement of this initiative to develop the supply chain in Saskatchewan for nuclear (TSASK is presently working to address this issue).

There is also the issue of **harmonized codes and standards**, which is not unique to the Saskatchewan nuclear supply chain but impacts all Canadian nuclear suppliers operating under CSA codes and standards. Considering the diversity of SMR designs and the numerous planned SMR deployments worldwide, Canadian suppliers may be required to also adhere to various international codes or standards in order to participate in global ventures. Consideration of harmonization between standards could be helpful to the development of a Saskatchewan based supply chain to capture global opportunities more readily. Work is underway by CSA and others to address this challenge.

Diversification of the SK economy: The manufacturing sector in SK is focused on the key local industries agriculture, mining, energy generation, and oil and gas. Introducing nuclear energy generation into the mix would diversify the economy, helping to mitigate the effect of sporadic downturns in these sectors. Nuclear energy generation offers a long-term spectrum of business opportunities throughout the plant's entire life cycle, spanning construction, operations & maintenance, refurbishments, and decommissioning.

Export opportunities: Should SaskPower decide to proceed with construction in 2029, the BWRX-300 may mark the first SMR deployment in Western Canada, which will still be among the few firsts worldwide. With experience from this deployment, Saskatchewan can potentially contribute to the export of SMR modules and provide SMR development training programs to other Canadian provinces or countries embarking on their FOAK deployments. Other provincial deployments under discussion, including the eVinci micro-reactor by SRC and industrial applications for SMRs can also help to prepare the local supply chain to participate in future global deployments.

7.4 Advanced Manufacturing Capacity in Saskatchewan

Saskatchewan is home to many innovative manufacturers building cutting-edge technologies across various industries. Examples include continuous mining equipment in the potash industry, remote-controlled machinery used in uranium mining, autonomous farm equipment, unmanned aerial vehicles and deep-space antenna systems. However, while some AMT capabilities exist in the province, the adoption of AMT remains more of an exception than the norm. According to the survey results from SIMSA/IMCN members, nearly half of the respondents indicated they are currently not leveraging any of the AMTs highlighted for nuclear considerations in Section 4.

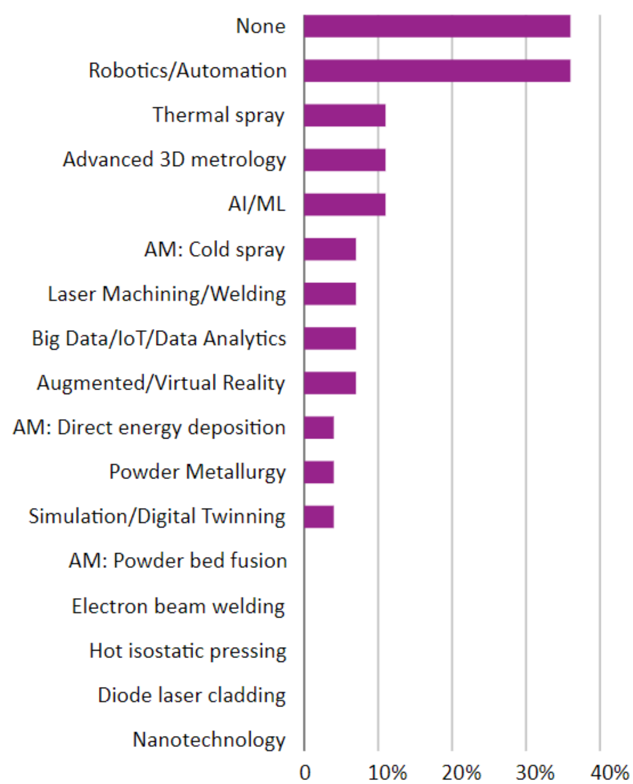


Figure 34: AMTs adopted by survey respondents.

The survey data in Figure 34 illustrates that robotics and automation are the most widely adopted AMTs among respondents, while the utilization of 3D printing technology remains relatively low. In addition, emerging technologies like PM-HIP, EBW, and DLC are absent from the supply chain. It is worth noting that some suppliers not captured by the survey may already be employing these techniques, albeit without expressed interest in nuclear.

These findings suggest that the Saskatchewan supply chain will require increased investments in advanced technologies to match the AMT capabilities of external competitors when SMRs are deployed. However, substantial integration of AMT into SMR manufacturing isn't anticipated until the major obstacles to their adoption, as discussed earlier, are addressed. Supply chain development for AMTs is for NOAK, not FOAK. This provides Saskatchewan suppliers time to deliberate on their next steps regarding AMT adoptions. Notwithstanding, AMT investment decisions for these suppliers will most likely require a stronger business case across multiple sectors and may not be totally reliant on the nuclear industry.

Fabrication, welding, machining, and inspection emerged as the primary manufacturing processes where AMTs are predominantly used by the respondents. Conversely, fewer suppliers employ AMTs in material/asset tracking and administrative operations, signaling that AMT adoption has primarily centered on the manufacturing floor. Preparation for the nuclear supply chain may be the opportunity to develop digital AMTs such as IIOT, data analysis, AI & ML, which can significantly enhance productivity and decision-making through effective materials/shop floor assets tracking, data collection, analysis, and transfer within organizations. A data-driven approach helps to equip businesses with the agility to respond to unforeseen disruptions like the COVID-19 pandemic by facilitating informed decisions, rapid adaption to changes, and bolstering resilience in operations.

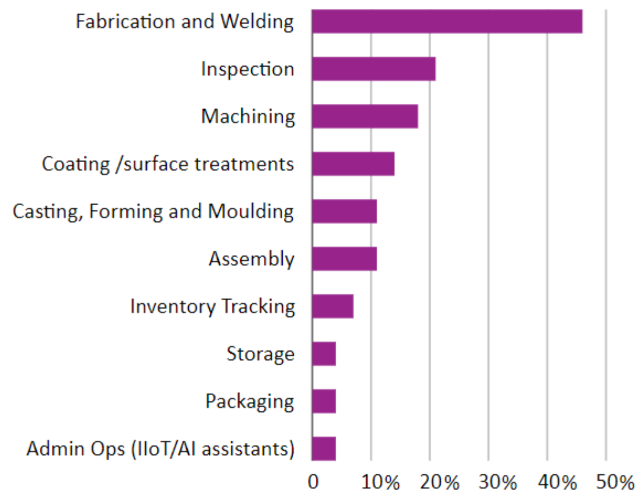


Figure 35: Manufacturing processes where AMTs are currently employed by SK supplier survey respondents.

Factors affecting adoption of AMTs in Saskatchewan

Despite the evident benefits that AMTs offer, the question arises as to why more Saskatchewan manufacturers aren't currently investing in them. The answer may be multifaceted, with different factors influencing their adoption, including economic conditions, market demand, corporate leadership, and local business culture. It is generally recognized that there are three basic steps to successful AMT adoption in manufacturing:

- Identifying the right technology to invest in - transition effects to existing operations,
- Ensuring there's a business case – the benefits of investment must outweigh the costs, and
- Training the workforce to operate and integrate the new technology with minimal disruption and maximal effectiveness.

Several barriers within each of these steps can hinder manufacturers from maximizing the potential of AMTs. The survey respondents highlighted some of these obstacles, as follows:

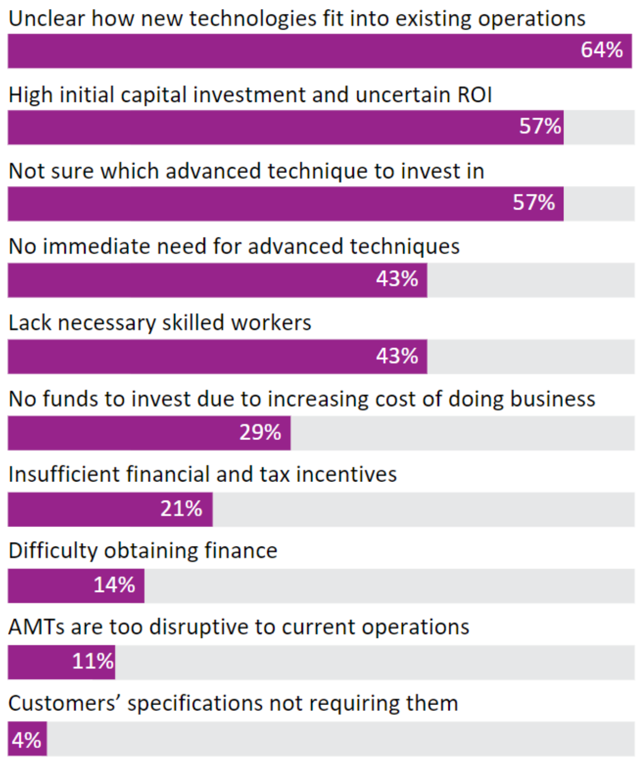


Figure 36: Obstacles preventing SK suppliers from investing more in AMTs.

Understanding the technology

The first step in successfully adopting AMTs typically involves determining which techniques are the best fit and hold the highest priority for the business. This decision requires access to comprehensive information and a thorough understanding of the considered techniques. However, tailored information directly addressing the specific type of business and how the specific techniques could impact existing workflows may not be readily available, often necessitating further R&D efforts. According to survey participants, uncertainty about which AMT to invest in and how these new techniques fit into existing operations ranks among the top barriers to technology adoption. These obstacles are especially pronounced for small businesses, which may have limited resources to research and implement new technologies (refer to Figure 37).

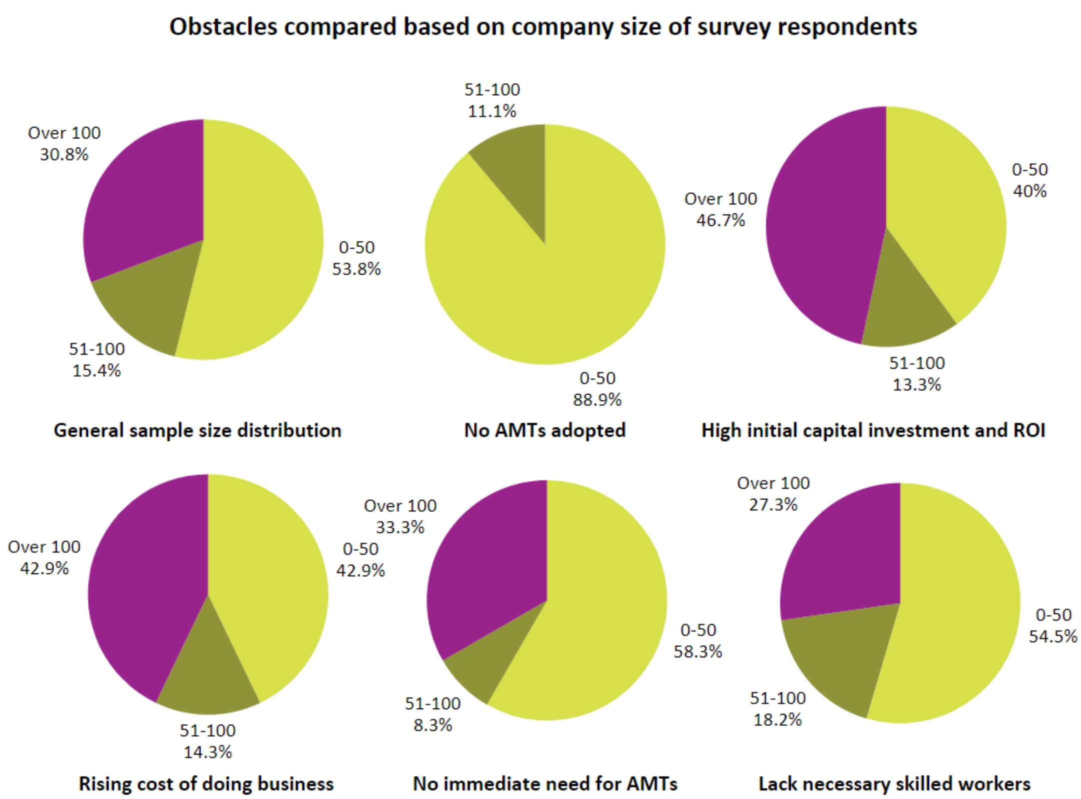


Figure 37: AMT adoption obstacles compared based on company size (by number of employees).

Businesses are more likely to invest in new technologies if they fully understand the technique and how it fits into their operations. Saskatchewan suppliers could benefit from available outside support in identifying which AMTs warrant investment. Programs for technology assessment, demonstration, testing hubs for emerging technologies, and access to R&D funding are all effective means of facilitating information access and enhancing SK manufacturers' understanding of the technology. Technology assessment programs are especially valuable, as they involve site visits by qualified professionals who evaluate a company's performance and offer recommendations for implementing AMTs. Potential resources include organizations such as CME, NGen, SIMSA, Technology Access Centres, and Sask Polytech. SIMSA could also work with the provincial and federal governments to develop a program similar to Ontario's former SMART program, which was instrumental in subsidizing the cost of technology assessment and diagnostic services and supporting AMT adoption initiatives for SMEs.

High initial capital and investment risks

High initial capital requirements and investment risks can present significant barriers to the adoption of AMTs. Survey respondents identified these factors as the second major obstacle to AMT adoption. Many Saskatchewan suppliers may be hesitant to make substantial initial investments in new technologies, especially when existing production methods meet current market demands. However, relying solely on current capabilities to meet market demands may not suffice in the long run. AMTs offer much more than just meeting immediate market demands; they ensure businesses remain adaptable and resilient in the face of technological advancements and market changes. While initial investments in AMTs may be higher, they often lead to cost savings over time (refer to section 4). With a proper adoption strategy, businesses can plan and spread-out initial investment costs without necessarily making it a one-time investment, thus reducing the immediate impact on their balance sheet. Additionally, AMT investment decisions can be made with a plan to serve multiple industries, which can be an effective risk management approach.

Advanced manufacturing isn't solely about acquiring new equipment; it is about achieving manufacturing improvements in innovative ways. This may involve upgrading the capabilities of existing equipment with new software and accessories or combining digital AMTs, such as AI/ML, with existing equipment to improve manufacturing processes. Some OEMs accept old equipment as trade-in and offer newer equipment to suppliers at discounted prices. Depending on their business needs, suppliers can also explore options with used equipment or leasing to mitigate initial investment costs. In some cases, manufacturers can purchase equipment from other large companies looking to offload equipment after completing a project. A few Saskatchewan suppliers have already adopted this strategy for acquiring advanced equipment economically.

Businesses require assistance offsetting the costs and risks associated with investing in new technologies. Federal and provincial government programs designed to provide financial support and tax incentives to SK suppliers to encourage investments would assist in accelerating AMT adoption. Some possible financial resources for SK suppliers are Innovation SK, PrairiesCAN, IRAP, among others.

Labour shortages

Labour shortages pose a significant challenge to Saskatchewan manufacturers, impacting technology adoption and overall productivity. Effectively addressing this issue can be enhanced through collaboration between federal and provincial governments, academic institutions, and manufacturers. Efforts can be focused on increasing awareness of manufacturing career opportunities and enhancing advanced manufacturing skills through early exposure, curriculum development, mentorship programs, and job grants. This can include expanding post-secondary education capacity to accommodate higher enrolment in relevant fields.

Saskatchewan's large Indigenous population presents an under-tapped resource for talent. Programs that enhance awareness and skills development for STEM careers, particularly in manufacturing, can help address labor shortages while also addressing economic reconciliation goals. Local organizations, including the Indigenous Manufacturing and Contracting Network (IMCN), the First Nations University of Canada and Saskatchewan Indian Institute of Technologies (SIIT) can help inform and support initiatives in this area.

Saskatchewan manufacturers looking to adopt AMTs could prioritize training culture, offering internal training, and upskilling programs to enhance the efficiency and productivity of their existing workforce. An existing funding program, the Canada-Saskatchewan Job Grant could be leveraged to support these activities. Additionally, provincial government streamlining of regulatory processes to recognize skills obtained outside the province or internationally, could enhance workforce participation and enable skilled newcomers to contribute to the economy more swiftly.

While efforts to bolster the local workforce are underway, international recruitment programs like the Saskatchewan Immigration Nominee Program (SINP) can provide immediate relief for skill shortages. By implementing a comprehensive approach that combines education, training, regulatory reform, and international recruitment, Saskatchewan can effectively address labour shortages, foster technology adoption, and drive economic growth in the manufacturing sector.

8.0 Conclusion & Next Steps

8.1 Summary

An ever-increasing demand for clean, secure, and reliable supplies of electrical generation, coupled with recent technological advances in the nuclear industry, driven in part by the development of SMRs, has created a demand for nuclear energy not seen in decades.

Canada is a Tier-1 nuclear nation with significant installed generation capacity, and we continue to play a leading role in the industry with the support of Small Modular Technologies development, reactor licensing, and as a host for first of a kind SMR installations. These inherently safe SMR technologies offer important flexibility to support or replace existing energy systems, they can be feed into existing distribution systems or operate off grid in remote locations, and they can be employed to provide not just electricity generation, but also process heat for industry, hydrogen generation, or desalination etc.

Assembly line type construction of SMR modules built in a controlled factory setting hold promise to provide enhanced quality control, and improve cost competitiveness, along with reductions in schedules and project risks. Canada has numerous SMR build projects in several provinces at some stage of development or consideration, in sizes ranging from 5 to 300 MW, which will not only help drive the country towards achieving its zero emission targets by 2050, but which also promise to yield significant domestic economic development in the process.

In addition to reducing costs, the implementation of Advanced Manufacturing Techniques can be an important driver for reducing time to market and environmental impacts, while at the same time increasing quality and cost competitiveness. With limited growth in the nuclear industry for several decades, the industry has been relatively slow to adopt new technologies such as AMTs. The recent advancement of new SMR technologies presents new opportunities and a heightened interest in developing designs and manufacturing processes which can reap the technical, quality, and commercial benefits that AMTs can provide. Major companies and consortia globally, including Canadian companies, are already undertaking numerous AMT demonstration projects specific to the demands of nuclear.

As presented in this report, the nuclear industry operates to established stringent codes and standards, which will present challenges to the adoption of some AMT technologies, until such a time as considerations unique to AMT are fully embodied in these documents. There are other challenges which the adoption of AMTs faces also, such as the development, supply or testing of new materials, or existing materials for new conditions, and addressing other such issues which are absolutely critical to the nuclear industry such as cyber security. On the commercial side there are challenges of understanding the market sufficiently to develop adequate business cases to justify the adoption of these technologies, and then having them sufficiently funded. Where there are challenges however, there are also opportunities which present themselves, many of which are unique to adopting these advanced techniques specifically for this technically demanding emerging market to produce SMRs.

Canada has a well-established supply chain driven in recent years by significant reactor refurbishment projects. The US, although it has had little new build experience in recent times, has also over the years put considerable effort into increasing actual nuclear generation at many of its stations through reactor uprates, and in recent years has made significant investments into emerging SMR technologies. Globally there is already a significant upward trend in nuclear power plant construction originating primarily from Asian countries.

Several SMR technologies are making their debut on Canadian soil, with some likely to be positioned in Saskatchewan. Given the inherent advantages of manufacturing proximity to construction sites, and understandable government preferences for localization, this presents unique opportunities for the Saskatchewan supply chain to develop capabilities and experience saleable to subsequent projects beyond the Saskatchewan, or even our national border. Opportunities to employ AMTs may be limited for the first off deployments but should develop further for future replications of the reactor technology.

All reactor vendors surveyed plan to adopt AMTs in the next decade to produce their SMRs. The survey indicated that AMTs would most likely be pursued for manufacturing pain points such as, providing alternative fabrication methods for components that would otherwise be long lead, improving quality control and inspection, and data management, as just a few examples.

Several key technologies of interest identified by vendors include PM-HIP technology, additive manufacturing, automated welding and joining, and robotics/automation and digital twinning. The potential implementation of these techniques was explored by our Technical Advisory Committee and was also part of our consultation with industry stakeholders.

Saskatchewan has an existing robust, diversified construction and manufacturing sector currently focused primarily on the agriculture, construction, mining, and oil and gas industries. These capabilities should be readily transferable to the nuclear SMR supply chain with appropriate training, however nuclear vendors and suppliers will need to coordinate their efforts to mitigate potential labour shortages that are likely to result from this increased industrial activity. To effectively engage in this new market opportunity, some smaller firms might find it advantageous to partner in some way with existing larger nuclear supply companies. Saskatchewan also holds a leadership role in innovation, applied R&D, and technology commercialization, and it has a dynamic research cluster, who can play a instrumental role in shaping the future of the SMR industry. The Saskatchewan government encourages innovation and investments in the manufacturing sector by providing a number of business incentives and tax credits to manufacturers.

Results of our survey indicate that most Saskatchewan suppliers are currently non-nuclear suppliers, but the majority expressed interest in becoming nuclear suppliers, either for nuclear island, or for balance of plant type components. In support of this interest, and in light of the challenges of nuclear accreditation such as for compliance with nuclear quality assurance programs such as the CSA N299 series of standards, government funding has been provided to help prepare local companies for their preparation to participate in this market.

Current AMT involvement within the Saskatchewan community revolves primarily around welding, machining, and inspection techniques, i.e. activities centered on the shop floor, although opportunities in nuclear could result in an expansion of this interest to material/asset tracking and administrative operations and the development of digital AMTs such as IIOT, data analysis, AI & ML.

The survey exposed that the limited AMT involvement thus far is largely due to lack of clarity about incorporating AMTs into existing operations, uncertainties about which AMTs to employ and concerns about high costs or cost uncertainties. In some cases, there has simply not yet been a need identified.

The survey results also exposed the need that companies have for outside support to address their unknowns, as well as the need for collaboration between federal and provincial governments, academic institutions, and manufacturers, to build the skilled labour force which will be required to fully engage in the upcoming AMT opportunities for this emerging SMR market.

8.2 Pathways to Success: Next Steps

A number of suggestions to accelerate the adoption of AMTs for SMRs have been included throughout this document. The key next steps and a framework illustrating a pathway to developing specific concepts are presented here.

Ensuring a skilled workforce is paramount to meet the demands of a growing nuclear industry and the development and adoption of advanced manufacturing processes. Investment in both traditional and innovative solutions to address the existing and future shortage of skilled workers is needed. Strategic programming at educational and academic institutions can enable a vibrant manufacturing industry to serve the nuclear sector, driving GDP activity alongside energy transition. Further detail on the role of these institutions is provided in Figure 38.

Strategy for supplier development and qualification: There may be opportunities to streamline supplier development and qualification to accelerate supply chain readiness. The UK's Fit for Nuclear program provides funding and mentorship to support the process of adopting nuclear quality programs – a similar program in Saskatchewan would be advantageous. Development of a vendor qualification process that allows for early qualification based on existing capabilities (pre-capital investment in AMTs), can help to establish collaborative relationships, reduce risk, and foster co-investment strategies that support common goals to development.

Academic Collaborations Ahead of SMR Deployment in Saskatchewan

Key actions to support the nuclear and advanced manufacturing sectors:

- **Industrial Training:** Create programs focused on nuclear and AMTs for the local workforce development.
- **Developing Skilled Talent:** Promote the development of skilled professionals through specialized educational programs, apprenticeships, and hands-on training to meet the evolving needs of the manufacturing and nuclear industries.
- **Research and Development:** Undertake research to develop and characterize advanced manufactured components, providing evidence for the qualification of AMTs with regulatory bodies and facility owners. The establishment of a post-radiation testing facility, ideally situated at USask, would enhance research capabilities and facilitate comprehensive component testing.
- **Access to Funding:** Collaborate to access R&D funding only available to academic institutions.

Figure 38: Academic contributions to the SMR and AMT ecosystem.

Access to funding: To propel the adoption of AMTs for SMR projects forward, access to capital to develop and qualify these approaches will be required. SMEs, academic institutions, and research labs with access to federal or regional funding can proactively engage with vendors and suppliers to collaborate on areas requiring further work. Our research affirmed that nuclear vendors are looking for suppliers with AMT capacity and for the right concepts and projects, they are interested in developing relationships to furthering manufacture of components involving these methods. By initiating early engagement with vendors, suppliers position themselves favorably for future deployment opportunities.

Enhanced Collaboration: Fostering increased industry collaborations is essential for advancing AMT development and optimizing research and development costs. While nuclear vendors invest heavily in independent AMT R&D for direct benefit to their projects, collaborative initiatives on overlapping AMT research efforts could lead to substantial cost savings and accelerated innovation. Activities to bring together nuclear vendors with shared interests and facilitate connections with capable and interested suppliers, research institutions, and post-secondary institutions would help enable the development of these sorts of collaborative projects. International collaboration between SDOs can also help expedite the development of codes and standards for these techniques.

Pathway for AMTs for SMRs: The project that supported the development of this report also involved workshops to bring together nuclear vendors and Saskatchewan suppliers to discuss which manufacturing challenges held the most potential for AMTs to support enhancements in SMR manufacturing. The intent was to develop more specific common areas of interest in the thematic areas identified in the study that hold the greatest opportunity and potential for nuclear vendors: welding and joining, additive manufacturing and advanced materials, automation and sensors, and data management.

The relationships developed through this process help to build trust alongside the identification of common interest areas, which helps to further the development of joint development programs that bring together vendors, suppliers, SDOs, academia and investors, including government. These discussions can foster collaborations between a single vendor and supplier, resulting in a solution to a sourcing challenge that proves mutually beneficial and creates economic gains for both parties. Additionally, areas of broad interest across a collection of ecosystem stakeholders may be identified, which can foster collectively funded program-based work to address common challenges. For example, a coordinated test program for sharing resources and accessible data could accelerate codes and standards qualification of AMTs. Continuation of these sorts of discussions, following the framework visualized in Figure 39 has the potential to find solutions that will accelerate SMR deployments and foster economic development in the province of Saskatchewan and beyond.

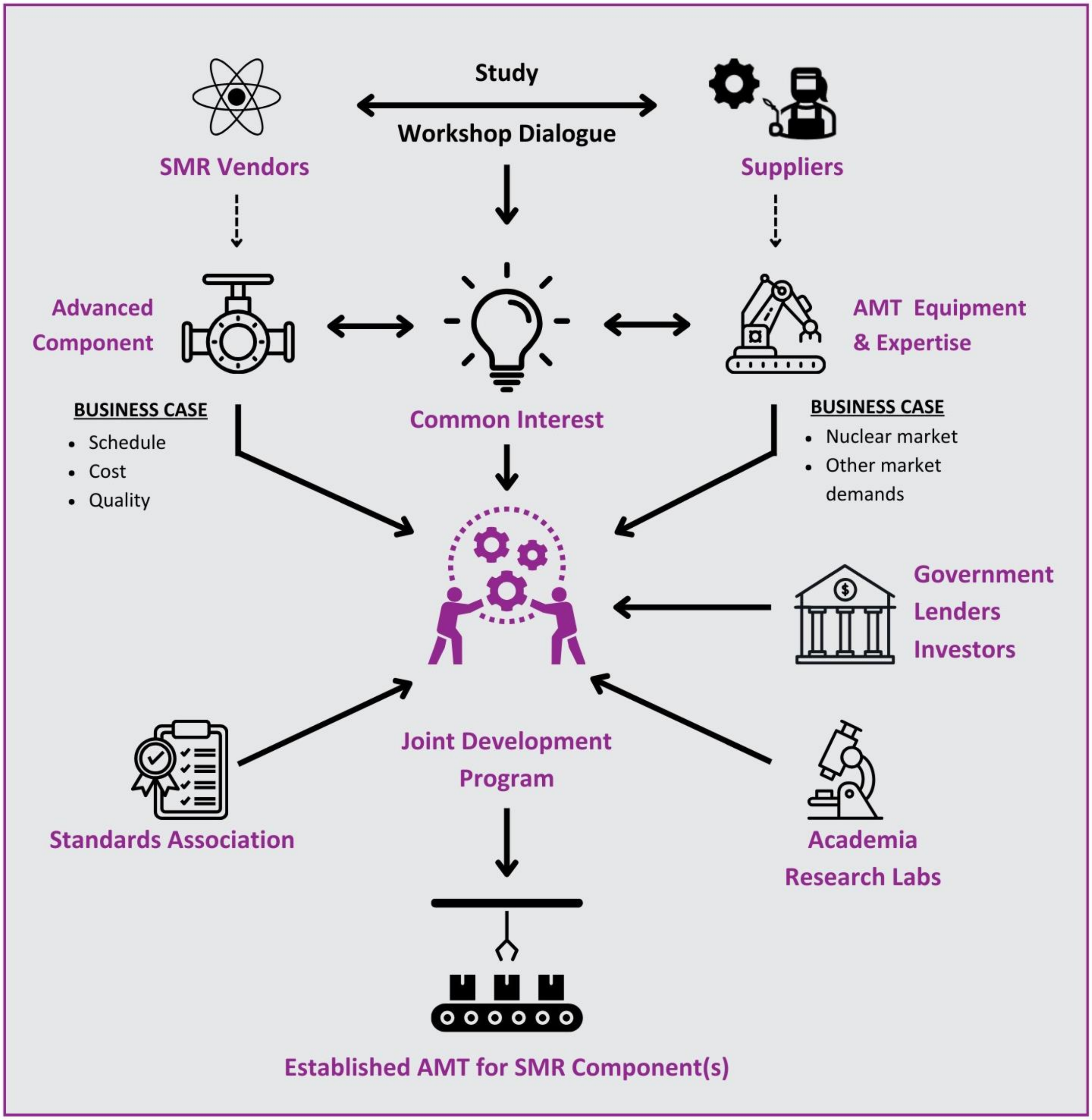


Figure 39: Pathway for development AMTs for SMR Manufacturing

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Appendix A: Detailed Descriptions of Advanced Manufacturing Techniques

A. Description of AMTs

1. Electron Beam Welding (EBW)

Electron beam welding is a fusion welding process that utilizes heat from a high-velocity beam of electrons to bond two materials. An electron gun generates the beam, which is focused by magnetic fields. Upon impact, the kinetic energy of the electrons is converted to heat, melting the workpiece, and creating a joint. The entire process must be performed in a vacuum to prevent gases from scattering the electron beam. This can be achieved by placing the entire workpiece in a vacuum chamber or using a recently developed local method of EB welding, where just the electron beam gun is enclosed in a vacuum box on the side of the components to be joined. Additionally, specialized fixtures and Computer Numerical Control (CNC) tables are essential components of an EBW process, facilitating precise movement and positioning of workpieces within the vacuum chamber.

Advantages of EBW

- Works rapidly (up to 200 mm/s) and runs on a single pass, with no filler material required to join metals [67].
- Since welding is done in a vacuum environment, there are very few chances of oxidation and impurities left by the process.
- Can weld materials thicknesses of < 0.5 mm to about 300 mm [68].
- Offers precise weld penetration with repeatable accuracy and good-quality welds, maintaining up to 95% of the base material's strength.
- Creates only a small heat-affected zone, which minimizes distortion and material shrinkage while allowing welding near heat-sensitive components.

Disadvantages of EBW

- Technology is expensive and requires frequent maintenance to keep it functioning correctly.
- Process requires highly skilled operators and effective precautions must be taken to protect the operator from the ionizing radiation that the process produces.

Applications – Automotive industry (transmissions), aerospace components & aircraft engine industry, electronic components, pressure vessels, etc.

2. Laser welding

Laser beam welding is a process used to join metals or thermoplastics using a laser beam to form a weld. A laser welding system can deliver a tremendous amount of energy very quickly and with pinpoint accuracy to produce high-quality welds. Unlike the EBW, which requires a vacuum, the laser beam can be transmitted through the air using a cover gas to prevent oxidation and improve weld purity. Laser welding can be done in two ways – heat conduction welding and keyhole welding, depending on the power density across the beam hitting the workpiece. In the heat conduction welding process, the metal surface is heated above the melting point of the metal without vaporizing it. The power density for this process is typically < 105 W/cm^2. However, in the keyhole welding process, the laser beam penetrates the workpiece, forming a cavity called a 'keyhole,' filled with metal vapour or, in some cases, plasma. Typical power density is > 106-107 W/cm^2 [69].

Advantages

- Offers precise, intricate welds with high accuracy, minimizing the heat-affected zone and keeping distortion and material waste to a minimum.
- Can be used to join a wide range of materials, including dissimilar materials.
- Results in high-quality welds with consistent mechanical properties. The welds tend to be free from defects such as porosity, inclusions, and fractures.
- Easy to automate, delivering high-volume production and consistent quality.

Limitations

- Equipment costs more than that of electrical or traditional thermal welding.
- Lasers can be hazardous, so they require good safety practices to prevent burns or eye injuries.
- Best suited to thin, light, and precise applications with very close-fitting parts which the optical parts can easily access.
- Some types of laser welding equipment require intensive maintenance and setup, increasing operational costs.
- Joints require precise preparation – must be smooth, closely fitted, and free of contaminants and surface oxidation.

Applications – Commonly used in the automotive industry (body panels, engine components), aerospace (aircraft engine, landing gear), and medical industries (prosthetics, surgical instruments), as well as electronics manufacturing (circuit boards, sensors)

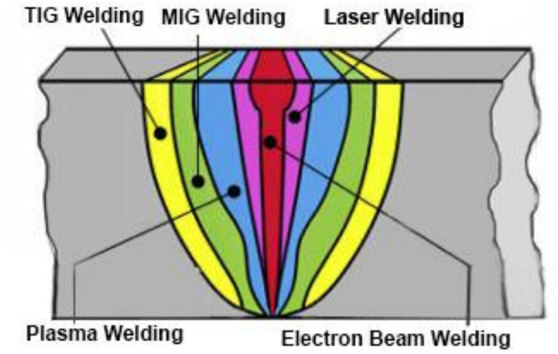

Figure A1: Heat affected zone of different welding processes [70].

3. **Powder Metallurgy Hot Isostatic Pressing (PM-HIP)**

PM-HIP is a process where metal powder is capsulated in a container or mold and exposed to high isostatic pressure and temperature (>1000 °C and >100 MPa) under a high vacuum to consolidate and densify the powder within the mold. After densification, the capsule is removed, yielding a near-net-shaped component with a uniform microstructure, which is then subjected to final machining and inspection.

Advantages of PM-HIP

- Enables manufacture of near-net shape for complex components (reducing material cost and machining)
- Eliminates welds, which reduces stress in critical joint regions.
- Produces uniform and homogenous microstructures which tend to improve material properties and reduces inspection requirements.
- Provides alternative supply chain options.

Applications - Casting densification, metal powder densification, 3D-printed part densification, radioactive waste processing, etc. PM-HIP can produce large, near-net-shaped, complex components with superior hardness, tensile, creep, and toughness properties for use in the power industry.

4. Digital Twins (DTs)

A digital twin is a digital replica designed to reflect a physical asset accurately and is often used as a basis for making decisions. The digital twin is usually updated with real-time data obtained from various sensors embedded in the physical object. Once informed with such data, the virtual model can be used to run simulations, study performance issues, and generate possible improvements, to produce valuable insights which can be applied back to the original physical object. Machine learning and artificial intelligence can be used to train the twin and make it intelligent.

Advantages *(Manufacturing Applications)*

- Process design and optimization: Digital twins can enable more effective research to improve the design of products.
- Preventive maintenance: DTs can effectively estimate, predict, detect, or diagnose the condition of a component/system for maintenance.
- Improved operational awareness: DTs can virtually monitor the operating conditions of assets, make predictions, and give suggestions about how to avoid potential problems.
- Improved efficiency: Personnel can be more efficient because of the opportunity to simulate a process or task before the actual implementation.

Applications – Manufacturing, Aerospace, Construction, Utilities, Agriculture, Healthcare, Retail, Mining, etc.

5. Additive Manufacturing

Additive manufacturing, also known as 3D printing, is a computer-controlled process that creates three-dimensional objects by depositing materials, typically layer by layer. It is the opposite of subtractive manufacturing, such as machining, where parts are created by removing surplus material from a solid block of material until the final product is complete.

The additive manufacturing process begins with designing the 3D model, typically done using CAD software or by taking a 3D scan of an existing object. The model is then sliced into thin layers using specialized software, after which the 3D printer prints the object layer by layer using materials such as resin, plastic, or metal.

Although many types of additive manufacturing techniques exist, this report only covers those with applications to produce nuclear structural components. The choice of additive manufacturing for a specific project depends on material, precision, speed, cost, size, and weight.

Directed energy deposition (DED) is a complex 3D printing process commonly used to repair or deposit material in existing components. In this process, powder or wire is pushed through a nozzle and melted using a focused energy source at the point of deposition. The nozzle can move in multiple directions (five-axis) and is not fixed to a specific axis like most AM processes.

Laser powder bed-fusion (LPB-F) – With LPB-F, a thin layer of metallic powder is spread over the build platform, and then the laser selectively melts based on the model. Another thin layer is spread down, and the laser melts that. The process repeats until the build is complete.

Cold Spray Additive Manufacturing – Cold spray is an additive manufacturing process that enables rapid deposition of powder materials in a solid state at temperatures below their melting points. In this process, small particles of 5 - 100 µm diameter are accelerated in a supersonic jet of heated gas to high velocities of about 300 – 1200 m/s, then sprayed onto the substrate. At optimum spray conditions, particles bond to their target by converting the kinetic energy from impact to heat and undergoing significant and rapid plastic deformation. Unlike conventional thermal spray and vaporizing methods, the cold spray technique avoids high-temperature particle heating during deposition, eliminating oxidation and retaining the original properties of the feedstock particles. CSAM can be used to repair existing parts or to create complete parts.

Applications/Advantages

- Allows for the manufacture complex geometries that are impossible with traditional subtractive technologies or are more expensive.
- Reduces lead times – because there are fewer production steps, and enables part consolidation and optimization.
- Can be readily used to manufacture in-kind replacements for obsolete parts via reverse engineering.
- Enables faster design cycles to bring new products to market faster.
- Provides improved material design and properties.
- Reduces waste
- Provides for simplified inventory and supply chain management – (Digital parts warehouse)

6. Thermal Spray

Thermal spray is a coating process that heats or melts metallic or ceramic materials and deposits them onto a surface. The feedstock, usually in powder or wire form, is heated to a molten or semi-molten state by electrical (arc or plasma) or chemical means (combustion flame) and accelerated towards the substrate in micrometre-sized particles.

Several variations of thermal spray include plasma spray, detonation spray, flame spray, arc spray, high-velocity oxy-fuel coating (HVOF), and high-velocity air fuel (HVAF). The choice of a suitable thermal spray process depends on the desired coating characteristics, size and shape, substrate material and the service environment of the component.

Applications/Advantages

- Thermal spray can be used for preventive wear and corrosion management, or for repairing and overhauling damaged components.
- Offers a wide selection of spray materials and substrate materials.
- Speed of coating formation is fast.

Disadvantages

- Thick coatings are difficult to achieve.
- Requires high temperatures to bond properly with the substrate.
- Coatings do not always indicate the characteristics of the original material.
- Requires measures to combat noise, light, dust, fumes, and other issues.

7. Diode Laser Cladding

Diode laser cladding (DLC) is a process that deposits a protective or functional layer onto a substrate using a diode laser beam. DLC is a valuable precision-driven process offering many advantages over conventional cladding processes due to a higher energy efficiency, smaller heat-affected region, reduced cladding material required and a faster cladding process [71]. The DLC process enables the production of high-quality, fine-grained cladding layers with low porosity, low warpage, and a uniform surface, requiring almost no post-processing necessary [72].

Applications/Advantages

- Used for surface restoration and repair of damaged components.
- Offers precision and accuracy in depositing materials.
- Control over the composition and microstructure of the coating.
- Enhances surface properties such as wear resistance, corrosion resistance, and thermal performance.

- Reduces material waste and cost savings.

Disadvantages

- High initial investment cost
- Limited deposition rates compared to other processes.
- Thermal stresses and distortion in the substrate.
- Limited range of suitable materials.
- Complex setup and parameter optimization are required.

8. AI/ML

Artificial intelligence (AI) and machine learning (ML) are the buzzwords in the industry these days. They are used across industries for automating different processes and achieving a competitive advantage. AI and ML are often used interchangeably because they are closely related; however, these trending technologies differ in several ways.

Artificial intelligence (AI) is a broad field which refers to the use of technologies to build machines and computers that can mimic cognitive abilities associated with human intelligence, such as decision-making, data analysis, and language translation. Although AI is often thought of as a system, it is an umbrella term covering a variety of interrelated but distinct subfields, including machine learning, deep learning, natural language processing, and robotics.

Machine learning (ML) is a subset of artificial intelligence that uses algorithms to analyze large amounts of data, automatically learn insights, recognizes patterns from data, and then makes informed decisions. The performance of ML algorithms improves over time as they are trained and exposed to more data.

Popular applications of AI and ML include AI chatbots like ChatGPT, cognitive supply chain management, forecasting, digital twins, predictive maintenance, etc. By incorporating AI and ML capabilities into their strategies and systems, organizations can boost productivity and efficiency, and enhance data-driven decision-making through predictive analytics.

9. VR/AR

Virtual reality (VR) and Augmented Reality (AR) are forms of extended reality that have been common in consumer technology space for a while. **Virtual reality (VR)** is a completely immersive experience that transforms your physical surroundings into a digital world using tools like motion sensors and headsets with some type of screen displaying a virtual environment. These headsets also use head tracking technology, which allows the display to follow whichever direction you move, providing a 360-degree view of the virtual environment. **Augmented reality (AR),** on the other hand, enhances user experience by combining computer-generated and real-world data to create an interactive and immersive experience. With AR, a virtual layer is added on top of the real world. Instead of being totally immersed in a digital world like in VR, you mostly see the real world with a few virtual additions.

Applications:

- Virtual meetings – VR can save cost of travels for trainings and offer direct access to a facility using a VR set. With VR, trainees can join training from anywhere in the world.
- Virtual training – VR & AR can eliminate the need to train on expensive equipment, or equipment in hazardous locations.
- Virtual designs – VR/AR technology helps designers and engineers replace many physical models and prototypes with virtual simulations. By pairing VR with CAD applications, they can replicate “real world” tests and evaluations in a virtual space.

10. Big Data/Data Analytics

Big data is a combination of unstructured, semi-structured or structured data that increases rapidly with respect to time. The big 5 Vs of big data – velocity, volume, value, variety, and veracity – are the five main characteristics of big data. These data sets can be mined to gain insights and used in ML projects, predictive modeling, and other advanced analytics applications.

Data analytics is the collection, transformation, and organization of data to draw conclusions, make predictions, and drive informed decision making. Data analytics uses big data and machine learning (ML) technologies to discover patterns from large volumes of data, which allow organizations to make effective decisions and optimize business development processes that drive growth.

11. Advanced 3D Metrology

3D metrology is the scientific study of precise measurements using technologies that can create a full three-dimensional representation of an object's geometric shape. It is a cover term for a range of technologies, such as non-contact structured blue light 3D scanners, tactile Coordinate Measurement Machines (CMMs) or computerized tomography (CT) scanners. Until recently, tactile CMMs were the go-to tool for metrologists. However, CMMs are too slow and do not usually generate a complete picture of complex parts. Alternatively, advanced 3D metrology tools like 3D scanners deliver accurate 3D visualization of an object using different sensors such as optical, laser, or sound waves, with an advantage of being faster, portable, and non-contact. These 3D metrology tools acquire data used to perform quality control, accuracy assessment, and various analyses of parts.

12. Robotics/Automation

Automation is the use of computer software, self-operating machines, or other technologies to perform tasks which people would otherwise do.

Robotics is a branch of engineering that incorporates multiple disciplines to design, create, and use robots to perform tasks.

Although these are similar, using them synonymously isn't always correct. Automation can range from mechanical to virtual, and from simple to very complex. While physical robots can be used in automation, not all robots are specifically designed or intended for automation tasks. Here is an illustration of the distinction:

- When a robot autonomously assembles a car in a factory, this is automation with robotics.
- When a robot is controlled by a trained surgeon for precise movements of surgical instruments inside the patient's body, it doesn't operate autonomously or replace the surgeon's expertise. In this case, the robot is not employed for automation but rather as a specialised assistive device.

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