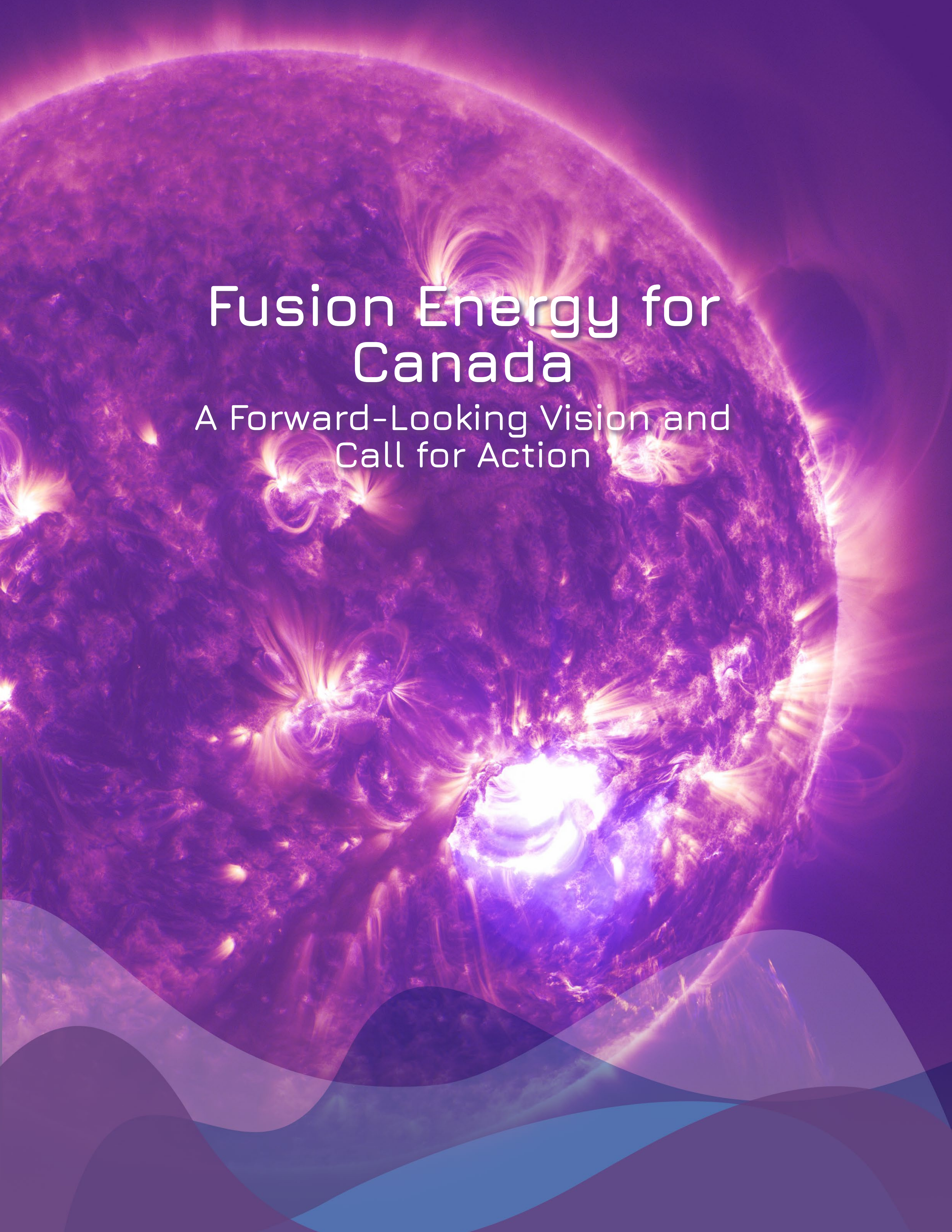
Fusion Energy for Canada

A Forward-Looking Vision and Call for Action



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Foreword & Contributors

This document presents a Canadian Nuclear Laboratories led vision, strategy, and roadmap for fusion energy in Canada. The organizations listed below have contributed to and reviewed this strategy with the aim to call for Canada to take action on developing a domestic fusion energy program and industry that will benefit Canadians and the global fusion sector. This document is intended to be a foundation for discussions and does not constitute a full body of work but does provide a holistic view of the journey that Canada needs to take in order to realize the potential of fusion energy.

Canadian Nuclear Laboratories | Laboratoires Nucléaires Canadiens

CNL is Canada's premier nuclear science and technology organization, and a world leader in developing nuclear technology for peaceful and innovative applications.

AECL EACL

Atomic Energy of Canada Limited (AECL) is a federal Crown corporation with a mandate to enable nuclear science and technology and to protect the environment by fulfilling the government of Canada's radioactive waste and decommissioning responsibilities.

Helixos

Helixos works at the intersection of strategy consulting and technical advisory to commercialize cleantech, including fusion technologies.

generalfusion

General Fusion is a Canadian company based in Vancouver, British Columbia, which is developing a fusion demonstration machine based on magnetized target fusion.

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Calian® is a consulting company that helps people communicate, innovate, learn, stay safe, and lead healthy lives with confidence.

TYPE ONE ENERGY

Type One Energy Group is a company developing a stellarator fusion power system. It has an office established in Vancouver, Type One Energy Group Canada, which is a subsidiary of the U.S.-based parent company.

FECC is a not-for-profit dedicated to mobilizing human, financial, and other resources for the participation of Canadians and Canadian enterprises in fusion energy.

Stellarex is a fusion energy technology development company, focused on the stellarator approach to magnetic fusion.

Kyoto Fusioneering Ltd. is a spin-off from Kyoto University in Japan that aims to accelerate the realization of fusion energy with advanced fusion plant engineering and technology.

UNENE is a network of universities, nuclear industry organizations, and government institutions dedicated to excellence in nuclear science, technology, and engineering.

Hatch is a global multidisciplinary management, engineering and development consultancy, that provides consulting, operations support, technologies, process design, and project and construction management to clients in the mining and metals, energy, and infrastructure sectors.

Canada's national particle accelerator centre, TRIUMF is an internationally recognized consortium of 21 Canadian universities providing diagnostics measuring subatomic particles that are highly relevant to fusion research and a training ground for top talent.

A leading international engineering and testing company based in Toronto, Kinectrics delivers innovative solutions to the clean energy market, including advanced fusion-enabling technologies.

Executive Summary

Fusion energy has the potential to provide far-reaching, positive impacts to Canada through reliable and resilient clean energy to support Net-Zero by 2050 and beyond. Fusion is a transformative innovation that has the potential to provide multiple decarbonization pathways through clean, secure, economic electricity and process heat.

Internationally, there has been significant progress in both the public and private arenas in fusion development. Fusion R&D is accelerating in maturity, moving from science experiments to solving engineering problems through to now building demonstrations and prototypes. Currently, there are a total of 98 operating fusion experiments and demonstration facilities globally, with 13 under construction, and a further 33 planned.

The market pull for commercial fusion has grown rapidly in the last five years, **with over 43 private fusion companies operating globally, attracting more than $8.2 billion* in funding.**

Furthermore, international governments are taking bold actions to support their own fusion programs and private industry by establishing national strategies, developing supportive policies and regulatory approaches, as well as allocating funding and resources.

Global Fusion Momentum

98 **Operating fusion experiments**

13 **Demonstration facilities under construction**

33 **Demonstration facilities planned**

43 **Private fusion companies globally**

>CA $8 billion

Total investment in **private fusion companies**

Canada's Contribution to Fusion

Canada has existing expertise in many of the capabilities required to develop a mature fusion industry. **Deuterium and tritium production and supply, storage, recycling, and handling technology for fueling fusion power plants are prime areas of Canadian expertise** that can be leveraged in the global fusion energy market. Canadian nuclear industry capabilities can also be adapted to support fusion development, **including robotics, remote handling, irradiation, materials science, thermal-hydraulics, reactor physics, activated waste management, nuclear plant operations and safety culture, and more**. With many overlaps in expertise, technologies, and workforce, the **continued development of nuclear fission and fusion are synergistic in Canada.**

Amongst its nuclear nation peers (e.g., France, Germany, Japan, UK, and U.S.), **Canada currently provides the least government support for the development of fusion R&D and a fusion industry**. Canada did have a robust national fusion program in the past, but has since then remained active primarily through the initiatives of academic/scientific institutions and entrepreneurs. To accelerate the development and deployment of fusion technologies in Canada, there will need to be far greater investment in both the public and private sectors.

* Unless otherwise noted, all dollar figures in this document are in Canadian dollars.

Leveraging our capabilities and providing more support to grow the domestic fusion sector, Canada is in a strategic position to significantly contribute to the growing global fusion industry and capitalize on significant economic opportunities for the nation.

Economic Benefits and Emission Reduction

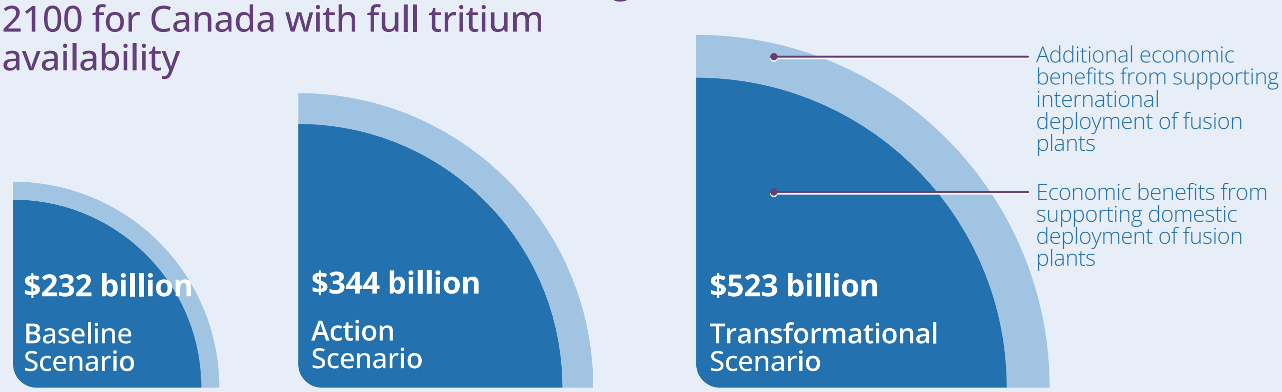
Commercial fusion energy can deliver significant economic benefits for Canada. The estimated cumulative economic benefits to Canada by 2100 for the broad deployment of domestic and international fusion plants range **from $232 billion in the baseline scenario, up to $523 billion in the transformational scenario**, increasing in each scenario with greater investment and enabling policy levers. There is the potential to create thousands of jobs across the economy for the construction and ongoing operations of fusion power plants, as well as to service international export markets. Domestic plant construction alone can result in over **63,000 new jobs by 2050**. Some of these potential benefits are attributable to the export of products and services to support international fusion power plant deployments. With the appropriate strategic investments, Canada could access **export markets with a cumulative value of over $147 billion by 2100**.

While accelerating fusion energy technology development is critical, the extent to which potential opportunities can emerge may also depend on the availability of tritium to support the deployment of domestic and international fusion power plants. This highlights the importance of Canada's world-leading capabilities in the production, supply, and handling of tritium, to support the global industry and maximize the potential benefits.

Fusion can also contribute to Canada's decarbonization goals to reach net-zero emissions by 2050 and beyond. There is an opportunity for nuclear fission and fusion power plants to work synergistically to provide safe, reliable electricity and industrial heat, supporting Canada's decarbonization efforts. Fission brings established infrastructure and dependable energy production, vital for ensuring consistent energy supply. Fusion, with inherently safer reactions and minimal long-term radioactive waste, offers a sustainable solution. Combining these technologies creates a diverse energy portfolio, guaranteeing stability, flexibility, and advancement towards cleaner energy futures.

By 2050, the deployment of domestic fusion power plants **can reduce cumulative emissions by up to 75 Mt, 121 Mt, and 192 Mt CO_2-eq** for the baseline, action, and transformational scenarios, respectively. By 2100, the broad adoption of fusion energy has the potential to **reduce Canada's emissions by over 88 Mt CO_2-eq per year, representing a 13.3% reduction on 2020 levels,** assuming that it only displaces electricity production.

Cumulative economic benefits through 2100 for Canada with full tritium availability



For Canada's nascent fusion industry to deliver sustainable and enduring impact, the challenges and opportunities must be understood across the policy, market, technical, and supply chain domains. The lack of a fusion strategy in Canada hinders R&D and growth of the industry. In addition, a risk-informed regulatory framework is required for Canada's nascent fusion industry to deliver sustainable and enduring impacts.

The scale of both federal and provincial investments in fusion energy is low in comparison to other Tier 1 economies and nuclear nations. This is apparent in the lack of dedicated, large-scale, comprehensive centres of excellence for fusion R&D or associated national experimental facilities. The broader Canadian industry needs further investment to become part of a fusion energy industrial supply chain or to become a key customer and adopter of fusion power plants. **Without this investment, there is a significant risk that Canada may be left behind by its international peers, and fail to capitalize on substantial economic, social, and decarbonization opportunities.**

Vision, Strategy, and Roadmap

The long-term vision is that fusion will provide a clean and safe energy source enabling a high standard of living in Canada and around the world. Fusion power plants will be supported by a robust supply chain and by several Canadian centres of excellence in fusion energy science and technology. As part of a renewed Canadian national fusion program, this vision is achievable through the implementation of a comprehensive strategy, guided by a roadmap for development.

Internationally, the technical feasibility of generating energy from fusion has not been fully demonstrated. Key areas that need further development include the extraction of energy from the fusion reactions to generate electricity, the fusion fuel cycle, the formation and sustainment of fusion plasmas, and tritium production, extraction, and removal. In addition to ensuring the materials like metals and alloys necessary for the fusion fuel cycle and tritium production are available, the raw materials supply chain for these components also needs to be in place to sustain the operation of the plant. Fusion power plant demonstrations are essential to showcase the scientific, engineering, operational, and economic feasibility of these integrated systems.

In response to these challenges, a fusion strategy has been developed based on where Canada is now, and where Canada needs to be in the development and implementation of fusion energy. In the near term, it is expected that several fusion prototypes will be operating in Canada and/or elsewhere in the world. Based on technology development timelines for leading fusion companies, the demonstration and adoption of fusion energy is expected to occur in the 2030s and 2040s with global expansion of this energy source beyond 2050.

The strategic roadmap proposed in this document is an ambitious plan based on a far-reaching vision for Canada to become an international leader in fusion technologies

NEAR TERM
2024 – 2034

DEMONSTRATION of fusion power plants in Canada and/or elsewhere in North America, Europe, and Asia

MEDIUM TERM
2035 – 2050

ADOPTION of fusion energy in Canada and in select regions, transitioning to mature commercialization

LONG TERM
2050+

EXPANSION of fusion energy in Canada and globally across all continents and services, with a goal to deploy commercial fusion energy in Canada by 2050, supporting net-zero carbon emissions targets. The fusion strategy and roadmap are divided into five foundational areas of focus or strategic pillars, as seen below.

With strategic investments in the Canadian industry, Canada can secure a position as a leading global supplier and developer of select fusion technologies and expertise in the near term, particularly with the production, supply, and handling of fusion fuels (deuterium and tritium), lasers, instrumentation, and computer modelling.

Research & Development	• Build international collaborations and partnerships • Leverage, grow, and adapt existing Canadian capabilities • Leverage R&D from CANDUs, small modular reactors (SMRs), and advanced reactors • Build fusion component and test facilities
Demonstration & Deployment	• Build and operate fusion experiments • Build and operate fusion demonstration plants • Establish consortia to share risks and rewards for the first builds of commercial-scale fusion prototypes
Supporting Services	• Develop a Canadian fusion energy industry supply chain • Develop fusion fuel cycle infrastructure • Develop distribution and export infrastructure for tritium and tritium production technologies
Skills, Capabilities, & Engagement	• Establish and grow education and training programs at Canadian universities and colleges • Engage with community groups, including indigenous communities, early to facilitate co-creation of the emerging fusion industry and gain public support and social acceptance
Policy & Regulation	• Develop a pan-Canadian fusion energy policy and strategy • Engage regulatory organizations early to develop appropriate regulations for fusion • Develop and support international policies and commercial arrangements for export/import of lithium, lithium-6, and/or enriched lithium • Participate in ongoing international efforts to develop and harmonize standards, policies, and regulations for the licensing of fusion energy systems

Call to Action

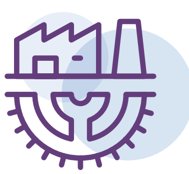
We are calling on the Canadian government to take action to invest in developing a fusion ecosystem in order to capitalize on the economic benefits available from the domestic implementation of fusion energy and supporting the international nuclear sector. Further, the government should incorporate fusion energy into their vision and strategy for clean energy development, as it aligns with their existing clean energy strategy. **This vision can be realized with the 10 recommendations below:**

Establish a pan-Canadian national fusion strategy supported by investment

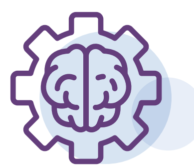
Build fusion experimental facilities for testing and training

Establish partnerships with other nations in the development of fusion

Build prototype/ demonstration fusion power plants



Grow and develop a fusion energy industry supply chain

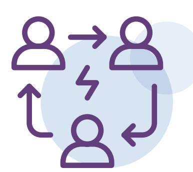


Build education and training programs for fusion

Engage, inform, and prepare key industrial sectors for use of fusion energy

Engage regulatory entities to develop the licensing framework for fusion energy

Establish Canadian Fusion Centres of Excellence



Implement a process for community consultation and stakeholder engagement

1. Introduction

1.1. What is Fusion Energy?

Fusion energy is created in the core of the Sun when multiple hydrogen atoms react through a multi-step process to release energetic helium, photons, and other particles. The fuels, at high temperature, density, and pressure in the Sun, are held together by massive gravitational forces.

Fusion energy refers to electrical and thermal energy derived from fusion that results from the conversion of mass into energy. Scientists and engineers around the world are working to develop fusion technologies capable of achieving fusion energy on Earth and use it as a clean and reliable energy source.

A fusion power plant is a complex technology consisting of the following key systems, as illustrated in Figure 1:

- **Plasma Confinement System** – The system responsible for creating and maintaining the plasma state where the fusion reaction takes place. There are various concepts to how this system operates, for example, magnetic and/ or inertial confinement fusion.
- **Fuel Management System** – The system responsible for injecting and circulating the fuel, which usually consists of hydrogen isotopes, into the plasma system and from this system for purification, recycling, and reuse. This system may include a breeding blanket which absorbs neutrons from the fusion reaction to

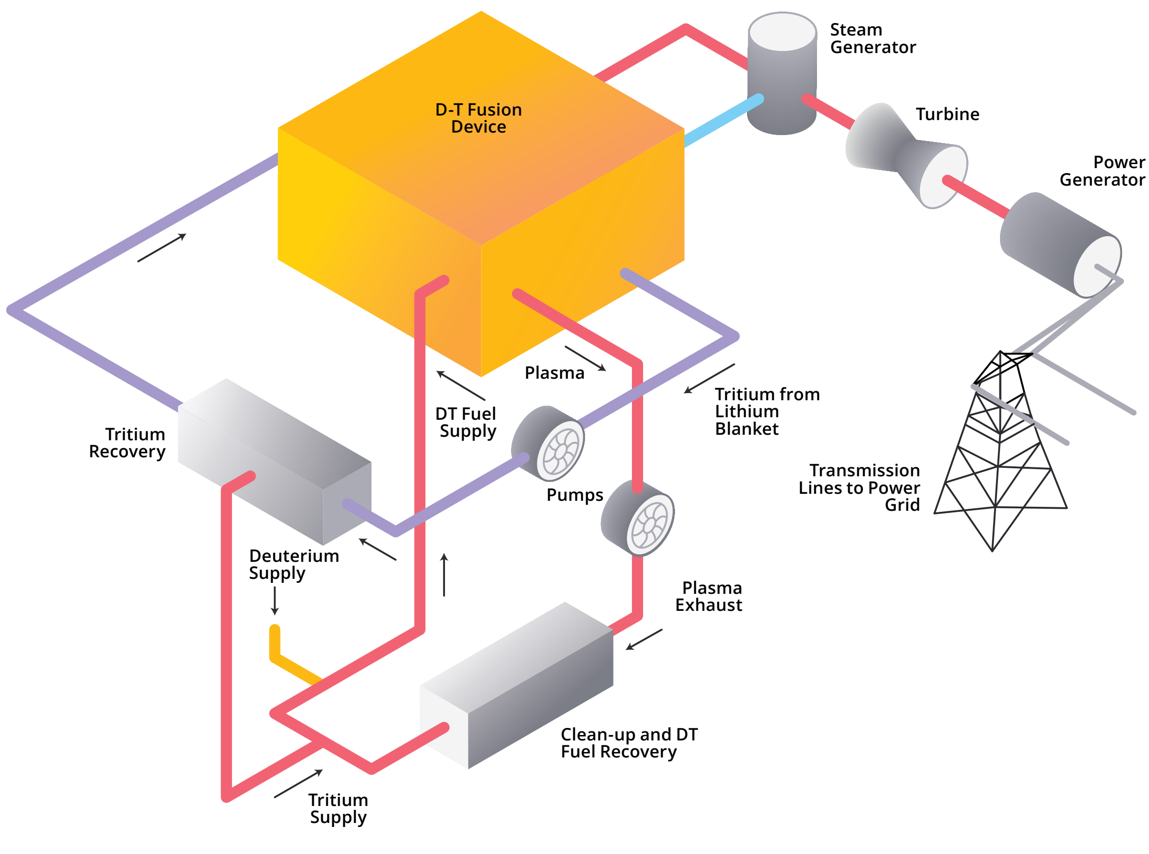


Figure 1. *Block diagram of a fusion power plant [adapted from [1]]. Graphic generated by CNL and Helixos.*

breed tritium fuel from lithium, to ensure the sustainable production of fuel.

- **Power Conversion System** – The system which converts the energy of the fusion reaction into electricity. This process is typically conceptualized using a steam cycle with a steam generator, turbine, and electric generator, like those used in conventional power plants. Novel approaches are exploring direct energy conversion from the fusion reaction.

No fusion technology or facility has yet demonstrated net engineering energy gain, which occurs when the amount of energy produced by a system exceeds the energy required to operate and maintain the system. Within the last 20 years, a number of fusion experiments have worked towards this milestone, with the recent achievement of the National Ignition Facility (NIF) at Lawrence Livermore National Laboratory (LLNL) in the United States achieving scientific energy breakeven**, which refers to the energy produced by a fusion reaction exceeding the laser energy used to drive it.[2]

1.2. Why Fusion Energy?

Fusion energy has the potential to transform the world's energy supply, help meet growing global energy demand, and make a meaningful contribution to the decarbonization of energy systems.[3] The benefits of using fusion as an emerging energy source are manyfold and include its **high energy density, reliability of energy supply, enhanced safety, no carbon emissions**, and **absence of long-lived radioactive waste**, as shown below.

To address climate change, Canada has joined over 120 countries in a commitment to have net-zero carbon emissions by 2050. While Canada's energy mix consists of zero and low-carbon energy sources, about 75% of Canada's primary energy still comes from fossil fuels.[4] Therefore, a multitude of energy sources will be required to serve Canada's residential, commercial, transportation, industrial, agricultural, and forestry sectors without emitting large amounts of greenhouse gases. There is an opportunity for fusion energy to be an important part of this mix.

High energy density	Fusion has a higher energy density than any other process achievable on Earth, with four million times more energy than a chemical reaction, such as the burning of coal, oil, or gas, and four times as much as nuclear fission reactions.[5, 6]
Reliable energy supply	Fusion can provide baseload electricity that does not depend on environmental conditions (such as wind or sun), and is location independent, making it deployable anywhere to support a diverse electricity grid and even potentially deployable to off-grid locations.
Enhanced safety	A large-scale nuclear accident is not possible in a fusion power plant. The fusion reaction requires precisely controlled conditions to start and maintain the reaction, and there is no risk of a chain reaction that could lead to a meltdown.
No carbon emissions	During operation, fusion power plants do not generate any greenhouse gas emissions and use a small amount of raw materials compared to other energy sources.
No long-lived radioactive waste	Unlike nuclear fission, fusion plants are not expected to produce high-activity or long-lived nuclear waste requiring significant investment and infrastructure for its lifecycle management.[7] Low- to medium-level radioactive waste will be produced and can be managed through already-established disposal pathways.

** The term 'scientific breakeven' is used throughout this document and represents the point where the energy produced from a fusion reaction is greater than or equal to the energy imparted directly to the fuel producing the reaction. This is distinct from 'engineering breakeven' which represents the point where the energy produced from the fusion reaction is greater than or equal to the energy required to power all systems within the fusion power plant.

1.3. Why Act Now?

International advancement and momentum in fusion science and technology (S&T) over recent years, coupled with newly available advanced manufacturing and computing capabilities, including quantum computing, means that developing a fusion power plant that generates more energy than it consumes is closer to implementation than ever before.

Specifically, advancements in electronics, high-temperature super-conducting magnets, high-efficiency and rapid pulse rate lasers, materials, computer simulations, and machine learning are helping to expedite fusion development.

Fusion research and development (R&D) is accelerating in maturity, moving from science experiments to solving engineering problems and building demonstrations and prototypes. International governments are taking bold actions to support their own fusion R&D programs and private industry by establishing national strategies, developing supportive policies and regulatory frameworks, and allocating funding and resources.

According to a Bloomberg Intelligence valuation, if successful in producing net electricity, the fusion industry could be valued at around US$40 trillion (CA$55 trillion) in the future.[8] International public and private sectors have been accelerating their efforts with large investments in promising fusion startups and R&D activities. To date, at least $8.2 billion of private funds have been invested to address the scientific and engineering challenge of developing fusion power plants with net energy gain, including many fusion prototypes. Several private sector fusion companies claim that their prototypes will be able to demonstrate net energy gain within the next five years, with subsequent commercial deployment anticipated in the 2030s. Commercial deployment is generally defined as a fusion power plant that is generating and selling electricity and/or heat to the grid or other customers.

- **International advancement and momentum** in fusion science and technology
- Acceleration in public and private **investment**
- **$55 trillion** market opportunity
- Canada's pre-established **tritium and nuclear expertise** and capabilities

As part of a diversified zero-carbon energy portfolio, Canada should continue to invest in both nuclear fission and fusion for a secure future in sustainable energy and synergistic pairing between fusion technologies and our CANDU fleet for the production and use of tritium.

1.4. Why Canada?

Canada holds distinct advantages and characteristics that position it well to build an industry that not only services domestic demand but also significantly contributes to the growing global fusion sector. These include **deuterium and tritium fuel availability and expertise, existing synergistic capabilities from the nuclear industry, a world-class supply chain and ecosystem, and a large domestic energy market**, as shown below:

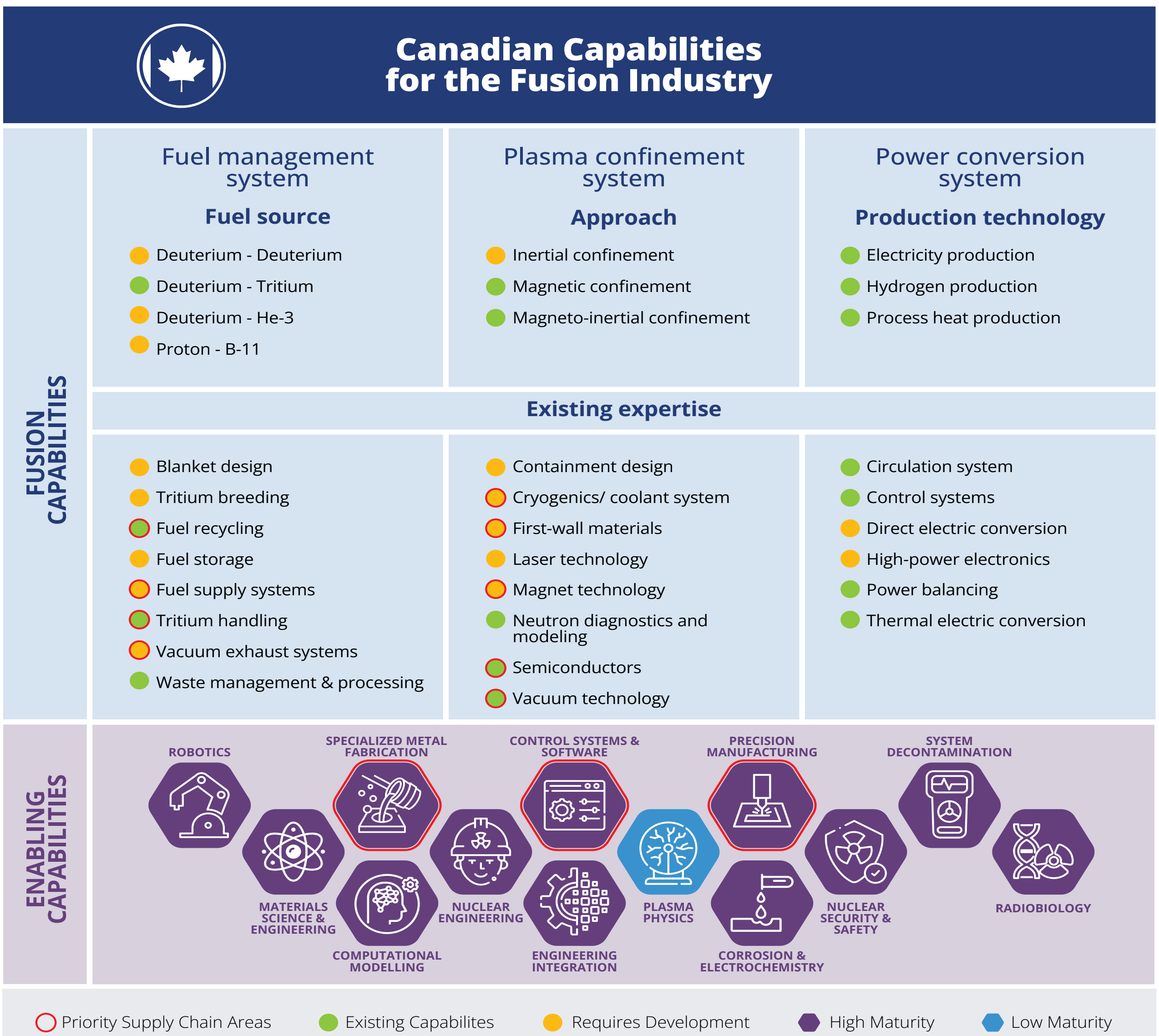
Fuel availability and expertise	The fuels used in fusion reactions are available in Canada. Deuterium can be readily extracted from water, using Canadian technology. An inventory of tritium can be produced as a by-product of Canada's CANDU fleet and can theoretically be bred within a lithium blanket in a fusion power plant. Further, deuterium and tritium production, storage, recycling, and handling technology for fueling fusion power plants are key areas of Canadian expertise.
Strong existing capabilities	Canada has many of the capabilities required to develop a mature fusion industry. Fusion and fission are synergistic and many existing capabilities within the Canadian nuclear industry can also be adapted to support fusion development, including robotics, remote handling, materials science, thermal-hydraulics, and reactor physics.
World-class supply chain and ecosystem	Canada has a mature supply chain and a world-class ecosystem of academic, government laboratories, industrial, and regulatory stakeholders, with proven success collaborating in complex emerging industries. Supporting this industrial base is a highly skilled workforce and a supportive business environment that fosters innovation and growth.
Large domestic market	Canada is a large user of energy and is in the top 10 nations in the world for energy consumption per capita. Fusion can enable Canada to maintain its prominence as an energy superpower while ensuring independence of energy supply and price, sustainability, and compliance with zero-carbon targets.

Of the G7 nations (Canada, France, Germany, Italy, Japan, UK, and U.S.), Canada currently provides the least government support for the development of fusion R&D and industrial development, both in total investment and on a per capita basis. All other G7 members either have dedicated national fusion programs with committed annual funding or are hosting several significant fusion projects.

However, despite a lack of funding and national policy for fusion, Canada has remained active in fusion development, primarily through the initiatives of academic/scientific institutions, and a small number of private sector entrepreneurs. Among these groups is General Fusion, a Canadian private company that is among the leading private fusion ventures in the world. Type One Energy Group, and its Canadian subsidiary based in Vancouver, are also broadening the spectrum of technologies present on the national landscape with its stellarator approach. The University of Alberta and the University of Saskatchewan have maintained small-scale fusion-related R&D programs and have internationally recognized fusion scientists.[9] McGill University has worked on compression science supporting magnetized target fusion, including liquid compression stability analysis and proof of concept experiments on-site. TRIUMF, Canada's national particle accelerator, has extensive experience in fusion-relevant diagnostics and has recently been collaborating with the private fusion industry on the development of state-of-the-art neutron diagnostics. The Nuclear Science Department at Simon Fraser University owns and operates a high-energy neutron generator and has also been involved in the development of neutron diagnostics for private fusion. The University of Sherbrooke has experience with cutting-edge electronics. However, to accelerate the development and deployment of fusion technologies in Canada, there will need to be far greater investment by both the public and private sectors.

Canada has existing expertise in many of the capabilities required to develop a mature fusion industry, as shown in Figure 2. Deuterium and tritium production, storage, recycling, and handling technology for fueling fusion power plants are prime areas of Canadian expertise that can be leveraged in the global fusion energy market. In particular, materials subject to irradiation by high-energy fusion plasmas and neutrons will be one of the key technology areas, offering scope for a wide variety of Canadian contributions by private companies and public institutions, such as Canadian Nuclear Laboratories (CNL) and Ontario Power Generation (OPG). Many of these areas have been identified as priority supply chain areas (circled in red in Figure 2) by the private fusion industry.[10]

In addition to its tritium expertise, CNL's diverse S&T capabilities and infrastructure can be adapted, upgraded, and applied for fusion S&T to support both domestic and international projects and initiatives. Other capabilities within the Canadian nuclear industry can also be adapted to support fusion development, including robotics, remote handling, materials science, thermal-hydraulics, and reactor physics.



Graphic generated by CNL and Helixos with data derived from FIA

Figure 2. *Canadian capabilities for the fusion industry.*[10, 11]

Thus, Canada's involvement in the development of fusion also presents a significant economic opportunity for the nation.

Canada's interest and capabilities in fusion extend beyond research institutions and academia. Existing Canadian private companies are already supporting the fusion industry with cross-cutting technology and expertise transferred from the fission industry. Some are adjusting corporate strategies to include fusion clients as a major market to support through existing staff, facilities, and investments. Companies such as Kinectrics have supported domestic and international public organizations and private fusion companies with expert services and specialized equipment. These companies self-fund R&D to develop these capabilities, underscoring their interest in the progression of fusion energy.

Canada also has significant lithium deposits and resources. Lithium is a critical mineral in the transition to renewable energies, and demand for lithium for fusion energy systems will be high and potentially essential for tritium production, putting Canada in a strong position on this front.

With strategic investments in the Canadian industry, Canada can secure a position as a leading global supplier and developer of select fusion technologies and expertise in the near term, particularly with the production, supply, and handling of fusion fuels (deuterium and tritium).

Leveraging these capabilities, Canada is in a strategic position to significantly contribute to the growing global fusion sector and capitalize on significant economic opportunities for the nation.

1.5. Approach to Strategy Development

To form a forward-looking vision, strategy, and roadmap for fusion energy in Canada, various elements were methodically considered. The approach in Figure 3 outlines the process of strategy development undertaken in this report.

Understanding the current status, including the value proposition for fusion and international and domestic developments in the industry, is important in informing the vision for Canada. Highlighting the challenges and opportunities allowed barriers to be identified in charting a practical path forward. Strategic pillars were identified to highlight the key areas where Canada can focus its attention to build an impactful fusion industry. Following this step, the roadmap provides an actionable plan for the short, medium, and long term to build this future for the nation.

Figure 3. *Strategy development approach.*

2. The Case for Fusion

Fusion represents the next evolutionary step in humanity's ingenuity by embracing the elegant and powerful processes of the stars to fuel the sustainable development of modern life.

Fusion has the potential to provide reliable, clean energy to support Net-Zero by 2050 and beyond. Fusion provides another baseload energy technology for clean electricity and process heat. This technology can offer a complementary addition to existing clean energy solutions in providing energy independence and electricity security to Canada's grid and industrial base. In addition, a fusion industry could deliver significant economic benefits to Canada with opportunities for domestic demonstration facilities and international export.

2.1. Decarbonization Pathways: Clean Electricity and Process Heat

Fusion can provide clean energy through the supply of electricity and process heat. With most of the nation's energy supply coming from greenhouse-gas-emitting sources, there is an urgent need to move towards a net-zero emissions economy to avoid the worst potential impacts of climate change.[12]

Canada's total primary energy supply is mostly from (~75%) fossil fuel sources, which generate greenhouse gas emissions and other types of air pollution. By analyzing the total greenhouse gas emissions (in terms of CO_2 equivalent) by economic sector, as shown in Figure 4, the areas where fusion's decarbonization potential is impactful can be identified.

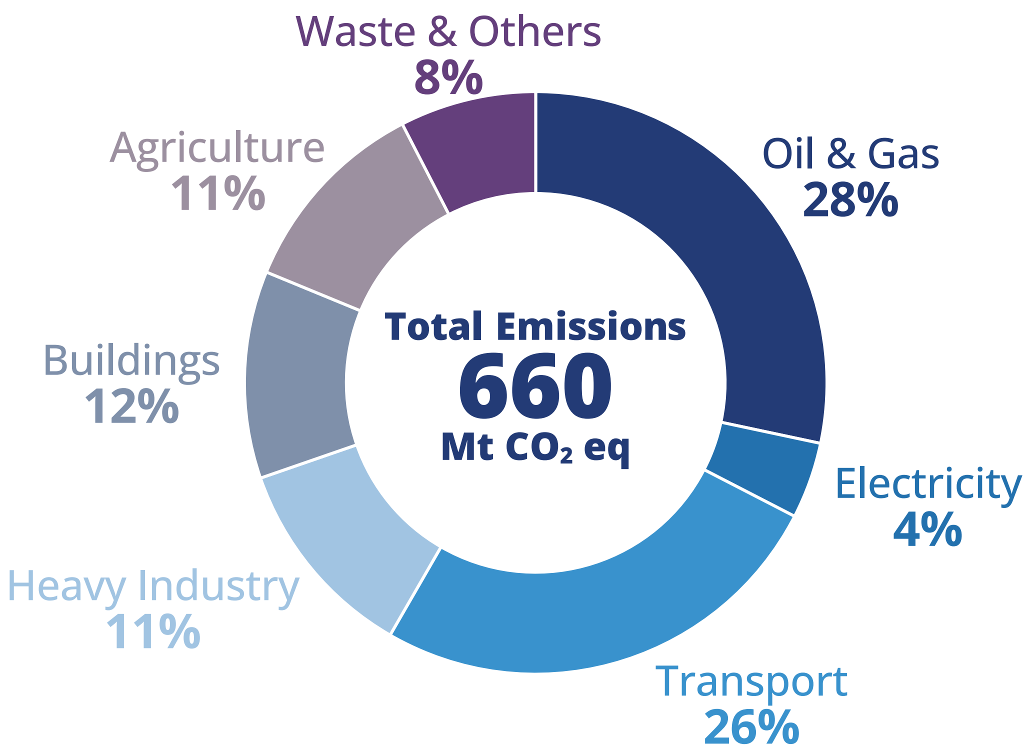


Figure 4. *Canada's Greenhouse gas emissions by economic sector (Mt CO_2 eq) for the reference case for 2030 (excluding land use, land-use change, and forestry).*[13]

Through the supply of electricity and process heat, fusion energy can be an important part of the future technology mix to decarbonize the oil and gas, transport, heavy industry, and electricity sectors.

Fusion plants can convert the energy generated from the fusion reaction into electricity through a steam-turbine power conversion cycle or through direct energy conversion. Fusion power plants co-located with industrial facilities can provide process heat for their operations and/or create valuable products, such as hydrogen. Low/zero-carbon process heat will be important for hard-to-abate sectors, such as steel manufacturing, as highlighted in the case study below.

2.2. Energy Security

Fusion can offer energy diversification, energy security, and complement the penetration of other zero-carbon energy sources by supporting grid stability.[14] Fusion utilizes accessible fuels and materials, such as deuterium and tritium, which can be available in Canada. With the ability to source these fuels domestically and reduce the country's reliance on foreign supplies of fuel, Canada's national security posture is reinforced. These fuels are energy dense and can be stored onsite or in centralized locations to provide inventories of fuel.

Fusion can provide baseload electricity and process heat without the need to rely on fossil fuel extraction or import. Fusion energy does not depend on environmental conditions (such as wind or sun) and is location independent, making it potentially deployable anywhere in Canada to support a diverse electricity grid and to provide reliable zero-carbon electricity to off-grid locations.

2.3. Economic, Social, and Decarbonization Benefits

Fusion deployment will result in a range of economic, environmental, and social benefits for many nations. International fusion deployment potentially offers Canada significant economic and social benefits through the export of products and services, such as deuterium, tritium, and fusion technologies and expertise. Additionally, domestic deployment within Canada will result in direct economic benefits attributable to fusion energy output (i.e., electricity, process heat, and downstream products, such as hydrogen), economic and social benefits associated with the development of a fusion supply chain and industry, and significant environmental benefits through the decarbonization of energy production.

Case Study | **Steel Manufacturing in Canada**

Steel is a key component of modern life, enabling a wide variety of physical infrastructure, transportation equipment, machinery, and appliances. Canada is in the top 20 nations currently producing approximately 13 Mt of steel per year.

Steel production is energy-intensive, with iron being produced in blast furnaces, direct reduction furnaces, or smelting furnaces. Smelting is mainly done by means of burning coke or hydrocarbons, creating a reducing mixture rich in carbon monoxide. The reduction of iron oxides through this approach produces carbon dioxide, which is typically emitted into the atmosphere, after thermal energy recovery and particulate collection.

Fusion energy, utilizing its electricity and/or process heat, can produce hydrogen to chemically reduce the iron oxide and replace the use of existing hydrocarbons. Based on Canada's steel production, a fusion plant with an electric design capacity of 1 GWe and an uptime (or availability) of 80% would enable steel production of approximately 2 Mt per year. This energy demand equates to a requirement of approximately **7 large-scale fusion power plants to decarbonize the entire steel industry in Canada.**

Modelling Scenarios

A range of scenarios have been developed to model the potential economic, social, and decarbonization benefits attributable to fusion deployment. These include different rates of domestic deployment based on investment and policy support levers, an international deployment scenario to model the potential export opportunities, and tritium production scenarios to illustrate the potential opportunities and impacts of fuel supply availability. These different scenarios have been combined and segmented across three deployment time horizons to frame the analysis.

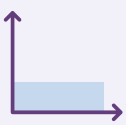
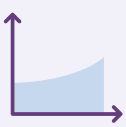
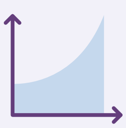
Domestic Deployment Scenarios and Generation Mixes

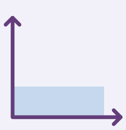
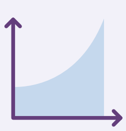
Three domestic deployment scenarios have been developed for this analysis. They represent three outcomes that are proportionate to the level of engagement, attention, and funding allocated toward the domestic deployment of fusion.

These deployment scenarios have been modelled across two future energy generation mixes based on the Canada Energy Regulator's (CER) Energy Future 2023 Energy Supply and Demand Projections.[15] The scenarios used were the CER Evolving Policies Scenario, and a business-as-usual (BAU) generation mix which assumes the 2023 generation mix[16] scaled for CER energy demand projections.

Tritium Availability Scenarios

Supply of tritium is an important factor for many fusion power plant designs, and supply availability can have a significant impact on power plant start-up and thus deployment rates. To recognize this constraint, the modelling has used two scenarios.

Domestic Deployment Scenarios and Generation Mixes	
	**Baseline:** This scenario is equal to, or close to, the status quo. Without a progressive policy environment to address climate change in a meaningful way, fossil fuels will continue to be a predominant part of the supply mix for electricity, heat, and transportation. Fusion technology would not be able to compete and would not be a key contributor to Net-Zero 2050 targets.
	**Action:** Government and private entities engage in a limited amount of effort towards fusion research, development, and demonstration (RD&D). Government and private entities contribute funding towards fusion RD&D, but not in a way that supports accelerated fusion deployment. Government policies start to align in a manner that is conducive to fusion deployment but are either not introduced in a timely manner or not emphasized enough compared to other technologies. Fusion can contribute in part to Net-Zero 2050 targets.
	**Transformational:** High levels of investment and policy creation are directed towards fusion development and timely deployment. Government and private entities engage in well-orchestrated and coordinated funding and mega-project deployment efforts, along with risk management strategies that are conducive to timely fusion development and deployment. There is a suitable level of regulatory harmonization between countries for streamlined fusion deployment. Fusion technology in this scenario can contribute in part to Net-Zero 2050 targets.

Tritium Availability Scenarios	
	**Tritium constrained:** Canadian tritium production is constrained to 1.8 kg of tritium per year to service both the domestic and international markets. Additional supply is brought online from 2070 to increase annual production to 3.6 kg/year in 2075. Finally, a third stream of production begins operation in 2095, increasing total annual tritium production to 5.4 kg/year in 2100. Non-Canadian producers come online in 2070, producing 1 kg of tritium a year, this increases to 2 kg of tritium per year in 2095.
	**Non-tritium constrained:** This scenario models fusion power plant deployment, and the resulting benefits, where there is no supply constraint on tritium. Under this scenario, Canada, other countries, and operating fusion power plants are able to fully meet both domestic and international demand across all deployment scenarios, which supports increased domestic deployment and a more significant export market.

International Deployment Scenario

International fusion power plant deployment was modelled across three phases, which broadly reflects the historical deployment of nuclear power plants. In the first phase, it was assumed that non-commercial demonstration plants are brought online from 2027 starting in North America, followed by Asia and Europe. An early-commercial phase then occurs between 2035 – 2050, with steady growth across those three regions to 17 GW in 2050. Global deployment then accelerates from 2050 - 2065, resulting in global capacity increasing to 311 GW. The final phase from 2065 – 2100 is typified by a slower growth rate, with first deployments occurring in the Middle East and Africa in 2065 followed by South America in 2070. These additions increase international deployed capacity to 386 GW in 2100.

Under the tritium-constrained scenarios, international deployment rates are significantly reduced. The degree to which they are impacted is a function of both the total annual production of tritium, and the proportion of tritium which is used for domestic deployments in the baseline and action scenarios.

Deployment Timeframes

In describing the economic, social, and decarbonization benefits, it is useful to work across three distinct timeframes to capture the different dynamics inherent to the short-, medium-, and long-term. These three timeframes are highlighted in Figure 5.

	NEAR TERM 2024 – 2034	MEDIUM TERM 2035 – 2050	LONG TERM 2050+
	DEMONSTRATION of fusion power plants in Canada and/or elsewhere in North America, Europe, and Asia	**ADOPTION** of fusion energy in Canada and in select regions, transitioning to mature commercialization	**EXPANSION** of fusion energy in Canada and globally across all continents
Tritium-constrained scenario	**Canada:** Baseline: 0 GW Action: 0 GW **International:** Demonstration: 1.5 GW	**Canada:** Baseline: 2 GW Action: 4 GW **International:** Baseline: 3 GW Action: 1 GW	**Canada:** Baseline: 5 GW Action: 10 GW **International:** Baseline: 19 GW Action: 14 GW
Non-tritium-constrained scenario	**Canada:** Baseline: 0 GW Action: 0 GW Transformational: 0 GW **International:** Demonstration: 2 GW	**Canada:** Baseline: 2 GW Action: 4 GW Transformational: 6 GW **International:** Deployment: 17 GW	**Canada:** Baseline: 5 GW Action: 10 GW Transformational: 15 GW **International:** Deployment: 369 GW

Figure 5. *Timeframes for the evolution of fusion deployment. The capacity (GW) additions of fusion power plants are noted across the three time periods in a tritium-constrained scenario and a non-tritium-constrained scenario. Domestic Canadian deployment is modelled across baseline, action, and transformational deployment scenarios, with no transformational deployment occurring in the tritium-constrained scenario.*

Economic Benefits

The economic benefits of fusion deployment result from both the direct production of electricity and process heat in the Canadian market and the delivery of supply chain products and services to domestic and international markets. These benefits, while closely related, are distinct and emerge over different time scales.

Near Term (2024 to 2034)

In the near term, the primary focus is likely to be centred on the development and demonstration of fusion power plants. Across all domestic deployment scenarios, and regardless of tritium supply constraints, there are no additions of fusion power plants into the domestic market during this period. Therefore, there is no direct economic benefit associated with domestic energy provision.

There is, however, an opportunity for product and service exports to fusion technology developers, both through the provision of tritium and the export of sub-system technologies, such as parts of the fuel management sub-system. The modelling assumes that three or four fusion power plants will be demonstrated through to 2034, divided across North America and Europe, dependent on tritium availability. The estimated economic benefit associated with the provision of products and services to this market ranges between $1.01 billion and $1.34 billion.

Medium Term (2035 to 2050) and Long Term (2050+)

From 2035, all scenarios assume fusion power plant deployment within the Canadian market. The baseline scenario assumes that 1 GW of fusion power is constructed every ten years. The action scenario assumes that 1 GW is being deployed every five years, and the transformational scenario assumes that 1 GW is deployed every three years. Under a tritium-constrained scenario, the transformational rate of deployment cannot be supported by tritium supply availability, constraining domestic growth.

Factors such as the maturation of supply chains, technology learning rates, and efficiencies gained through economies of scale will play a role in the levelized cost of energy (LCOE) decreasing over time. In the long term, as construction moves closer to the nth-of-a-kind (NOAK) plant, it is assumed that the LCOE will decrease as efficiencies are gained. This process of improvement through experience makes fusion technology even more economically viable over time.

Total Economic Benefits

Table 1 and Table 2 below show the results of the preliminary economic modelling for the domestic deployment scenarios. These figures represent the total economic benefits, including the direct benefits from domestic energy generation, and those related to supply-chain products and services including international exports.

The estimated cumulative economic benefits to Canada by 2100 range from $93 billion to $203 billion with a constrained tritium supply. With full tritium supply availability, this range increases to $232 billion to $523 billion.

Table 1. *Summary of the total economic benefits ($ billion) for Canada for fusion deployment scenarios in a* ***tritium-constrained scenario.*** *Results are presented across two domestic deployment scenarios. The future energy market generation mix and uses data from the Canada Energy Regulator Evolving Policies Scenario, and a business-as-usual scenario based on 2023 energy generation data.*

	Canada Energy Regulator Evolving Policies Generation Mix				Business-as-usual Generation Mix			
	2024 - 2034	2035 - 2050	2051 - 2100	Total	2024 - 2034	2035 - 2050	2051 - 2100	Total
Baseline Scenario	1.01	8.64	83.91	**93.56**	1.01	8.91	88.53	**98.45**
Action Scenario	1.01	12.81	178.55	**192.36**	1.01	13.25	189.04	**203.30**

Table 2. *Summary of the total economic benefits ($ billion) for Canada for fusion deployment scenarios in a* ***non-tritium-constrained scenario****. Results are presented across two domestic deployment scenarios. The future energy market generation mix and uses data from the Canada Energy Regulator Evolving Policies Scenario, and a business-as-usual scenario based on 2023 energy generation data.*

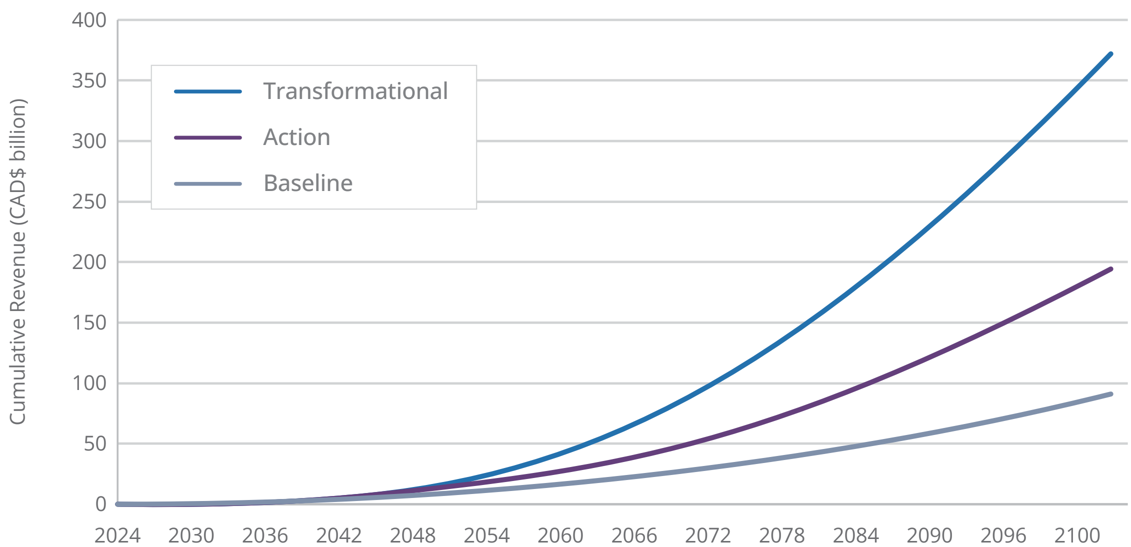
	Canada Energy Regulator Evolving Policies Generation Mix				Business-as-usual Generation Mix			
	2024 - 2034	2035 - 2050	2051 - 2100	Total	2024 - 2034	2035 - 2050	2051 - 2100	Total
Baseline Scenario	1.34	14.75	216.42	**232.51**	1.34	15.02	221.05	**237.40**
Action Scenario	1.34	19.51	312.94	**333.78**	1.34	19.95	323.43	**344.72**
Transformational Scenario	1.34	26.62	474.79	**502.76**	1.34	27.34	495.04	**523.72**

Economic Benefits from Domestic Energy Production

The proportion of the long-term economic benefits shown in Table 1 and Table 2 resulting from the domestic energy production is highly sensitive to the deployment scenario. Under the BAU generation mix scenario (Figure 6), the cumulative economic benefits from domestic energy generation by 2100 range from $88 billion for the baseline scenario to $371 billion for the transformational scenario.

The transformational domestic deployment scenario cannot occur under a tritium-constrained scenario. In this case, the cumulative economic benefits from domestic energy generation by 2100 range from $88 billion for the baseline scenario to $195 billion for the action scenario.

a) Non-tritium-constrained scenario



b) Tritium-constrained scenario

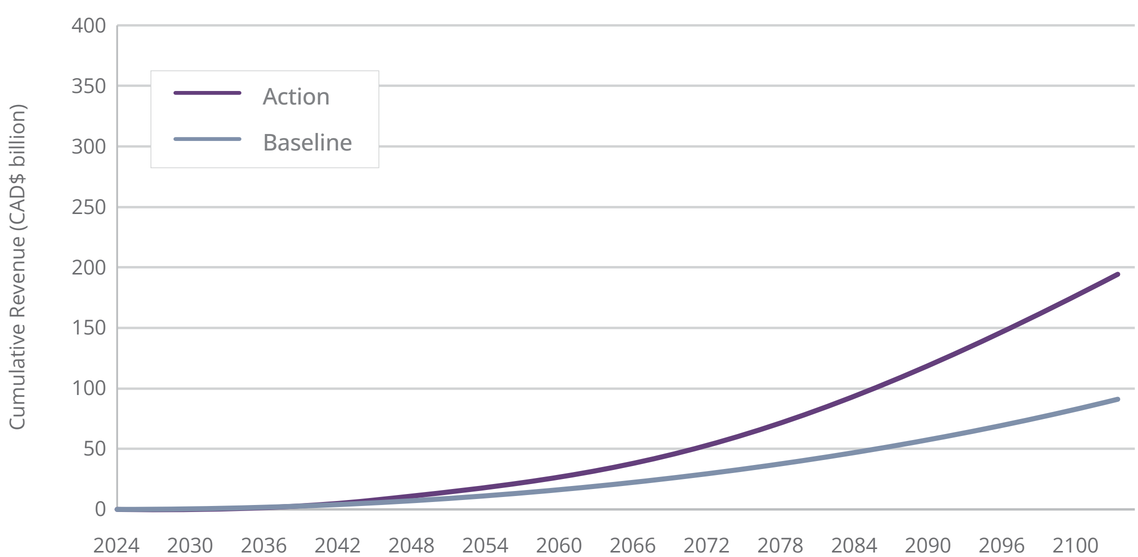


Figure 6. *Cumulative economic benefits for Canada from domestic fusion power plant deployment under the BAU generation mix for the* ***a) non-tritium-constrained scenario*** *and* ***b) tritium-constrained scenario****. Note that the transformational domestic deployment scenario is not achievable under the tritium-constrained scenario.*

Economic Benefits from Supply Chain Products and Services

The long-term potential economic benefits related to supply chain products and services are primarily driven by the provision of sub-system components and consulting services to the international market, along with the export of tritium for the start up of fusion power plants. This is highly dependent on the extent to which tritium is produced to meet market demand, as shown in Figure 7. In a non-tritium-constrained scenario, the potential cumulative economic benefits for supply chain products and services by 2100 is more than $151 billion. With tritium supply constraints factored in, however, the cumulative value of the export market by 2100 is approximately $10 billion. It is evident that there is a significant opportunity to export products and services into international markets, and a strong economic case for the domestic deployment of fusion power plants. An important driver in maximizing the economic potential for Canada will be the extent to which a robust tritium production supply chain can be developed. Other key factors that determine the magnitude of the benefits for the nation are the Canadian government's commitment through policy creation and investment, coupled with fusion technology's commercialization and mass deployment timescales.

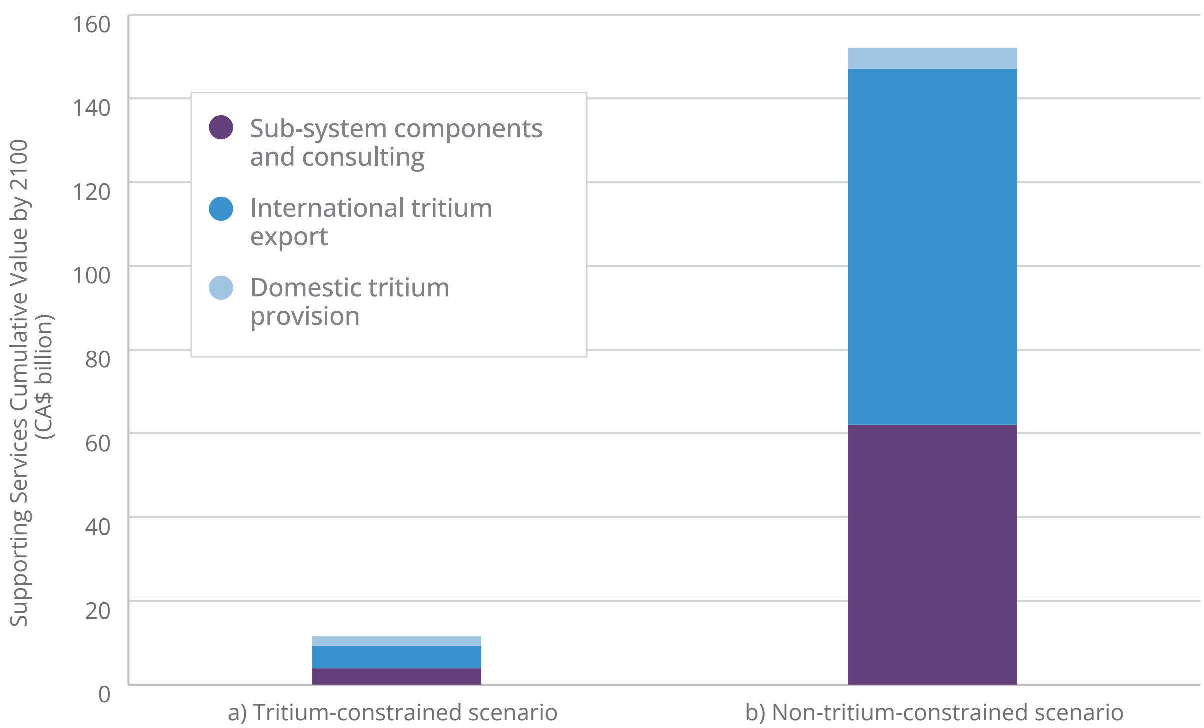


Figure 7. *Cumulative economic benefits for Canada from supply chain products and services from 2024 - 2100 for the* ***a) tritium-constrained scenario and b) non-tritium-constrained scenario.***

Social Benefits

The domestic deployment of fusion power plants and the continued growth of the fusion supply chain industry in Canada has significant potential for direct and indirect job creation. These jobs potentially span across industries and domestic geographies increasing opportunities for Canadians. The domestic deployment of fusion power plants and the continued growth of the fusion supply chain industry in Canada has significant potential for direct and indirect job creation. These jobs potentially span across industries and domestic geographies increasing opportunities for Canadians to access high-skilled employment.

Before the domestic deployment of fusion power plants, there is the potential to create Canadian jobs to export sub-system components and provide specialist services to international fusion technology developers as they develop and demonstrate their technologies. These will encompass both direct jobs, those created to directly deliver the products and services, as well as indirect jobs across other industries and the broader economy. It is estimated that more than 200 ongoing full-time equivalent (FTE) jobs will be created by 2030 to deliver these export opportunities.

Each of the domestic deployment scenarios results in significant growth in both direct and indirect employment from 2035. These jobs include direct and indirect plant construction jobs in the lead up to fusion power plant deployment (Figure 8), direct and indirect employment for ongoing maintenance over the lifecycle of the assets, and direct jobs for the workforce dedicated to onsite operations. For a transformational domestic deployment scenario, the estimated number of jobs created by 2050 includes over 63,000 jobs during plant construction, comprised of approximately 26,000 direct jobs and 37,000 indirect jobs across the broader economy. In addition, it is estimated that over this period more than 3,700 jobs will be created throughout the supply chain, and over 860 jobs created for ongoing on-site operations, both of which will be required for the lifetime of the operational power plants. Finally, a workforce of over 240 will be required to service international export opportunities by 2050, expanding to over 3,000 in the decade between 2060 and 2070, as global deployments accelerate.

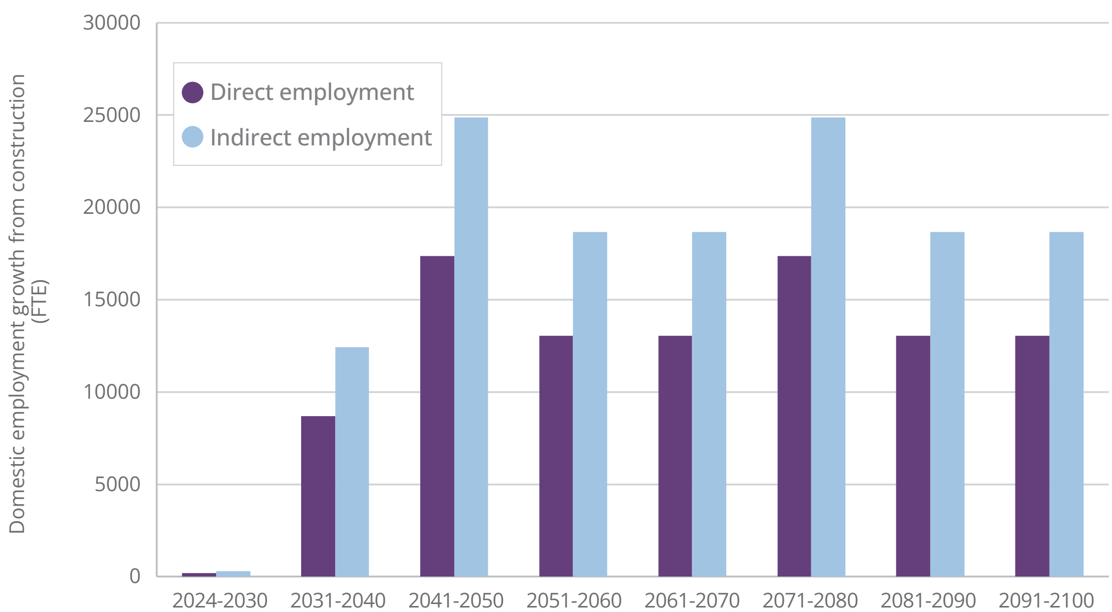


Figure 8. *Total estimated direct and indirect Canadian job creation from the domestic construction of fusion power plants by decade under the transformational deployment scenario.*

Decarbonization Benefits

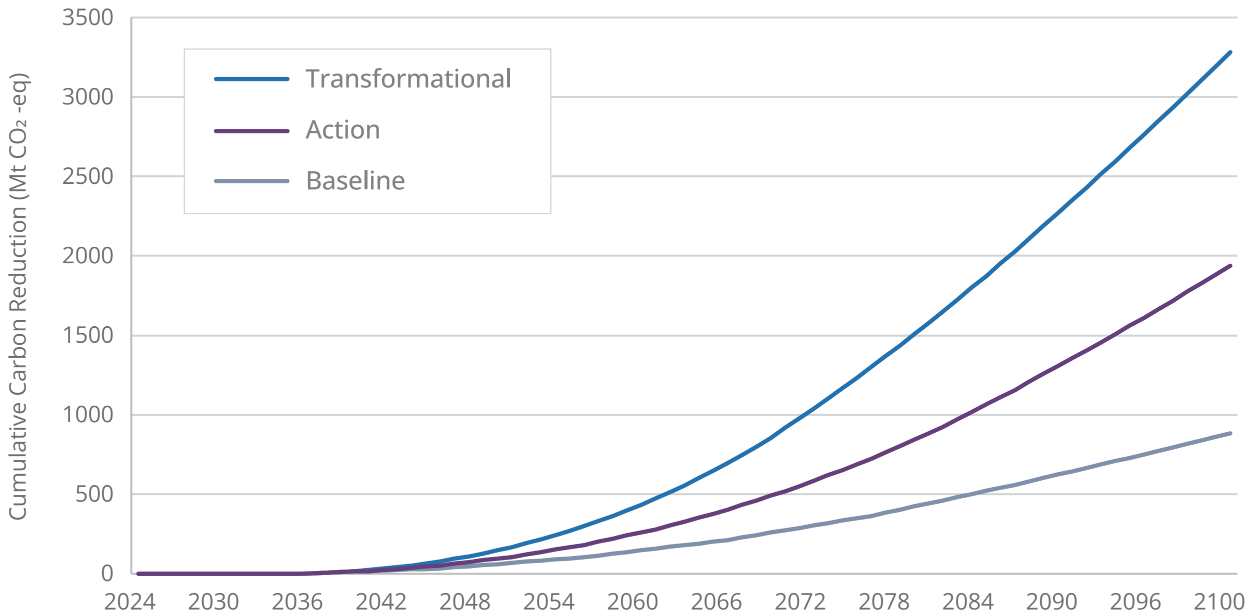
Canada's journey towards a net-zero economy requires immediate focus but also requires a sustained commitment to change over time, especially as the economy becomes increasingly electrified. Fusion technology can help enable this transition to a sustainable net-zero economy. Fusion technology is a complementary solution to the current strategy involving the increased deployment of clean energy technologies; one that requires a smaller environmental footprint, has favourable energy density, offers firm and flexible supply, and is potentially economically competitive. Fusion presents unique opportunities for decarbonizing industries with different characteristics to current renewable generation technologies. It offers solutions for high-capacity energy needs, can cater to remote installations, and ensure uninterrupted power supply for critical services, such as military bases and hospitals. This capability to meet diverse and demanding energy requirements sets it apart as a potential game-changer in the pursuit of sustainable industrial practices.

Figure 9 shows the cumulative decarbonization benefits over time across the three domestic deployment scenarios for both the non-tritium-constrained scenario, and tritium-constrained scenario. The modelling assumes that the electricity produced by fusion power plants replaces electricity produced by carbon-emitting generation sources. Once all carbon-emitting sources are replaced within the electricity system, then an equal proportion of other generation technologies are affected.

Deploying fusion energy becomes impactful towards preventing and mitigating climate change in the medium and long term, particularly in the action and transformational scenarios. Canada's 2030 Emissions Reduction Plan incorporates measures and strategies to reduce greenhouse gas (GHG) emissions by 40% by 2030 to 445 Mt CO_2-eq from the 2005 GHG emission level of 741 Mt.[17] To reduce emissions in Canada from 445 Mt in 2030 to zero in 2050, fusion technology can contribute reduction values of 75 Mt, 121 Mt, and 192 Mt for the baseline, action, and transformational scenarios, respectively. By 2100, these values increase to cumulative reductions of 906 Mt, 1,995 Mt, and 3,368 Mt.

By analyzing various outcomes and scenarios for fusion deployment over various timeframes, Canada can secure its position as a global supplier of fusion technologies and expertise in the near term, which will establish a foundation for the future. A national program for fusion will deliver significant economic benefits to Canada with opportunities for international export and set the stage for success in the medium and long term.

a) Non-tritium-constrained scenario



b) Tritium-constrained scenario

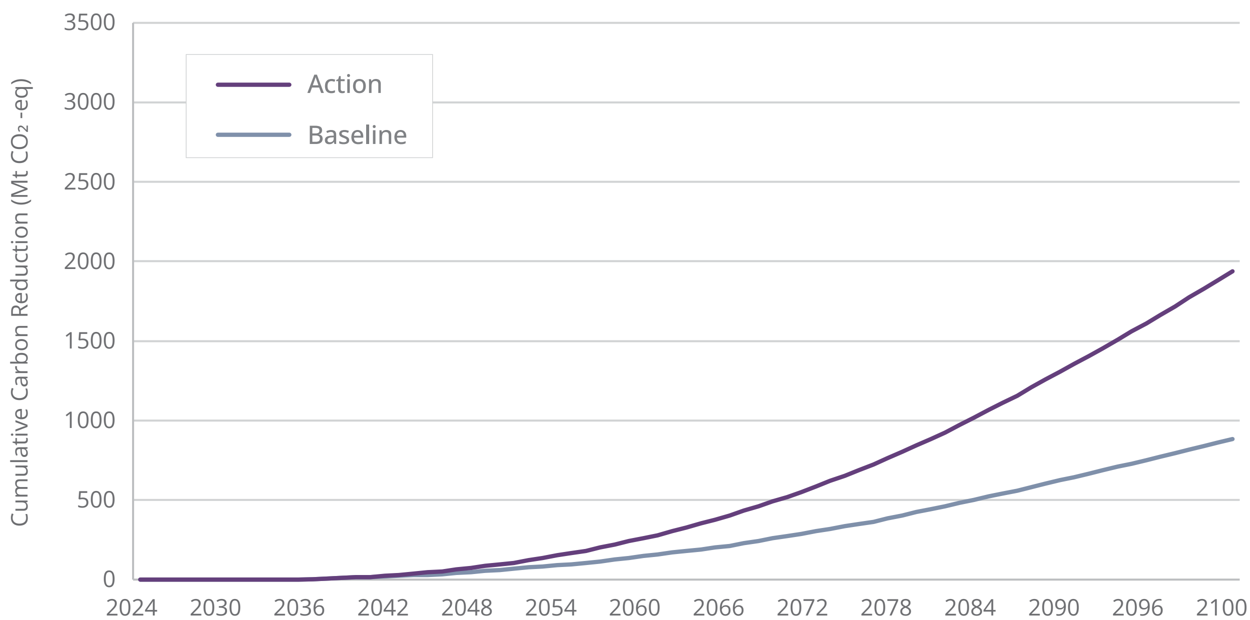


Figure 9. *Decarbonization benefit of deploying fusion energy in Canada using the BAU generation mix for the* ***a) non-tritium-constrained scenario*** *and* ***b) tritium-constrained scenario****. Note that the transformational domestic deployment scenario is not achievable under the tritium-constrained scenario.*

3. International Fusion Landscape

Internationally, there is significant progress in both the public and private arenas for fusion development. As of March 2024, there are a total of 98 operating fusion experiments and demonstration facilities globally, with 13 under construction, and a further 33 planned.[18] These fusion devices cover a diversity of configurations, including tokamaks, stellarators, heliotrons, laser-based inertial confinement, magnetized target, inertial electrostatic fusors (IEC), magnetic mirrors, z-pinches, field-reversed configuration (FRC) plasmoids, and other alternative concepts.

Unlike Canada, other major nuclear power countries and regions have national fusion programs with investments and demonstration programs. Canada is one of the only major economies that has significant nuclear capabilities without a national fusion strategy or vision.

3.1. Public Fusion Landscape

Many nations have strategies to support the development and commercialization of fusion energy technology. These strategies are at varying levels of maturity, with most of them emphasizing high-level scientific, technical, and logistical goals and key innovations.[19] An overview and status of the fusion strategy and R&D progress in key countries and regions is outlined in Table 3.

Table 3. *Overview of fusion strategies and R&D in key countries and regions.*

Country	Status
China	The key Government ministries and organizations coordinating China's fusion activities include the Ministry of Science and Technology of the People's Republic of China, Ministry of Education of the People's Republic of China, Chinese Academy of Sciences (ASIPP), China National Nuclear Corporation (CNNC), China Academy of Engineering Physics (CAEP), and China Government Procurement Network.[20] The three major domestic tokamaks now in operation in China are the EAST superconducting machine in ASIPP at Hefei, HL-2A(M) in the Southwestern Institute of Physics (SWIP) at Chengdu, and J-TEXT at the Huazhong University of Science and Technology (HUST).[21] China has ambitions to start generating fusion power using the world's largest pulse-powered energy plant by 2028.[22] China has joined ITER project as a member and is responsible for ~9% of the construction costs.[23] China is also developing the China Fusion Engineering Testing Reactor (CFETR), which is designed to bridge the fusion experiments between ITER and DEMO.[24]
European Union (EU)	The EUROfusion programme is based on the EU's Roadmap to the Realisation of Fusion Energy and includes two main goals: 1) preparing for ITER experiments; and 2) developing concepts for the future fusion power plant DEMO. The 30 European consortium members receive funding for fusion projects in accordance with their participation in the missions and experiments outlined in the roadmap.[25] The major institutions in the EU conducting fusion research and development include the French Alternative Energies and Atomic Energy Commission (CEA), where ITER is housed,[26] the Max Planck Institute for Plasma Physics (IPP) in Germany,[27] the National Fusion Laboratory at the Centre for Energy, Environmental and Technological Research (CIEMAT) in Spain,[28] and various R&D facilities in Italy.

Country	Status
India	India formally joined the ITER Project in 2005 and the ITER Agreement between the partners was signed in 2006 and is contributing ~9% of the construction costs. ITER-India is the Indian domestic agency, a specially empowered project of the Institute for Plasma Research (IPR), an aided organization under the Department of Atomic Energy, Government of India.[29] ITER-India is responsible for the delivery of the following ITER packages: Cryostat, In-wall Shielding, Cooling Water System, Cryogenic System, Ion-Cyclotron RF Heating System, Electron Cyclotron RF Heating System, Diagnostic Neutral Beam System, Power Supplies, and some Diagnostics. Additionally, related R&D and experimental activities are being carried out at the ITER-India laboratory in Gandhinagar, Gujarat. The IPR is an autonomous R&D organization under the authority of the Department of Atomic Energy (DAE), Government of India.[30] The IPR is largely involved in theoretical and experimental studies in plasma science including basic plasma physics, magnetically confined hot plasmas, and plasma technologies for industrial application. The IPR owns two operational tokamaks: ADITYA and Steady State Tokamak (SST).
Japan	All fusion research in Japan is overseen and managed by the National Institutes for Quantum Sciences and Technology (QST). The QST receives Japanese government funding to help with the development of fusion research in Japan. The National Institute for Fusion Science (NIFS) is an inter-university research institute that is playing an active role in mutual cooperation, with research organizations and universities both in Japan and in foreign countries. Japan operates a superconducting tokamak device, known as JT-60SA, designed to study advanced scenarios for fusion energy production and to test key technologies required for the development of a fusion power plant. The plant is the largest operational tokamak in the world. The Japanese government launched a comprehensive "Fusion Energy Innovation Strategy" in 2023 to leverage Japan's technological advantage towards the realization of fusion energy,[31] and established 'Diverse applications of Fusion Energy' as one of the ten goals under the Moonshot Research and Development Program late in the same year.[32]
Republic of Korea	South Korea's largest fusion project is KSTAR (Korea Superconducting Tokamak Advanced Research) at the National Fusion Research Institute (NFRI) in Daejeon. KSTAR is a superconducting tokamak facility with the purpose of long-term fusion plasma operation.[33] In November of 2020, KSTAR managed to operate its plasma at 100 million degrees Celsius for more than 20 seconds – the world's first fusion device to have maintained plasma for more than 10 seconds at that temperature.[34] KSTAR's experiments and research will contribute to ITER. A pre-conceptual design study for Korea's 2,200 MW fusion demonstration tokamak (K-DEMO) has been carried out since 2012.[35] K-DEMO was previously stated to be planned to complete construction in 2037.[36]
Russia	Russia is a founding and contributing member of the ITER project and contributes ~9% of the construction costs. Historically, Russia has been a world leader in the development of fusion and first pioneered the development of the Tokamak concept for magnetic confinement in 1968 with its T-1 Tokamak experimental facility. The Kurchatov Institute in Moscow is Russia's primary facility for fusion research.[37, 38, 39, 40] Currently, fusion research in Russia is supported under the third federal project (FP-3): "Development of controlled fusion and innovative plasma technologies", as part of Russia's DETS Program ("Development of equipment, technologies and scientific research in the field of atomic energy use in the Russian Federation for the period up to 2024".[37] Russian scientists at different universities and laboratories have also carried out R&D in several other fusion concepts and applications, including compact tokamaks, laser-based fusion, magnetic mirrors, hybrid fusion/fission reactors (HFFRs), and other technologies. In the present day, Russia has developed an upgraded, large-scale Tokamak experimental facility, the T-15MD, which will support technology development for ITER.[38, 39, 40]

Country	Status
United Kingdom (UK)	In 2021, the UK Government issued its fusion strategy with the overarching goals of demonstrating the commercial viability of fusion by building a prototype fusion power plant in the UK and to build a world-leading fusion industry that can export fusion technology around the world.[4] The UK Atomic Energy Authority (UKAEA) is the national research organization responsible for the development of fusion energy. The UK's program includes various technological approaches to fusion with a focus on magnetic confinement fusion. The UKAEA hosts the Joint European Torus (JET), a 40-year-old tokamak that has represented one of the most important fusion experiments in the world and is now entering its decommissioning and repurposing program in 2024 to gain valuable insight for future fusion power plant operation). The UKAEA's fusion subsystem initiatives at Culham also include LIBRTI, H3AT, Materials Research Facility, and RACE. The UK Government announced a site in Nottinghamshire as the home for STEP (Spherical Tokamak for Energy Production), with a target of 2040 for the prototype build.[41] In 2021-2022, the UK government opened a public consultation and published a regulatory decision to "help accelerate fusion energy progress." Future fusion energy facilities will continue to be regulated by the Environment Agency (EA) and Health & Safety Executive (HSE) in the UK, and not by the Office for Nuclear Regulation (ONR), under which fission power reactors are currently regulated.[42]
United States (U.S.)	The U.S. Government supports fusion through a number of different offices and programs within the Department of Energy (DOE), including the Office of Science, National Nuclear Security Administration (NNSA) and the Advanced Research Projects Agency – Energy (ARPA-E). In 2022, the Biden-Harris Administration announced a bold decadal vision to accelerate fusion in supporting net-zero goals and a commitment to a pilot-scale demonstration of fusion within a decade.[43] This has been supported by US$46 million in funding provided to eight companies in 2023 to advance designs and R&D for fusion power plants[44] and US$112 million into supercomputing projects to model plasmas and guide the design of fusion pilot plants.[45] Also in 2022, the NIF achieved fusion ignition, creating more energy from fusion reactions than the energy used to start the process.[46] The U.S. is a key partner and financial contributor to the ITER (International Thermonuclear Experimental Reactor) project, with an investment of ~9% of construction costs and ~14% of operations, including contributions of components and personnel.[47]

Public investment in fusion RD&D varies significantly by country. Since 2021, many of Canada's nuclear nation peers have made large investments in fusion technologies, as shown in Figure 10. **The UK, France, and Spain have dedicated more than 10% of their national energy technologies RD&D budget to fusion, with Canada falling significantly behind.**

The world's largest single fusion initiative is ITER, the multi-national US$25 billion fusion R&D facility currently under construction in France and designed to prove the feasibility of fusion power through the development of an experimental reactor. The ITER Project is a collaboration of 34 nations. The primary members and funders of ITER are China, the EU, India, Japan, South Korea, Russia, and the United States.[48]

In October 2020, a Nuclear Cooperation Agreement (NCA) was signed between Canada and ITER to facilitate and encourage collaboration in the ITER project. Canada's CANDU heavy water reactors produce tritium as a by-product, and tritium is a key fuel required for fusion power plants. Canada will be able to provide expertise in tritium technology and handling to the ITER project, as well as the transfer of Canadian-supplied tritium and tritium-related technology.[49]

Canada's absence from ITER (as a member) and from the development of this zero-carbon energy technology is inconsistent with Canada's general leadership in nuclear technologies and Net-Zero by 2050 initiatives. Canada can be more involved in ITER by applying

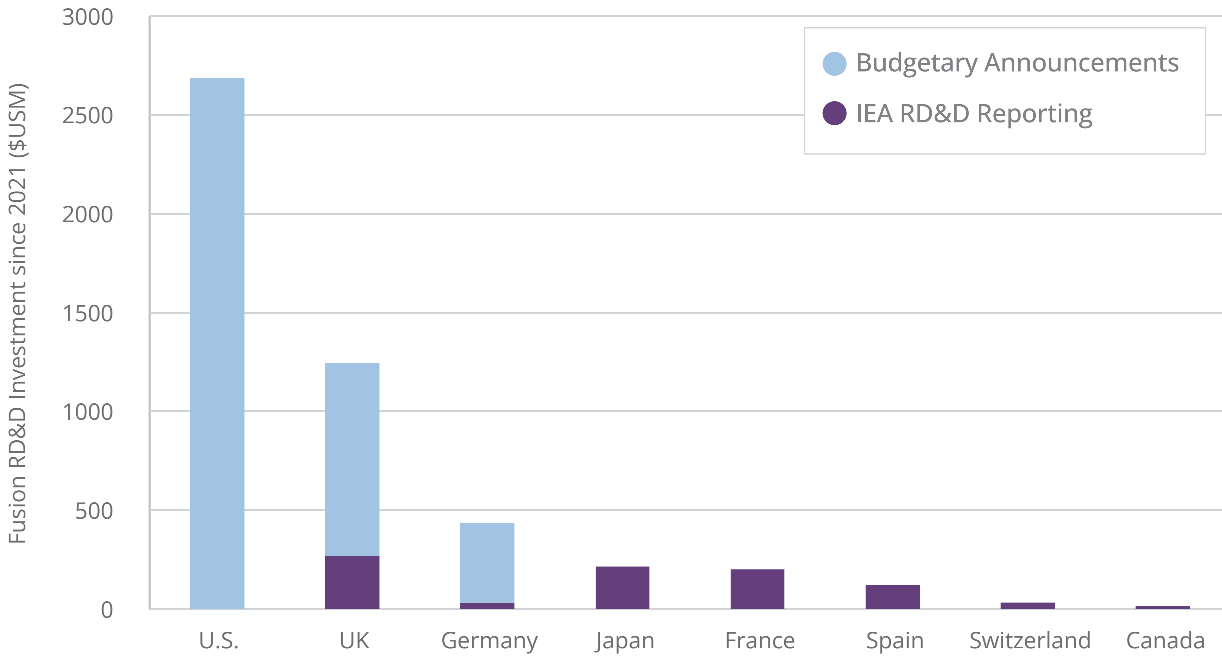


Figure 10. *Amount of fusion RD&D investment since 2021 as a percent of total national energy technologies RD&D budget as reported by the International Energy Agency (IEA),[50] and budgetary announcements.*

to become an Associate Member and supplying tritium and other services to the ITER project.

In addition to international collaborations, several of Canada's peers have also recently increased public investment to develop their own domestic industries and R&D capabilities. In 2024, the U.S. Fusion Energy Sciences (FES) budget increased to US$790 million.[51] In addition to the ongoing commitment of the U.S. to ITER, this funding will support a range of domestic programs, including US$46 million in grants for private fusion ventures. Additionally, the U.S. government increased the NNSA's Inertial Confinement Fusion program budget to US$690 million. These various budgets are appropriated each year in the U.S. and, therefore, may change in the future.

The UK has increased domestic investment in fusion technology over the last few years. In 2020, the UK government invested £222 million for initial design work for STEP, and an additional £184 million by 2025 for new fusion facilities, infrastructure, and apprenticeships at the Culham Science Centre in Oxfordshire.[52]

The UK also invested in fusion technologies as a part of a broader one-time R&D support package in late 2022. Within this package, the UK government committed £84 million for the continuation of the JET and launched the £42.1 million Fusion Industry Programme (FIP) to support private UK businesses commercializing fusion innovations.[53] Further, in late 2023 the government announced a further £650 million to support a suite of new R&D programs to support the fusion sector and strengthen international collaboration.[54] In late 2023, the UK government announced £650 million in funding for the country's Fusion Futures Programme. Measures include over 2,200 training opportunities nationwide, a fuel cycle testing facility dedicated to fusion commercialization, and funding for infrastructure development for private fusion companies.[55]

It is noteworthy that both the U.S. and the UK have channeled their funding through a mixture of programs and investment mechanisms. Both have taken a holistic view of industry development by funding government-led RD&D programs and academic research infrastructure, while also directly investing in the private sector. Canada has an opportunity to replicate this approach by considering a suite of investment levers to support the fusion industry.

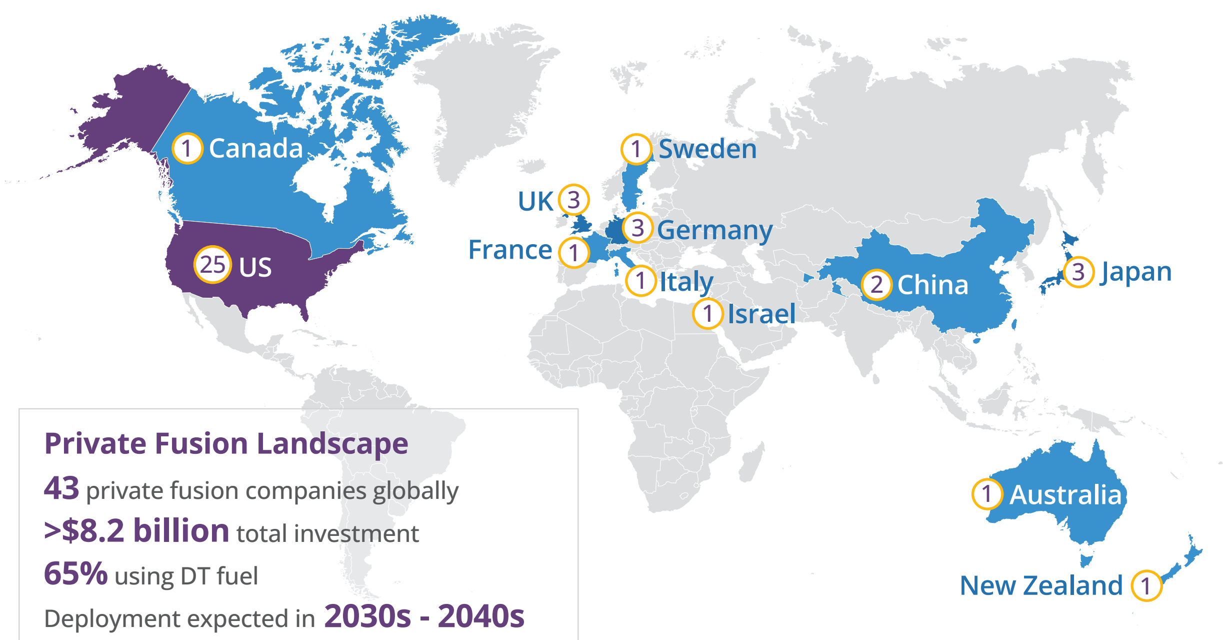
Within the EU, the French government has included fusion R&D as part of the country's new investments in its €54 billion investment plan for 2030.[56] In September 2023, Germany's Federal Ministry of Education and Research (BMBF) announced that they will provide more than €1 billion for fusion research by 2028.[57] In April 2024, BMBF also announced a new funding program for fusion research aimed at paving the way for the first fusion power plant to be constructed in Germany by 2040.[58] This new funding program will provide up to €100 million per year to fusion companies.

3.2. Private Fusion Landscape

Interest in fusion from technology developers, public and private investors, and potential users of energy derived from fusion, has grown rapidly in the last five years. The number of private fusion organizations has increased significantly, with over 43 companies operating globally as of mid-2023, as shown in Figure 11. This growth has been accelerated by significant private investments of more than US$5.9 billion and public investments of approximately US$272 million in private fusion companies to date, amounting to a total of approximately US$6.2 billion (CA$8.2 billion).[59]

Most private organizations are focused on deuterium-tritium (DT) fusion with 65% of them utilizing DT for fuel. Other concepts include different fuel variations, such as deuterium-helium-3 and hydrogen-boron-11. While their individual technology roadmaps may vary, the majority of fusion companies take an optimistic view of technological maturation, with most predicting that fusion will be delivering electricity to the grid by the mid-2030s to 2040s.[59]

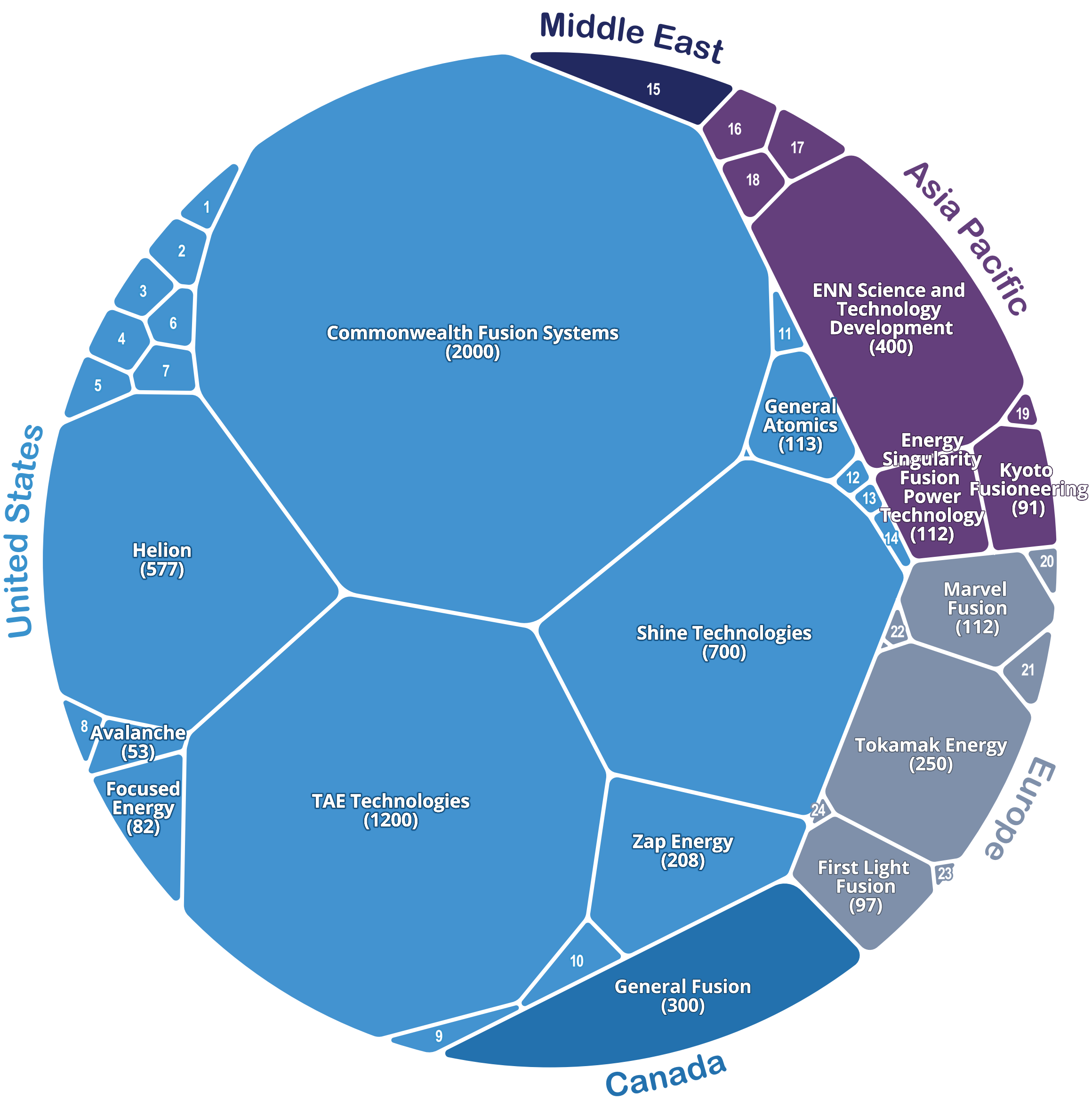
A robust private fusion industry can bring tremendous value to a country or region. It is apparent in Figure 12 that the U.S. not only has the largest number of private fusion companies, but also some of the most well-funded fusion companies in the world.[59] With Canada's existing fusion capabilities, infrastructure is in place that can serve as a foundation for a robust and



Graphic generated by CNL and Helixos with data derived from FIA

Figure 11. Number of private fusion companies per country and other key facts.[59]

globally competitive private fusion industry. Canada can advance this by providing incentives for private fusion R&D through formalized government programs and by acting as a catalyst to attract public-private partnerships and international investment to Canada's expanding fusion network.



Companies with <US$50M in declared funding

1. NK Labs (2.5)
2. Realta Fusion (12)
3. Helicity Space Corporation (2.4)
4. Magneto Inertial Fusion Technologies (12)
5. Fuse (18)
6. Horne Technologies (2)
7. Princeton Fusion Systems (3.6)
8. Xcimer Energy (12)
9. Thea Energy (23)
10. Type One Energy Group (30)
11. LPP Fusion (10)
12. Nearstar Fusion (0.5)
13. Blue Laser Fusion (0.5)
14. Electric Fusion Systems (0.4)
15. NT-Tao (28)
16. OpenStar Technologies (6.8)
17. Helical Fusion Co. (6.5)
18. HB11 Energy (5.1)
19. EX-Fusion (1)
20. Gauss Fusion (8.5)
21. Renaissance Fusion (17.6)
22. Proxima Fusion (8.1)
23. Novatron Fusion Group (3.2)
24. Deutelio (0.5)

Graphic generated by CNL and Helixos with data derived from FIA

Figure 12. *Private fusion companies scale by declared funding to date (US$M).*[59]

4. Canadian Fusion Landscape

Fusion technology activities started in Canada in the 1970s and a national program continued for a couple of decades. The fusion sector has continued to be active at a small scale due to the efforts of Canadian academia, research organizations, industry, and government. The historical timeline of fusion developments in Canada is summarized in Figure 13, with details on the following pages, along with a list of currently active players in the fusion space.

Canada had a small, but vibrant National Fusion Program (NFP) that existed for nearly two decades during the period of 1978 to 1997.[60, 61, 62, 63] For various reasons, but mainly dealing with efforts to drastically reduce government expenditures to avoid a national debt crisis,[64] the Canadian NFP was terminated in 1997.[63] Canada also withdrew its formal involvement and participation in the ITER project in 2003/2004.[65]

With renewed global interest in fusion and Canada's past and present fusion capabilities, it is time again for Canada to re-establish a national fusion program.

In recent decades, the Canadian fusion sector has continued to be active at a small scale due to the efforts and passion of scientists and grassroots supporters in Canadian academia, research organizations, industry, and government. There have also been a number of surprising and impressive new private sector developments in fusion in Canada, driven by highly motivated and visionary entrepreneurs and enthusiasts.

CNL has been carrying out many aspects of tritium-related research with its Tritium Facility, along with several small-scale fusion-related projects since 1998.[66, 67] CNL completed the construction of its refurbished Tritium Facility in 2019. This $40 million facility, with specialized

1970s

- National Fusion Program established

1980s

- Canadian Fusion Fuels Technology Project (CFFTP) established
- Two major tokamak experimental projects established (STOR-M research tokamak & Tokamak de Varennes)
- U.S. DOE signs a 5-year MOU with Canada on fusion research
- Canada starts involvement with the ITER project
- One major krypton fluoride project established at the University of Alberta

1990s

- National Fusion Program terminated due to funding challenges
- Plasmionique founded
- AECL/Chalk River Laboratories (CRL) started tritium-related research on fusion applications

2000s

- General Fusion founded
- Canadian Nuclear Society establishes Fusion Energy and Accelerator Science and Technology Division (CNS-FEASTD)
- Canada withdraws involvement and participation in ITER

2010s

- Alberta/ Canada Fusion Technology Alliance (ACFTA) established (now FECC)
- CNL refurbishes Tritium Facility
- Canada and ITER sign a Nuclear Cooperation Agreement
- Fusion 2030: Roadmap for Canada released

Figure 13. *Timeline of fusion activities in Canada.*

equipment in several laboratories, is licensed to handle up to 1 MCi (Mega-Curie) of tritium (~ 100 grams), and to store an additional 2.5 MCi (~250 grams) of tritium, making it a unique facility in Canada and within the international community. In addition, CNL has over 30 other experimental facilities and over 500 scientists and technical support staff with experience and expertise in various technical areas that could be leveraged to support fusion development.

Several professors and their support staff at the Universities of Saskatchewan, Toronto, and Alberta are well known internationally for their R&D programs and international collaborations in magnetic and inertial confinement fusion respectively. The University of Alberta group shifted from CO_2 to krypton fluoride (KrF) laser development in the 1980s becoming a major international centre with funding support by the Alberta government Energy Resources Research Fund (ERRF). This project was a contributor to the development of techniques for efficiently extracting and compressing laser pulses, and studies of laser-plasma interaction physics, demonstrating that ultraviolet wavelength lasers were ideal for inertial fusion energy drivers. Currently, the University of Alberta is a consultant to a U.S. fusion energy company using KrF as a laser driver. Smaller-scale fusion-related research is ongoing at Queen's University and Ontario Tech University, usually in collaboration with the University of Saskatchewan, or private-sector fusion companies.

Within the Canadian nuclear energy industry, Canadian utilities, such as OPG, Bruce Power, and New Brunswick Power, have deep expertise in the operation of nuclear energy infrastructure and can also serve as a rare and lucrative source of tritium and related expertise.

> The broader Canadian supply chain has a wealth of expertise, facilities, resources, and assets that could be harnessed to enable the development of a successful fusion energy industry.

This includes Kinectrics, a key Canadian private sector service provider, that caters to several international fusion industry players, offering a diverse range of services that span the entire fusion life cycle.

General Fusion, founded in 2002, is the only major Canadian private fusion technology developer and is based in Vancouver, British Columbia. The organization has a team of over 140 people and has raised $421 million as of 2023, with 24.3% coming from the Canadian government and 1.6% from the British Columbian government.

General Fusion is pursuing magnetized target fusion (MTF), utilizing a liquid-metal blanket to capture energy. They have successfully demonstrated key elements of proprietary plasma compression technology and have approximately 170 patents and patents pending. They are now accelerating their progress by building a new machine at their headquarters in British Columbia, called Lawson Machine 26 (LM26), which is designed to achieve fusion conditions of 10 keV (or over 100 million degrees Celsius) by 2025, with a goal of achieving scientific breakeven equivalent by 2026 using their MTF technology. General Fusion has strong partnerships across Canada, which include technical collaborations and partnerships with advanced research institutions and Canadian government entities.

Type One Energy Group Canada Inc., founded in 2018 in Madison Wisconsin USA, now has a Canadian subsidiary based in Vancouver, and is one of the 8 recipients of DOE funding in the USA to build a pilot plant for the production of energy from fusion within the next 10 years. Type One Energy Group announced in February 2024 the company's plans to locate to the Tennessee Valley Authority's (TVA) Bull Run Fossil Plant in Clinton, Tennessee to build Infinity One, the company's stellarator fusion prototype machine. Type One will proceed directly to design and construct a fusion pilot plant that is intended to achieve stellarator fuel ignition conditions (Q = infinity) and put fusion-generated electricity on the grid.

In February 2024, the Canadian and U.K. governments signed a new partnership agreement on fusion energy. This Memorandum of Understanding, signed between the U.K. Department of Energy Security and Net Zero and Natural Resources Canada, will enhance collaboration on key fusion activities, including R&D, regulatory harmonization, and skills and workforce development.[68]

An overview of institutions and capabilities in fusion R&D in Canada is mapped in Figure 14 and further detailed in the list in Table 4. The combination of knowledge, expertise, equipment, and facilities at Canada's government laboratories, universities, utilities, nuclear industry suppliers, and fusion/plasma-related private sector companies places Canada in a good starting position to launch an integrated domestic fusion program.

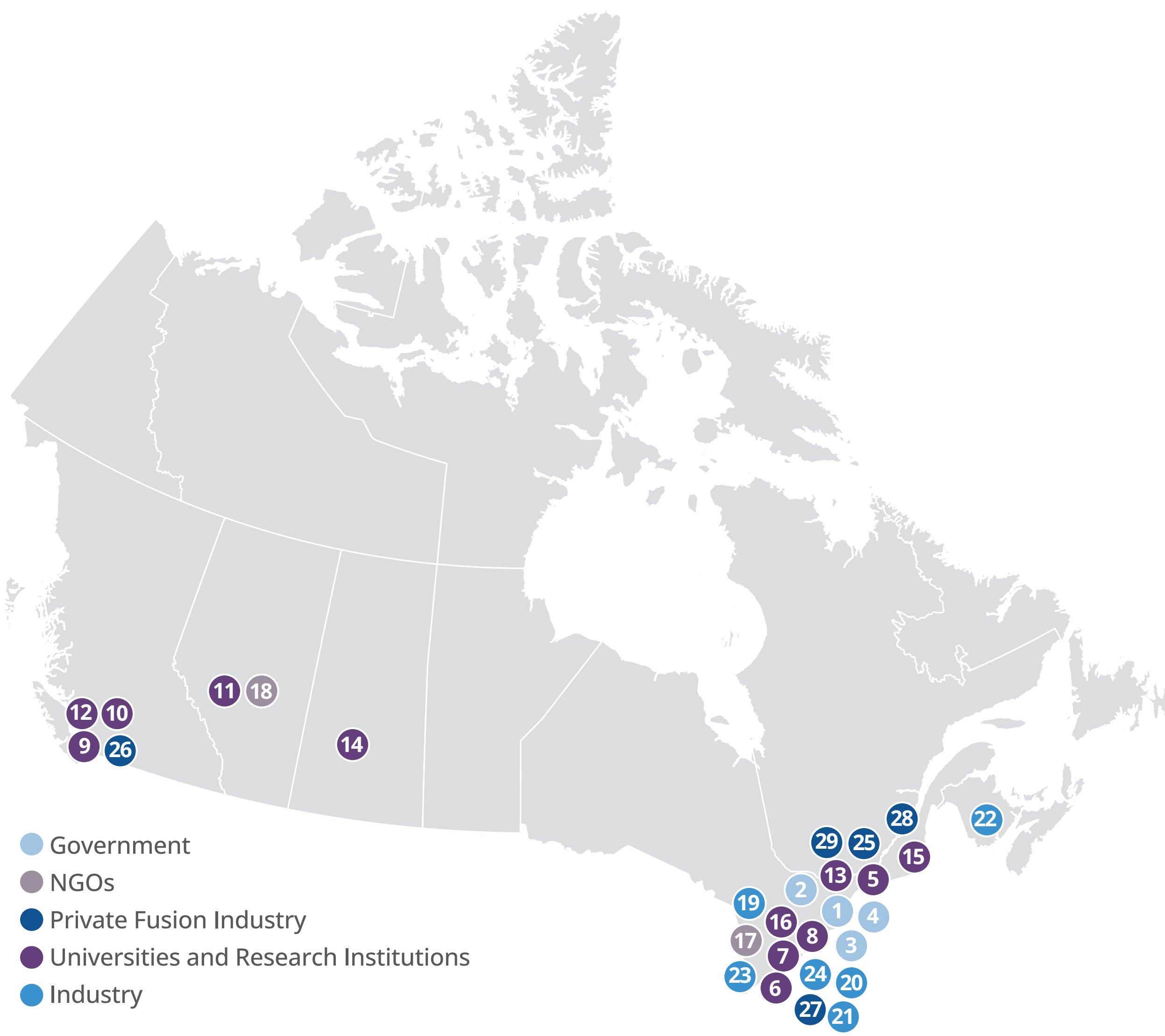


Figure 14. *Map of institutions conducting fusion R&D in Canada, corresponding to Table 4.*

Table 4. *Overview of institutions and capabilities in fusion R&D in Canada*[69, 70, 71]

	Stakeholders	Main Location	Capabilities/Activities
Government			
1	**Atomic Energy of Canada Limited (AECL)**	Chalk River, Ontario	Provides oversight and guidance to CNL and the private sector consortium that operates CNL. Serves as an interface between CNL and different federal government agencies and stakeholders, such as NRCan, CNSC, and others.
2	**Canadian Nuclear Laboratories**	Chalk River, Ontario	Significant expertise in tritium production/handling supported by a world-class tritium facility. Over 500 scientific staff with expertise in several fields relevant for fusion technology development, including tritium handling, robotics, materials science, thermal-hydraulics, neutron/radiation transport, and computational sciences.
3	**Canadian Nuclear Safety Commission (CNSC)**	Ottawa, Ontario	Regulates the use of nuclear energy and materials within Canada. In 2021–2022, CNSC commissioned a research report to review its regulatory framework for readiness to regulate fusion technologies.
4	**Natural Resources Canada (NRCan)**	Ottawa, Ontario	Federal agency maintaining a watching brief on domestic and international developments in fusion energy science and technology. Providing guidance to AECL and CNL on S&T priorities.
Universities and Research Institutions			
5	**McGill University**	Montreal, Quebec	The Shock Wave Physics Group in the Department of Mechanical Engineering has expertise in fluid dynamics stability and shockwave propagation. They have experience in liquid cavities and imploding liquid metal liners.
6	**McMaster University**	Hamilton, Ontario	Department of Engineering Physics has specific research areas in fusion technology, nuclear instrumentation, plant thermal hydraulics, reactor simulations, safety system performance, and probabilistic methods.
7	**Ontario Tech University**	Oshawa, Ontario	Small-scale plasma physics research through its Advanced Plasma Engineering Laboratory (APEL), with studies being carried out on Z-Pinch and dense plasma focus (DPF) fusion devices.
8	**Queen's University**	Kingston, Ontario	Department of Physics undertakes small-scale experimental and computational plasma physics and electromagnetics research. The Department of Mechanical and Materials Engineering also undertakes fusion-related activities.
9	**Simon Fraser University**	Vancouver, British Columbia	The Nuclear Science group at SFU owns and operates a deuterium-tritium neutron generator, as well as several gamma ray and charged particle detectors.
10	**TRIUMF**	Vancouver, British Columbia	As Canada's particle accelerator centre, TRIUMF is a research laboratory owned by a consortium of 21 Canadian universities and specializes in science and technology development applicable to fusion research.
11	**University of Alberta**	Edmonton, Alberta	Department of Electrical Engineering, Photonics, and Plasma Research Group, focuses on laser-based inertial confinement fusion science with strong coupling to international centres and workforce development. The university has experimental and theoretical strengths in laser/plasma interaction and diagnostics.

	Stakeholders	Main Location	Capabilities/Activities
12	**University of British Columbia (UBC)**	Vancouver, British Columbia	UBC has a unique Engineering Physics undergraduate program with a co-op component that has placed many students in private fusion research. Their Department of Mechanical Engineering conducts research in computational fluid dynamics, which is relevant to liquid-solid metal interaction relevant to several fusion approaches.
13	**University of Ottawa**	Ottawa, Ontario	The Department of Mechanical Engineering conducts research in fluid dynamics and shock waves that is relevant to liquid metal compression.
14	**University of Saskatchewan**	Saskatoon, Saskatchewan	Focuses on Tokamak-based Magnetic Confinement Fusion science and technology with the only experimental Tokamak in Canada – STOR-M. Also works on alternative fusion concepts and fueling technologies. It also operates the Sylvia Fedoruk Canadian Centre for Nuclear Innovation.
15	**University of Sherbrooke**	Sherbrooke, Quebec	The Department of Electrical Engineering and Information Engineering is developing a novel type of electronics known as Photon-to-Digital Converters, which will have applications to several fusion diagnostics.
16	**University of Toronto**	Toronto, Ontario	Experimental/computational modeling of plasma-wall interactions and conducts materials research. Supports tokamak research and the ITER project indirectly through international collaborations with different universities and research laboratories.
	Non-Governmental Organizations		
17	**Canadian Nuclear Society (CNS)**	Toronto, Ontario	Not-for-profit professional society that promotes the exchange of information on all aspects of nuclear science and technology and its applications.
18	**Fusion Energy Council of Canada (FECC)**	Edmonton, Alberta	The Fusion Energy Council of Canada is a non-profit organization established in 2016. Its membership consists of engineers, scientists, government representatives, the energy and utility industries, financiers, businesspeople, academics, and individuals with an interest in fusion and their spin-off technologies.
	Industry		
19	**Bruce Power**	Tiverton, Ontario	Potential customer for first builds of fusion power plants.
20	**Kinectrics**	Toronto, Ontario	Provides a comprehensive range of services across the fusion life cycle. These include tritium and deuterium handling, materials laboratories, irradiated materials testing, process skid design, tooling development, engineering design and integration, project management, fuel cycle management, original equipment manufacturer parts supply and custom skids, pulsed power sources, high voltage and high current evaluations, safety and regulatory support, remote maintainability and operability, neutron shielding, tritiated materials management, waste management, and decommissioning. Kinectrics is committed to self-funded R&D to develop innovative solutions for the fusion industry.
21	**Laurentis Energy Partners**	Toronto, Ontario	Commercial subsidiary of OPG that provides project management and engineering services for small- and large-scale power projects.
22	**New Brunswick Power (NB Power)**	Fredericton, New Brunswick	Potential supplier for tritium and customer for first builds of fusion power plants.

	Stakeholders	Main Location	Capabilities/Activities
23	**Ontario Power Generation (OPG)**	Toronto, Ontario	Interested in providing required tritium (and decayed helium-3) for fuel to fusion projects in the international community. Also, a potential customer for the first builds of fusion power plants.
24	**Organization of Canadian Nuclear Industries (OCNI)**	Pickering, Ontario	Interested in marketing capabilities of its member companies to the international community (such as the ITER project) for fusion energy engineering and S&T development.
	Private Fusion Industry		
25	**Fuse Energy Technologies**	Montreal, Quebec	Small startup fusion R&D company developing a variant of a fusion Z-Pinch; looking at alternative applications; seeking out near-term customers and partners.
26	**General Fusion**	Richmond, British Columbia	Canada's only major technology developer with a fluid mechanically-driven MTF concept. Currently building a fusion machine in Richmond, B.C. that is planned to demonstrate fusion conditions by 2025, with the goal of achieving scientific breakeven equivalent by 2026. Preparing to deploy a fusion demonstration.
27	**Hope Innovations**	Mississauga, Ontario	Small startup company that is working on an alternative concept related to Z-Pinch and X-Pinch devices.
28	**Norax Canada**	Lévis, Quebec	Develops pulsed and radio frequency (RF) power supplies for induction heating systems, some of which could be employed in different fusion energy technologies. Small-scale efforts on an alternative fusion concept.
29	**Plasmionique**	Varennes, Quebec	R&D company created by scientists at the Université du Québec à Montréal (UQAM) Institut national de la recherche scientifique (INRS) after the closure of the TdeV fusion project. Develops and sells plasma processing technology and supports R&D.

5. Vision for Fusion in Canada

A transformational vision for Canada's fusion future, and its related benefits, is presented across three lenses: national benefits, capabilities, and international leadership.

National Benefits

- Canada has a net-zero economy.
- Canada has a large fleet of large-scale and small-scale fusion facilities.
- Canada has fusion power plants operating in every province and territory.
- Canadian fusion technology is economic and competitive.
- Canadian fusion power plants are augmenting other zero-carbon energy sources.
- Canadian utilities, industry, and resource sectors are using fusion plants to supply their energy needs for electricity and industrial heat.
- Canada is a home and headquarters for private sector fusion companies and vendors.
- Canada has a fully developed and complete fusion power industrial supply chain.

Capabilities

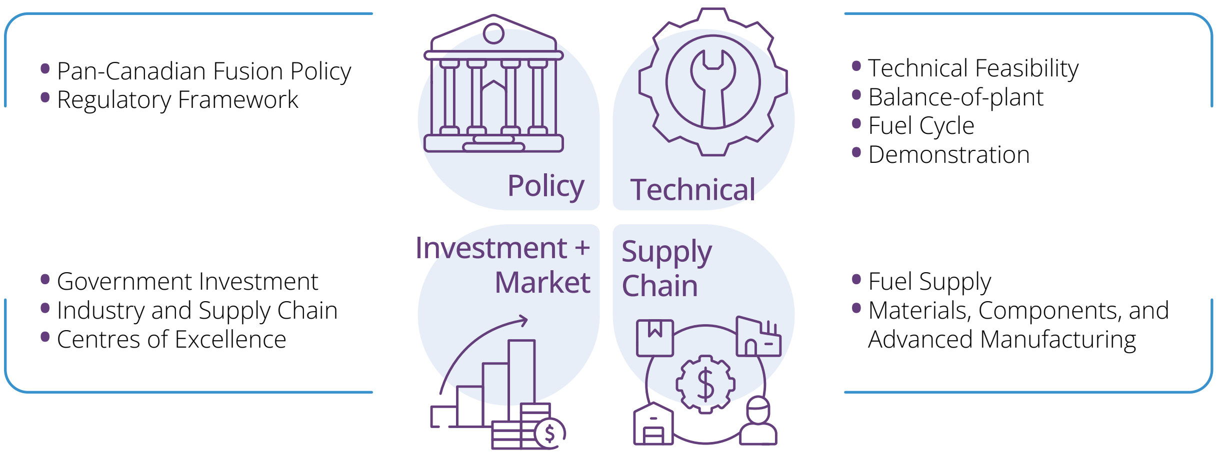
- Canada has several national "Centres of Excellence in Fusion" at universities and government laboratories to train Highly Qualified Personnel (HQP) and develop innovations in S&T.
- Canada can provide effective and risk-informed safety, licensing, and regulatory oversight frameworks with the agility to support fusion systems.
- Canada has operating storage facilities to manage intermediate- and low-level radioactive materials produced by the activation of fusion components.
- Canada's stakeholders, including indigenous communities, are engaged as partners, supporters, and benefactors to achieve social acceptance of fusion energy as a zero-carbon energy source.

International Leadership

- Canada is an international supplier for deuterium and tritium fusion fuels, other advanced materials, and raw materials such as lithium.
- Canada is an international supplier for fusion components and enabling plant equipment, such as fuel cycle components, instrumentation, and simulators.
- Canada is an international supplier for fusion expertise and services, including design, operations, and financing.
- Canada takes a leadership role in helping mature international non-proliferation practices for fusion.
- Canada becomes a leading exporter, particularly of tritium fuel, and tritium breeding/fuel-cycle technologies – maturing this part of the value chain.

6. Challenges and Opportunities

In order to deliver Canada's anticipated future vision for fusion, the existing challenges and opportunities must be identified and understood across the policy, investment and market, technical, and supply-chain domains as outlined below and described in the following sections:



6.1. Policy Gaps

The lack of fusion policies in Canada hinders R&D and growth of the industry.

At present, Canada has no policies specifically focused on fusion energy. This policy gap is partly due to the cancellation of the NFP in 1997. However, Canada is now in a favorable position to develop appropriate fusion policies. The purpose of Canada's new policies would be the rapid and comprehensive creation of scientific and technical capabilities, business and financial expertise, industrial infrastructure, and public support for fusion, all integrated and aligned with a broader clean energy strategy for Canada.

Canada lacks assertive, facilitative, and stable policies that enable human resource development across a wide spectrum, ranging from research scientists and engineers to fusion plant designers, fabricators, and operators, as well as experts in supply chains, intellectual property (IP), finance, insurance, and marketing. Canada lacks policies that facilitate and encourage collaboration and multilevel government investment from federal, provincial, and municipal governments. Private fusion companies are looking to first participate in jurisdictions and markets that have established, favorable policies and regulatory pathways.

Fusion is an international industry sector, with countries and companies collaborating and competing worldwide. Canadian fusion policies should therefore align with policies of other countries. Such alignment can be achieved by Canada collaborating proactively with other countries (especially the UK, U.S., Japan, and the Republic of Korea) and regions (especially the EU) in the development of policies.

Canada has an agreement focused on fusion with ITER,[72] but it still awaits action. Canada has no broad-based international policies and strategies for fusion that facilitate cooperation and IP agreements with other nations to leverage scientific/technical progress and join international supply chains.

The present lack of policies must be addressed to stimulate and guide the development and deployment of fusion energy, and also provide essential certainty and confidence for companies and investors to commit to this new technology in Canada. Progressive experience with fusion development will subsequently lead to regulations supplementing Canada's new fusion policies.

Regulatory and international non-proliferation frameworks have yet to be developed for fusion energy.

The fusion regulatory framework does not fit under the legacy fission regulatory framework, a fact that has been recognized by the UK and U.S. Governments.[42] While Canada's fission regulatory policies are widely seen as more flexible than those of some other countries, they do not cover the full range of fusion energy needs, particularly in development, commercialization, and deployment.

Facilitating appropriate policies is essential to Canada's successful and competitive participation in the development, commercialization, and deployment of fusion energy.

While the nuclear weapons proliferation risk associated with fusion technology is low, tritium will likely be subject to additional international non-proliferation requirements by the International Atomic Energy Agency (IAEA) and select fusion technologies may be subject to export controls. The proliferation risks that have been identified related to fusion include the use of neutrons to create fissile material, leveraging research of ignited, inertially confined plasmas for thermonuclear weapon development, diversion of tritium to boost nuclear weapons, and diversion of radioactive material towards a radiological dispersion device.[73]

Canada currently has significant experience in managing tritium and works closely with the IAEA to institute international safeguards. As the international regulatory regime concerning fusion power plants develops, however, it is likely that more attention will be placed on the calibration of non-proliferation controls to prevent the use of tritium by bad actors. Canada is well-placed to take an international leadership role in developing and testing the appropriate international non-proliferation framework for fusion energy facilities.

6.2. Investment and Market

Government (both federal and provincial) investment in fusion energy development is low in comparison to other Tier 1 economies.

The IEA reported US$13.7 million of public investment in fusion RD&D for Canada in 2022. Although there has been year-on-year growth in this figure over the previous five years,[48] Canada is still lagging behind its peers. Notable examples of other nations that are making more significant investments in the development of fusion through domestic programs include:

- **United States:** The DOE-FES office has a budget of over US$790 million (in 2024), which not only supports several domestic fusion research programs but also directly invests in private fusion ventures through a US$46 million milestone investment fund.[51] In addition, the NNSA has an allocated budget of over US$690 million (in 2024) for the Inertial Confinement Fusion program.

- **United Kingdom:** The UK government has invested £222 million for the design phase for STEP, and an additional £184M for new fusion facilities and infrastructure at the Culham Science Centre.[52] In late 2022, the UK government also committed £84 million for the continuation of JET and launched the £42.1 million Fusion Industry Program to support the private UK fusion industry.[53] In late 2023, the UK government announced £650 million in funding for the country's Fusion Futures Programme, which will support over 2,200 training opportunities nationwide, a fuel cycle testing facility dedicated to fusion commercialization, and funding for infrastructure development for private fusion companies.[55]

For Canada to capture the significant economic, security, and decarbonization opportunities associated with a mature fusion industry, it should increase its level of public investment to levels proportional to countries like the U.S. and the UK. In addition to the scale of investment, it is critical that Canada take a holistic view of industry development by funding a mixture of government-led RD&D programs, academic research infrastructure, and investing in the private sector. While venture capital has increasingly become available to early-stage fusion companies globally, the challenge of continued funding through to the proof-of-concept stage remains.[59] There is an opportunity for Canada to help bridge this gap through direct investment in private Canadian companies, participation in public-private partnerships, and funding technology translation support initiatives such as pivot-support programs.

The Canadian industry is positioned to become a significant part of a fusion power industrial supply chain, or to become a key customer and adopter of future fusion power plants with the right support and strategic investments.

Both short-term and long-term investments in industrial and manufacturing infrastructure are needed for Canada to become a supplier of fusion components and fuel (deuterium and tritium).

Investments in infrastructure and demonstration/prototype/pilot plant facilities are needed by Canadian industry (including electric utilities). Industry may be able to leverage government seed investments and other incentives to take economic advantage of having access to a reliable source of zero-carbon energy to provide electricity and process heat.

Government investments in dedicated university fusion R&D, education, and training programs, augmented and leveraged by private-sector investments, will help enable a sustainable, highly skilled workforce that is ready to support a fusion energy industry.

Engagement of industry will enable it to prepare to adapt and grow quickly, such that it can exploit fusion energy as a reliable and economically competitive zero-carbon energy source.

Other Canadian industries can also leverage scientific and engineering progress made in the fusion industry. As advances are made in fusion R&D, there is the potential to accelerate “fusion adjacent” technologies, such as high-field magnets, superconductors, robotics, heat and neutron-resistant materials, computing, lasers, and precision measurement technologies. These advances will be relevant to a range of industries, such as healthcare, transport, aerospace, telecommunications, and mining, as shown in Figure 15.[74, 75] It is crucial that this knowledge and IP is effectively translated.

The Canadian government can have a role to play in this. Mechanisms such as pivot-support programs can help reorientate private technology developers in the fusion industry, enabling them to translate knowledge generated from R&D, demonstration, and deployment activities into other industries.[76] Building a robust technology transfer framework around the fusion industry will be vital to ensure the best return on investment.

With the right investment, Canada can accelerate the development of dedicated, large-scale, comprehensive centres of excellence for fusion R&D and associated national experimental facilities.

Canada does not have large-scale scientific infrastructure and institutions similar or analogous to what exists in the U.S. (such as NIF), the UK (such as CCFE), or South Korea (such as NFRI). These facilities are critical in building capabilities for the nation.

Figure 15. *The fusion industry will add value to a range of other sectors through the acceleration of "fusion adjacent" technologies.*[74,75]

It is recognized that in other scientific and engineering disciplines, Canada does have several notable research sites and facilities, such as CNL, the Canadian Light Source (CLS) at the University of Saskatchewan, and TRIUMF based at the University of British Columbia that could provide critical discovery and research on fusion technology, as well as providing talent and expertise.

6.3. Technical Challenges

There are several gaps and challenges in the technical domain that require further science and engineering efforts to make fusion energy viable in Canada and anywhere else in the world.

> The technical feasibility of generating energy from fusion has not yet been demonstrated.

After nearly 70 years of R&D in fusion technology, no fusion device has yet achieved net energy generation – a requirement for electrical and thermal energy generation.

There has been significant progress in the last 20 years, along with several important innovations and technological developments (such as high-temperature superconductors, and high-efficiency laser systems) that give high confidence that new experimental fusion prototypes under development will be able to demonstrate net fusion energy output. Recent experiments at the NIF at LLNL in 2022 have demonstrated fusion energy output that was greater than the laser energy input to the fusion fuel target pellet. In Canada, General Fusion's new demonstration in British Columbia has a goal to achieve scientific breakeven equivalent in 2026.

To ensure the success of achieving technical feasibility, it is critical for Canadian scientists and engineers to take a more active and substantial role in solving the problems across a range of disciplines, including the confinement and control of fusion plasmas, the development of heat and neutron-resistant materials, and the optimization of power conversion systems. This will require investment in developing and growing Canadian scientific expertise in fusion and building larger-scale fusion device experiments and facilities in Canada, particularly at several select Canadian universities.

Extraction of energy from the fusion process to generate electricity needs to be developed.

The balance-of-plant (BOP) of a power plant includes all the systems outside of the primary energy generation source. Although it is anticipated that the first generation of commercial fusion power plants will be similar to existing nuclear power reactors in terms of power generation, where there will be technical and engineering challenges in how energy is extracted to generate electricity.

In addition, because of the relatively large electrical energy inputs required for the operation of a fusion power plant, and its associated costs, it will be necessary to develop optimized systems to convert fusion energy into electricity to reduce the costs of electricity production and make the fusion power plant more practical, economical, and competitive.

Another important consideration is that if a fusion power plant is to be used for alternative applications, such as hydrogen production or high-temperature process heat, then further modifications to the BOP will be required.

Canadian industry will need to develop the expertise to be able to design and improve the BOP for fusion power plants. It is anticipated that the Canadian nuclear industry could adapt its expertise for fusion power plants and could be assisted by the fusion R&D workforce and facilities.

Tritium breeding has yet to be demonstrated.

A major challenge in the development of fusion power plants is the fusion fuel cycle. Most fusion approaches require both deuterium and tritium as fuel. A reliable supply of tritium is a requirement for the majority of fusion programs, globally, and supply availability will become an increasing priority.

With Canada's experience and expertise in the production and handling of heavy water (D_2O) for the fleet of CANDU heavy water reactors, the Canadian nuclear industry has the capability to resume deuterium fuel production.

The challenge of sustainably producing tritium by breeding in a fusion power plant blanket containing a lithium-based compound and consuming it in a fusion prototype has not been demonstrated. To complete this fuel cycle, recycling the tritium will be important as the process results in a low tritium burning fraction (for magnetic confinement designs), providing the opportunity for reuse. This process is also yet to be demonstrated at scale. Breeding blanket designs vary,[77] some current magnetic confinement designs require enriched lithium-6 to attain tritium breeding rates which allow self-sufficiency for a fusion power plant,[78] however there is an active investigation in the industry to seek alternatives to address the challenges with lithium-6 availability.

There are no large-scale experimental facilities in the world yet to demonstrate the practical production/breeding of tritium in lithium-based blanket materials and components that would be used in a demonstration or full-scale prototype fusion power plant. Such facilities would also be needed to train Canadian scientists and engineers, and help identify unknown scientific, technical, and engineering challenges. This is a key opportunity for Canada which leverages existing expertise and current collaborative arrangements with international partners in breeding blanket technologies.

Fusion power plant prototypes have not yet been demonstrated.

Commercialization of complex new technologies, like fusion, requires a staged deployment process beginning with verification gained from small-scale research facilities and pilot units, and then near full-scale demonstration plants. For example, the success of Canada's nuclear fission industry was built on experience gained with several small research reactors, a demonstration unit (NPD-2, a 20 MWe reactor), and then the Douglas Point plant (with a 200 MWe reactor).

Given the expansion of scientific knowledge of current fusion systems, their associated technologies (including fuel recycling, tritium breeding, and balance of plant technologies), and powerful design and simulation tools, it may be possible to progress directly to near full-scale plants. Such plants, typically called DEMO in national programs, or demonstration or pilot plants, would produce electricity on a scale and over periods of time that enable comprehensive technical, economic, safety, and environmental evaluations, thereby providing a sound basis for subsequent commercialization. Demonstration plants also provide excellent opportunities to evaluate potential design improvements, capital and operating cost reductions, plant start-ups, shutdowns and trips, maintenance procedures, and operator training. Going directly from research facilities to demonstration is an approach pursued in Europe and the United States.

Canada's participation in fusion development, thus far largely limited to plasma science, tritium, and fission-related technologies, suggests collaboration in demonstration facility development with foreign private and public sector organizations. Demonstration plants located in Canada would maximize national benefits, and could leverage existing licenses for tritium handling across several sites. Demonstration plants in other locations would also create important value, including design, simulation, manufacturing, and financial services. They would also provide major opportunities for advanced research and HQP development.

6.4. Supply Chain Challenges

Canada can be a leader in the fusion fuel supply chain with strategic investments in the required infrastructure.

Canada has existing expertise and infrastructure which can be leveraged to make an important contribution to the international fusion fuel supply chain through the export of fusion fuels such as tritium.

In a fusion power plant, the form in which tritium will exist is different than in a CANDU reactor. The amounts of tritium that will need to be handled in a large-scale fusion power plant (~2000 MWth) could be much larger, ranging somewhere between 5 to 15 kg of tritium for magnetic confinement fusion systems and 1 to 3 kg for inertial confinement fusion systems.[79] To remain operational, new tritium will need to be bred and handled in the fusion power plant blanket and then recycled back into the fusion plasma.

At present, however, there is a lack of maturity in the supply chain infrastructure required to leverage this opportunity. The production and export of tritium will require scaled-up processes to produce, store, containerize, package, handle, and transport the resource at a scale which currently does not exist.

Further efforts will be needed to better understand how to handle and process tritium in large amounts both in an operational large-scale fusion system and as part of an effective supply chain. Currently, no such large-scale, large-volume, nor high-flow rate/throughput experimental facilities exist in Canada or any other nation.

Tritium is also radioactive and requires specialized infrastructure and experienced personnel to ensure the protection of people and the environment. Canada has expertise in handling tritium in small amounts (~0.1 kg at a time) from the operation and maintenance of CANDU power reactors and research reactors.

In addition, given the radiation safety and proliferation concerns associated with tritium, it will also be necessary to develop suitable licensing and regulations for large-scale tritium handling facilities associated with the operation of fusion plants.

It is, however, also recognized that Canada (through both OPG and CNL) has deep experience and expertise in handling tritium and is well-positioned to take the lead in technology development for tritium handling for a fusion power plant.

The component and material supply chains to support fusion power plant deployment require scaling up.

The growth of the fusion industry creates a significant business opportunity for existing and emerging suppliers of materials and components to facilitate fusion power plant development. Many of the materials and components required, such as high-powered magnets, laser components, heat management technologies, advanced first-wall materials, and high-powered semiconductors are highly specialized and require advanced manufacturing processes to produce.

At present there is, however, a lack of long-term certainty for suppliers due to a low volume of firm production commitments, and a lack of external investment to support innovation, build scale, and drive component cost reductions.[10] This is a significant challenge as fusion power plant developers are likely to increasingly require larger volumes and cheaper materials and components as they move towards commercial deployment.

Building and scaling this supply chain infrastructure will require capabilities and expertise across many domains including science, engineering, finance, law, and logistics. It is critical in the short term that fusion-related knowledge and skills development pathways are developed for these domains, and that they are integrated into industrial development strategies.

Governments such as Canada can support the development of a robust supply chain through direct mechanisms including grants, tax credits, and loan guarantees and by recognizing the fusion supply chain as eligible for financial incentives and government support that are provided as a part of clean energy support mechanisms. They also have a vital role in ensuring that national laboratories and national fusion programs work in collaboration with private developers to support fusion supply chain development.

7. Strategy for Fusion in Canada

To achieve Canada's vision for fusion energy, a fusion strategy and a roadmap are needed. This strategy and roadmap for Canada is built on five key foundational areas or "Pillars", as outlined in Table 5. A number of strategic actions can be taken in parallel, while others are sequential, depending on the successful completion of previous actions and steps. These pillars are discussed further in this section.

Table 5. *Overview of "Pillars" for Fusion in Canada.*

Research & Development	• Build international collaborations and partnerships • Leverage, grow, and adapt existing Canadian capabilities • Leverage R&D from CANDUs, small modular reactors (SMRs), and advanced reactors • Build fusion component and test facilities
Demonstration & Deployment	• Build and operate fusion experiments • Build and operate fusion demonstration plants • Establish consortia to share risks and rewards for the first builds of commercial-scale fusion prototypes
Supporting Services	• Develop a Canadian fusion energy industry supply chain • Develop fusion fuel cycle infrastructure • Develop distribution and export infrastructure for tritium and tritium production technologies
Skills, Capabilities, & Engagement	• Establish and grow education and training programs at Canadian universities and colleges • Engage with community groups, including indigenous communities, early to facilitate co-creation of the emerging fusion industry and gain public support and social acceptance
Policy & Regulation	• Develop a pan-Canadian fusion energy policy and strategy • Engage regulatory organizations early to develop appropriate regulations for fusion • Develop and support international policies and commercial arrangements for export/import of lithium, lithium-6, and/or enriched lithium • Participate in ongoing international efforts to develop and harmonize standards, policies, and regulations for the licensing of fusion energy systems

Research & Development

Build international collaborations and partnerships

- To build a robust domestic R&D program, Canadian entities should also collaborate with international governments, research organizations, industry, and fusion companies.

Leverage, grow, and adapt existing Canadian capabilities

- Canada has existing capabilities, facilities, and expertise that are directly relevant to fusion S&T development.
- These capabilities exist at government laboratories, universities, power utilities, private sector companies, and companies within Canada's existing nuclear energy industry supply chain.

- Other capabilities within the Canadian nuclear industry can also be adapted to support fusion development, including robotics, remote handling, materials science, thermal-hydraulics, reactor physics, and more.
- Direct investment in private and public industries would help advance fusion research and technical milestones in Canada, further strengthening and formalizing Canada's fusion sector.

Leverage R&D from CANDUs, SMRs, and advanced reactors

- Research groups at government laboratories, universities, and private sector technology developers are carrying out S&T work in support of the continued and extended operation of CANDUs, along with the development of SMRs and advanced reactors (ARs).
- Private sector companies and vendors are looking to build prototype and commercial-scale SMRs/ARs.
- Many of the design and operating features, including advanced materials, system components, and coolants, being considered for SMR/ARs, particularly those in the BOP, and the associated S&T, share commonality with fusion technology development.
- Tritium management systems used in relation to CANDUs are also relevant technologies that can be adapted to use in fusion systems.

Build fusion component and material test facilities

- The development of components and advanced materials for fusion will require test facilities for the evaluation of performance under irradiation by high-energy neutrons, hydrogen isotopes, charged particles, gamma-rays, and X-rays. It will also be necessary to perform testing of components under operational conditions of the fusion power plant.
- Examples of components and materials include first-wall plasma-facing components, field magnets, coolants, lithium-based blanket materials, piping, heat exchangers, welding materials, fusion exhaust gas processing equipment, lasers, photonics, vacuum pumps, extreme condition diagnostics/instrumentation/sensors, lithium enrichment technologies, and structural materials.
- Domestic test facilities will prioritize the needs of Canadian interests and will also provide facilities for the training and development of Canadian fusion HQP.

Demonstration & Deployment

Build and operate fusion experiments

- The most effective way to shape, develop, maintain, and retain domestic expertise in fusion technology to support a domestic fusion energy industry is to conceptualize, build, operate, and optimize experimental fusion devices.
- To help grow Canada's fusion energy industry, a valuable pre-cursor will be to build several new experimental fusion devices and supporting facilities at different organizations, academic institutions, and government laboratories, to support scientific and engineering development in several fusion technologies, including magnetic fusion, laser-based inertial confinement fusion, and alternative fusion technologies.

Build and operate fusion demonstration plants

- A key precursor to a successful domestic fusion energy industry will be the construction and operation of one or more demonstration fusion power plants.
- The construction and operation of smaller-scale prototypes help train and educate utilities and the industrial supply chain on how to improve performance.

- Demonstration plants can also be used as test beds for improved components, materials, systems, and sub-systems, along with operating and maintenance procedures.

Establish consortia to share risks and rewards for the first builds of commercial-scale fusion prototypes

- Commercial-scale fusion prototypes will be the first-of-a-kind fusion plants to generate and sell energy and/or heat for the electricity grid, industry, or other applications. Therefore, these are crucial first steps in establishing a commercial fusion energy industry.
- To reduce the financial burden and risk in developing new technologies and bringing them to market, it is advantageous to spread the risk over multiple investors, customers, and stakeholders.
- The creation of consortia to invest in building prototype/demonstration fusion power plants, and to share in the risks, rewards, profits, and expertise gained will help enable fusion energy commercialization.

Supporting Services

Develop a Canadian fusion energy industry supply chain

- The industrial supply chain for Canada's existing nuclear industry is evolving and adapting to support the development of the next generation of advanced reactor technologies (SMRs and ARs). This industrial supply chain has ensured the success of Canada's nuclear energy industry and will continue to ensure its success in the future. Building on this experience, Canada can develop an industrial supply chain for fusion technology development, deployment, and operation in Canada.
- A fusion energy industry supply chain is needed for the manufacture of all fusion technology components, systems, sub-systems, and special materials, and to supply services for the monitoring, testing, maintenance, and replacement of components.
- Existing industrial companies in Canada should be incentivized to expand their capabilities to serve a future fusion energy industry.

Develop fusion fuel cycle infrastructure

- Canada's existing experience and infrastructure can be leveraged to make an impact in the fusion fuel supply chain through the following initiatives:
    - Re-build Canada's heavy water production capabilities using Canadian innovations to minimize the cost of large-scale heavy water production. Build hydrogen production facilities using advanced Canadian technologies to extract deuterium from heavy water.
    - Explore producing large amounts of tritium derived from CANDU reactor operations using lithium-based irradiation targets, and consider the potential expansion of Tritium Removal Facilities for CANDU plants to further detritiate the existing heavy water inventory. This pathway for tritium production would allow Canada to keep its lead for the global supply of tritium.
    - Build tritium fuel cycle infrastructure, including breeding, storage, and handling facilities, using Canadian expertise domestic and international pilot experiments and start up of commercial fusion power plants. Develop transportation technology, networks, and protocols for transporting tritium to customer nations through waterways and land routes.
- It is also necessary to develop distribution and export infrastructure for tritium and tritium production technologies.

Skills, Capabilities, & Engagement

Establish and grow education and training programs at Canadian universities and colleges

- It is necessary to develop and support a highly skilled workforce of HQP that can support a future fusion energy industry, and that can also support R&D activities within academia, government, and public and private industry to achieve new innovations in fusion S&T.
- Canada should build educational and training programs at universities and community colleges that are aligned with the needs of fusion energy development. This situation is parallel or analogous to that of other high-technology sectors in Canada, such as nuclear energy, information, and communication technology, robotics, advanced manufacturing, and others.

Engage with community groups, including indigenous communities, early to facilitate co-creation of the emerging fusion industry and gain public support and social acceptance

- Based on experiences obtained from the existing nuclear industry, early and continual engagement, communication, and consultation with different stakeholder community groups (such as municipal governments, grassroots advocacy groups, NGOs, First Nations, Metis, Inuit, and other groups) is critical to ensure co-creation of the emerging fusion industry.
- A long-term strategy for community engagement will help ensure the successful wide-scale deployment of fusion power plants in Canada, particularly to remote communities that are in need of economical and reliable low-carbon energy, and communities that seek economic benefits through direct participation in a domestic fusion energy industry.

Policy & Regulation

Develop a pan-Canadian fusion energy policy and strategy

- An integrated long-term strategy is needed for fusion, to achieve time and cost efficiencies. Such a strategy needs to address the application of fusion to all energy needs, including electricity generation, and applications in the commercial, industrial, and transportation sectors.
- To ensure such a strategy is practical, feasible, and successful, its development requires financial participation, contributions, and long-term commitments by all provincial and territorial governments.
- A multi-province strategy has been proposed for the development of SMRs in Canada. A similar process could be adapted for further developing a pan-Canadian fusion energy strategy.

Engage regulatory organizations early to develop appropriate regulations for fusion

- Fusion technology vendors, industrial supply chain companies, utilities, investors, and any potential customer for fusion power plants need certainty and clarity on the regulatory process to ensure a timely and cost-effective process for the licensing of fusion plants.
- Efforts are underway within the international community to develop a harmonized regulatory framework and guidelines for fusion. The U.S. and UK are already establishing frameworks for regulating fusion energy. It will be prudent for the regulatory entity to leverage those efforts and adopt a framework that is appropriate for Canada and that will encourage fusion vendors to license their technology in Canada.
- The fusion regulatory framework does not fit under legacy fission regulatory frameworks because fusion systems pose no risk of runaway chain reactions, contain orders of magnitude less radioactivity, and produce less active and shorter-lived nuclear wastes.
- To ensure the success of a domestic fusion energy industry, it is necessary for Canada to develop or adapt existing policy and regulatory/licensing framework, along with guidelines and processes, that will ensure fusion power plants meet all necessary and appropriate requirements for safety. To achieve this

objective, regulators will likely need additional resources and expertise through support from both the federal government and licensing fees charged to fusion technology vendors.

- Furthermore, because Canada has unique experience in instituting international safeguards on tritium, Canada should also work with the IAEA and other international partners to help mature the framework for international non-proliferation and export controls for fusion technology and facilities.
- Canada should also develop and support international policies and commercial arrangements for the export and import of lithium, lithium-6, and/or enriched lithium.
- Finally, participation in ongoing international efforts to develop and harmonize standards, policies, and regulations for the licensing of fusion energy systems will be important.

8. Fusion Roadmap

The roadmap proposed and presented in this document is a strategic and ambitious vision for Canada to become an international leader in fusion technology and services, and to deploy commercial fusion energy by 2050 and beyond to help meet net-zero goals.

A high-level fusion roadmap, showing the key actions and milestones to be achieved under the different pillars over the next three decades and beyond, is outlined in the following pages.

The roadmap takes a pathway along three time periods: near term (now up to 2034), medium term (2035 through 2050), and long term (beyond 2050). The major milestone for each of these time periods is to demonstrate, adopt, and expand fusion energy, respectively.

LONG TERM
2050+

EXPANSION of fusion energy in Canada and globally across all continents

MEDIUM TERM
2035 – 2050

ADOPTION of fusion energy in Canada and in select regions, transitioning to mature commercialization

NEAR TERM
2024 – 2034

DEMONSTRATION of fusion power plants in Canada and/or elsewhere in North America, Europe, and Asia

NEAR-TERM ROADMAP 2024 – 2034		
VISION: DEMONSTRATION of a fusion prototype in Canada and/or elsewhere in the world		
	OBJECTIVES	**ACTIONS**
Research & Development	• National centres of excellence for fusion R&D and business innovation • Fusion Innovation Ecosystem • Strong international partnerships	• Investment into research facilities, private industry, and national centres of excellence • Build partnerships with research organizations and companies in fusion, especially in the UK, U.S., and EU
Demonstration & Deployment	• Demonstration facility in Canada or elsewhere	• Provide investments and incentives for a demonstration plant in Canada or elsewhere • Engage industry and utilities • Issue Requests for Proposal (RFP) for demonstration fusion plants
Supporting Services	• Fuel cycle research and development services • Canadian supply chain engagement in fusion projects	• Demonstrate tritium production on a large scale • Provide tritium and services to ITER and other fusion facilities • Expand Canadian tritium production through the introduction of Lithium-6 targets in Canadian nuclear power plants and expanded use of Tritium Removal Facilities from CANDU reactors
Skills, Capabilities, & Engagement	• Trained workforce for fusion R&D • Foundations for social license	• Establish fusion-focused university programs • Engage the general public and key stakeholder groups, including indigenous communities • Provide internships and early career opportunities in fusion
Policy & Regulation	• National fusion policy • Inclusive clean energy policies • Facilitate involvement of Provinces and Territories • Regulatory framework • ITER involvement	• Establish pan-Canadian fusion strategy and roadmap • Establish regulatory approach • Join ITER as an Associate Member • Create standards for specific pieces of the fusion sector • Align and harmonize standards, policies, and regulations with other countries

MEDIUM-TERM ROADMAP 2035 – 2050		
VISION: ADOPTION of fusion energy in Canada and around the world		
	OBJECTIVES	**ACTIONS**
Research & Development	• Technology development enables commercial fusion deployment, efficiency gains, and cost reductions	• Test and improve systems and components in R&D facilities and centres • Incorporate lessons learned from previous decade
Demonstration & Deployment	• Deploy fusion power plants in Canada • Fusion meets the needs for new electricity and heat requirements • Establish a pan-Canadian approach for fusion power plant deployment	• Provide investments and incentives for deployment in Canada • Evaluate sites for fusion power plants
Supporting Services	• Revenue-generating services offered in Canada and abroad • Fusion sector also supports other industries • Support delivery of fusion pilot and first commercial plants domestically and internationally	• Scale up production of deuterium and tritium • Develop integrating technologies from various industries
Skills, Capabilities, & Engagement	• Trained workforce for commercial fusion operations, construction, and manufacturing • Social license for first fusion plants	• Continue to invest in fusion-focused university programs and related technical and non-technical education • Cross-train professionals from adjacent industries • Continue to engage the general public, key stakeholder groups, indigenous communities, and host communities
Policy & Regulation	• Fusion is a key part of the national energy policy and net-zero goals • Mature regulatory framework and standards	• Regulate commercial fusion power plants • Continue to create and adjust standards and align internationally

LONG-TERM ROADMAP 2050+		
VISION: EXPANSION of fusion energy in Canada and the world		
	OBJECTIVES	**ACTIONS**
Research & Development	• Further efficiency gains and cost reductions supported by R&D	• Test and improve systems and components in R&D facilities and centres • Incorporate lessons learned from previous decade
Demonstration & Deployment	• Fusion contributes in a major way to decarbonization	• Reduce commercial fusion costs through economies of scale, reduced downtime, and mature supply chain
Supporting Services	• Mature and profitable service offerings in Canada and abroad • Fusion sector supports other industries in a major way	• Continue to scale up production of deuterium and tritium
Skills, Capabilities, & Engagement	• Strong workforce for commercial fusion operations, construction, and manufacturing • Communities welcome fusion power plants	• Continue to invest in fusion-focused university programs and adjacent technical and business education • Cross-train professionals from adjacent industries • Continue to engage the general public, key stakeholder groups, indigenous communities, and host communities
Policy & Regulation	• Fusion helps Canada achieve net-zero goals	• Determine national and provincial policies and strategies on transitioning other energy technologies to fusion

9. Conclusions, Recommendations, and Next Steps

9.1. Conclusions

Fusion is an advanced energy technology that could provide zero-carbon electricity and high-temperature process heat to displace the use of fossil fuels and augment the use of other zero-carbon energy sources in Canada. Fusion can provide energy independence through domestic fuel accessibility, and has the potential to provide economical, resilient, and reliable energy.

Global momentum around the development of fusion energy is high and continuing to grow. Internationally, governments have made substantial investments into building national fusion programs with numerous institutions and internal infrastructure. Within the private sector, as of mid-2023, there has been over $8.2 billion invested in over 43 fusion companies.

Canada has a mature supply chain and a world-class ecosystem of academic, government laboratories, industrial, and regulatory stakeholders with proven success collaborating in complex emerging industries. Supporting this industrial base is a highly skilled workforce and supportive business environment. Based upon Canada's expertise and Tier 1 Nuclear Nation status, Canada is in a strong position to significantly contribute to this fusion movement through its renowned scientific and technological capabilities.

The long-term vision for Canada is to have a fleet of fusion power plants providing zero-carbon energy to support its economy and to provide extensive economic, environmental, and social benefits for citizens and industry. This fusion fleet will be supported by an effective supply chain, and by several Canadian centres of excellence focused on fusion S&T. This vision is achievable, through the implementation of a comprehensive and sensible strategy, following a roadmap for development, as part of a renewed Canadian national fusion program.

For Canada's fusion industry to deliver this sustainable and enduring impact, the challenges and opportunities must be understood across policy, market, and technical domains. The lack of fusion policies in Canada hinders R&D and growth of the industry. In addition, a risk-informed regulatory framework is required to ensure a sensible foundation for the development and deployment of fusion technologies.

The amount of government (both federal and provincial) investment in fusion energy development is low in comparison to other Tier 1 economies. This deficiency is also apparent in the lack of dedicated, large-scale, comprehensive centres of excellence for fusion R&D or associated national experimental facilities. The broader Canadian industry is not yet positioned to become part of a fusion energy industrial supply chain, or to become a key customer and adopter of future fusion plants. However, this situation can be changed with committed investment in both public and private industries.

To achieve the vision for fusion energy in Canada, a strategy has been built upon five pillars: Research & Development; Demonstration & Deployment; Supporting Services; Skills, Capabilities, & Engagement; and Policy & Regulation. The roadmap is divided into three time periods: near term (now up to 2034), medium term (2035 through 2050), and long term (beyond 2050). The major milestone for each of these time periods is to demonstrate, adopt, and expand fusion energy, respectively. Various actions and recommendations have been identified to support establishing Canada's enduring leadership in the fusion industry.

We are calling on the Canadian government to take action to invest in developing a fusion ecosystem in order to capitalize on the economic benefits available from the domestic implementation of fusion energy and supporting the international nuclear sector.

9.2. Recommendations

Based on the assessments described in this document for Canada's need for fusion energy to support a future net-zero economy, Canada's unique capabilities to develop a domestic fusion energy industry and to become an international supplier, and the various challenges and opportunities for Canada, the following are identified as key recommendations for Canada. These recommendations will guide the implementation of the strategy and roadmap to achieve a long-term vision for fusion energy development for the benefit of Canada:

1. Establish a pan-Canadian national fusion strategy supported by investment
2. Establish partnerships with other nations in the development of fusion
3. Grow and develop a fusion energy industry supply chain
4. Build education and training programs for fusion
5. Establish Canadian Fusion Centres of Excellence
6. Build fusion experimental facilities for testing and training
7. Build prototype/demonstration fusion power plants
8. Engage, inform, and prepare key industrial sectors for use of fusion energy
9. Engage regulatory entities to develop the licensing framework for fusion energy
10. Implement a process for community consultation and stakeholder engagement

9.3. Next Steps

Now that a vision for fusion in Canada has been illustrated and there is a proposed strategy and roadmap to achieve that vision, Canada should prepare to implement the above ten key recommendations.

The following are the crucial next steps in this process for embarking on this fusion journey for Canada:

- This document will need to be provided to key stakeholders, advisors, and leaders in federal and provincial government agencies and ministries, and leaders and planners in Canadian industries and utilities.
- Engagement with Canadian stakeholders, federal and provincial governments, and international partners help to refine and further develop Canada's strategy for fusion energy development, thereby maximizing probabilities of success, economic, environmental, and social benefits for all Canadians.

References

1 K. Inyea, S. Shin, J. Ko, et al., 2017, "Functional Li-M (Ti, Al, Co, Ni, Mn, Fe)-O energy materials", https://www.researchgate.net/figure/Schematic-diagram-of-fuel-cycle-system-of-nuclear-fusion-reactor-79_fig5_313271375

2 National Ignition Facility (NIF), 2023, "National Ignition Facility Achieves Fusion Ignition", https://lasers.llnl.gov/science/pursuit-of-ignition#:~:text=On%20Oct.,time%20on%20an%20ignition%20target

3 R. Fedosejevs, C. Xiao, B. Bromley, et al., 2017, "Fusion 2030: Roadmap for Canada", https://www.cns-snc.ca/wp-content/uploads/2022/08/Fusion-2030-Roadmap-for-Canada.pdf

4 Natural Resources Canada (NRCan), 2022, "Energy Fact Book 2021-2022", https://www.nrcan.gc.ca/sites/nrcan/files/energy/energy_fact/2021-2022/PDF/2021_Energy-factbook_december23_EN_accessible.pdf

5 ITER, 2023, "Advantages of Fusion", https://www.iter.org/sci/Fusion#:~:text=The%20following%20advantages%20make%20fusion,reactions%20(at%20equal%20mass)

6 Department for Business, Energy & Industrial Strategy, 2021, "Towards Fusion Energy: The UK Government's Fusion Strategy", https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1022540/towards-fusion-energy-uk-government-fusion-strategy.pdf

7 International Atomic Energy Agency (IAEA), 2023, "Fusion - Frequently asked questions", https://www.iaea.org/topics/energy/fusion/faqs

8 Bloomberg Intelligence, 2021, "Nuclear fusion market could achieve a $40 trillion valuation", https://www.bloomberg.com/professional/insights/trading/nuclear-fusion-market-could-achieve-a-40-trillion-valuation/

9 B.P. Bromley, H. Boniface, B. Ellis, et al., Canadian Nuclear Laboratories, 2021, "Fusion Energy: Current State of Affairs in Canada and on the World Stage in 2021", CNL Report, 153-129000-REPT-004, Revision 1, https://www.cns-snc.ca/wp-content/uploads/2022/08/Redacted-NRCan_CNL-Technical-Reference-Document-Fusion-Energy-Current-State-of-Affairs-in-Canada-and-on-the_.pdf

10 Fusion Industry Association (FIA), 2023, "The Fusion Industry Supply Chain: Opportunities and challenges", https://www.fusionindustryassociation.org/wp-content/uploads/2023/05/FIA-Supply-Chain-Report_05-2023.pdf

11 Organization of Canadian Nuclear Industries, Fusion Energy Council of Canada, 2022, "Canadian Fusion Capabilities Directory 2022 Edition", https://www.ocni.ca/wp-content/uploads/2022/10/Final_Fusion-Directory.pdf

12 Environment and Climate Change Canada, 2021, "Exploring Approaches for Canada's Transition to Net-Zero Emissions", https://unfccc.int/sites/default/files/resource/LTS%20Full%20Draft_Final%20version_oct31.pdf

13 Environment and Climate Change Canada, 2021, "Canada's Greenhouse Gas and Air Pollutant Emissions Projections 2021", https://publications.gc.ca/site/eng/9.866115/publication.html

14 The White House, 2022, "U.S. Innovation To Meet 2050 Climate Goals"

15 Canadian Energy Regulator, 2023, "Scenarios and Assumptions", https://www.cer-rec.gc.ca/en/data-analysis/canada-energy-future/2021/scenarios-and-assumptions.html

16 Canadian Energy Regulator, 2023, "Electricity generation and capacity in Canada", https://open.canada.ca/data/en/dataset/2cdf43fc-d4aa-4604-9f21-29777d955810

17 Government of Canada, 2023, "Net-Zero Emissions by 2050", https://www.canada.ca/en/services/environment/weather/climatechange/climate-plan/net-zero-emissions-2050.html

18 International Atomic Energy Agency, 2021, Fusion Device Information System - FusDIS (2021), https://nucleus.iaea.org/sites/fusionportal/Pages/FusDIS.aspx

19 National Academies of Sciences, Engineering, and Medicine, 2022, "Key goals and innovations needed for a U.S. Fusion Pilot Plant", https://www.nationalacademies.org/our-work/key-goals-and-innovations-needed-for-a-us-fusion-pilot-plant

20 ITER China, 2022, "ITER China", https://www.iterchina.cn/index.html

21 Y. Song, Nuclear Engineering International, 2019, "China's fusion roadmap", https://www.neimagazine.com/analysis/china-fusion-roadmap-7436879/

22 Futurism, 2022, "China Announces Plan for Hybrid Fission-Fusion Power Facility", https://futurism.com/china-nuclear-fission-fusion-power

23 Global Times, 2022, "Chinese-led team helps finish main engine installation of world's largest fusion reactor ITER", https://www.globaltimes.cn/page/202109/1234577.shtmll

24 Y. Wan, J. Li, Y. Liu, et al., 2017 "Overview of the present progress and activities on the CFETR"

25 EUROfusion, "The EUROfusion Programme", 2023, https://www.euro-fusion.org/programme/

26 The French Alternative Energies and Atomic Energy Commission (CEA), 2016, "Nuclear fusion for energy production", https://www.cea.fr/english/Pages/

research-areas/nuclear-energy/cea-research-on-nuclear-fusion-for-energy-production.aspx

27 The Max Planck Institute for Plasma Physics (IPP), 2023, “Fusion Research at IPP”, https://www.ipp.mpg.de/en

28 Centre for Energy, Environmental and Technological Research (CIEMAT), 2022, “National Fusion Laboratory”, http://www.fusion.ciemat.es/home/

29 ITER-India, 2023 “India’s contribution to ITER”, https://www.iterindia.in/indias-contribution-iter

30 Institute for Plasma Research - India, “R&D Activities”, 2023, http://www.ipr.res.in/ and at http://www.ipr.res.in/r_d_landing_page.html

31 The Integrated Innovation Strategy Promotion Council, 2023, “Fusion Energy Innovation Strategy”, https://www8.cao.go.jp/cstp/fusion/230426_strategy.pdf

32 Government of Japan Cabinet Office, 2023, “Moonshot Research and Development Program”, https://www8.cao.go.jp/cstp/english/moonshot/top.html

33 Korea Institute of Fusion Energy, 2022, "KSTAR Project", https://www.kfe.re.kr/menu.es?mid=a20202030100

34 National Research Council of Science & Technology, 2020, “Korean artificial sun sets the new world record of 20-sec-long operation at 100 million degrees”, https://phys.org/news/2020-12-korean-artificial-sun-world-sec-long.html

35 S. Kwon, K. Im, S. H. Hong, et al., 2020, Fusion Engineering and Design, “Recent progress in the design of the K-DEMO divertor”, https://www.osti.gov/servlets/purl/1811752

36 ITER, 2013, “Korea Aims at Completing a DEMO by 2037”, https://www.iter.org/newsline/255/1481

37 V.I., Ilgisonis, K.I., Ilyin, S.G., Novikov et al., 2021, “On the Program of Russian Research in the Field of Controlled Thermonuclear Fusion and Plasma Technologies”, Plasma Physics Reports, Volume 47, pp. 1085–1091, https://doi.org/10.1134/S1063780X21110179

38 R. Arnoux, ITER, 2010, “The Second Life of Tokamak T-15”, https://www.iter.org/newsline/152/477

39 Bashny.net, 2014, “Upgraded Russian Tokamak T-15 Launch in 2018”, https://bashny.net/t/en/295165

40 ITER, 2021, “T-15MD Comes On Line In Russia”, https://www.iter.org/newsline/-/3622

41 UK Department for Business, Energy & Industrial Strategy (BEIS) and UK Atomic Energy Authority (UKAEA), 2022, “Site of UK’s first fusion energy plant selected”, https://www.gov.uk/government/news/site-of-uks-first-fusion-energy-plant-selected

42 UKAEA, 2022, “Regulation decision to help ‘accelerate’ fusion energy progress”, https://www.gov.uk/government/news/regulation-decision-to-help-accelerate-fusion-energy-progress

43 The White House, 2022, “Fact Sheet: Developing a Bold Vision for Commercial Fusion Energy”, https://www.whitehouse.gov/ostp/news-updates/2022/03/15/fact-sheet-developing-a-bold-vision-for-commercial-fusion-energy/

44 U.S. Department of Energy, 2023, “DOE Announces $46 Million for Commercial Fusion Energy Development”, https://www.energy.gov/articles/doe-announces-46-million-commercial-fusion-energy-development

45 The Register, 2023, “US shovels cash into supercomputers hoping to stoke fusion future,” https://www.theregister.com/2023/08/15/us_shovels_more_cash_into/

46 Thomas, Lawrence Livermore National Laboratory’s (LLNL), 2022, “A shot for the ages: Fusion ignition breakthrough hailed as ‘one of the most impressive scientific feats of the 21st century’”, https://www.llnl.gov/news/shot-ages-fusion-ignition-breakthrough-hailed-one-most-impressive-scientific-feats-21st

47 Fusion Energy Sciences Advisory Committee, 2021, "Status of US ITER", https://science.osti.gov/-/media/fes/fesac/pdf/2021/McCarthy-Status-of-US-ITER.pdf

48 ITER, 2022, “What is ITER?”, https://www.iter.org/proj/inafewlines

49 ITER, 2020, “CANADA RETURNS TO THE TABLE”, https://www.iter.org/newsline/-/3503

50 International Energy Agency (IEA), 2023, “Energy Technology RD&D Budgets Data Explorer”, https://www.iea.org/data-and-statistics/data-tools/energy-technology-rdd-budgets-data-explorer

51 US Department of Energy, 2024, “FY 2025 Congressional Justification – Science”, https://www.energy.gov/sites/default/files/2024-03/doe-fy-2025-budget-vol-5.pdf

52 Department for Business, Energy and Industry Strategy, 2020 “Home sought for UK’s ground0breaking prototype fusion power plant”, https://www.gov.uk/government/news/home-sought-for-uks-ground-breaking-prototype-fusion-power-plant

53 Department for Business, Energy and Industry Strategy, 2022 “Government commits nearly half a billion pounds for UK research to cover EU shortfall”, https://www.gov.uk/government/news/government-commits-nearly-half-a-billion-pounds-for-uk-research-to-cover-eu-shortfall

54 Department for Energy Security and Net Zero, 2023, “Government announces up to £650 million for UK alternatives to Euratom R&T”, https://www.gov.uk/government/news/government-announces-up-to-650-million-for-uk-alternatives-to-euratom-rt

55 UK Department for Business, Energy and Industrial Strategy, UKAEA, and A. Bowie, 2023, “Thousands of

new training places created as part of £650 million fusion package", https://www.gov.uk/government/news/thousands-of-new-training-places-created-as-part-of-650-million-fusion-package

56 Euractive, 2023, "France unveils plan to up investments in nuclear fusion, natural hydrogen", https://www.euractiv.com/section/energy/news/france-unveils-plan-to-up-investments-in-nuclear-fusion-natural-hydrogen/

57 World Nuclear News, 2023, "Germany stepping up investment in fusion", https://www.world-nuclear-news.org/Articles/Germany-plans-massive-investment-in-fusion

58 Fusion Industry Association, 2024, "Germany Announces New Fusion Funding Program", https://www.fusionindustryassociation.org/german-government-announces-new-fusion-funding-program/

59 Fusion Industry Association (FIA), 2023, "The Global Fusion Industry in 2023", https://www.fusionindustryassociation.org/fusion-industry-reports/

60 B.P. Bromley, Canadian Nuclear Laboratories, 2021, "UNREDACTED: NRCan/CNL Technical Reference Document: Fusion Energy: Current State of Affairs in Canada and on the World Stage in 2021", CNL Report # 153-129000-REPT-003, Revision 0

61 C. Daughney, 1991, "The Canadian National Fusion Program", Journal of Fusion Energy, Vol. 10, No. 2

62 R. MacPhee, Fusion Canada – Bulletin of the National Fusion Program, 1987, ISSN 0835-488X, Issue # 1, July, https://www.cns-snc.ca/wp-content/uploads/2021/12/Fusion-Canada-1-1987.pdf

63 R. MacPhee, Fusion Canada – Bulletin of the National Fusion Program, 1997, ISSN 0835-488X, Issue #32, July, https://www.cns-snc.ca/wp-content/uploads/2021/12/Fusion-Canada-32-1997.pdf

64 W. Watson, J. Clemens, Fraser Institute, 2020, "THE BUDGET THAT CHANGED CANADA", https://www.fraserinstitute.org/sites/default/files/budget-that-changed-canada-execsum.pdf

65 Fusion Power Associates, 2004, "Canada Withdraws from ITER Negotiations", FPN04-03, http://qedfusion.org/FPA/ARC04/fpn04-03.shtml

66 B.P. Bromley, 2016, "Assessment of Alternative Fusion Reactor Concepts", Canadian Nuclear Laboratories, CNL Report 153-129200-REPT-004, Revision 0

67 B.P. Bromley (AECL/CNL), 2014, "Preliminary Studies of a Pressure-Tube Blanket Lattices with Thorium-Based Fuels for a Hybrid Fusion-Fission Reactor", Proceedings of the 21st Topical Meeting on the Technology of Fusion Energy, TOFE 2014, Anaheim, CA, U.S.A.

68 UK Department for Energy Security & Net Zero (DESNZ), 2024, "UK-Canada cooperation on fusion energy: memorandum of understanding", https://www.gov.uk/government/publications/uk-canada-cooperation-on-fusion-energy-memorandum-of-understanding/uk-canada-cooperation-on-fusion-energy-memorandum-of-understanding

69 B.P. Bromley, 2020, "CNL Contributions to Comprehensive Reference Document to Support Joint NRCan/CNL White Paper: Fusion Energy: Current State of Affairs in Canada and on the World Stage on Fusion Energy", Canadian Nuclear Laboratories, CNL Report 153-129000-REPT-002, Revision 0

70 Canadian Nuclear Safety Commission, 2023, "Research report summaries 2021-2022", https://nuclearsafety.gc.ca/eng/resources/research/research-and-support-program/research-report-abstracts/research-report-summaries-2021-2022.cfm#RSP-762-1

71 TRIUMF, 2023, "FAQ About TRIUMF", https://www.triumf.ca/home/about-triumf/about-us/faq-about-triumf

72 Government of Canada, 2020, "Agreement between the Government of Canada and the ITER International Fusion Energy Organization for Cooperation in the Peaceful Uses of Fusion Energy", https://www.treaty-accord.gc.ca/text-texte.aspx?lcid=1036&id=105606&t=637587081129001642

73 M.Y. Hua, S.S Desai, A.C. Roma, et al., 2022, "Nonproliferation and fusion power plants", ResearchSquare Preprint, Under Revision with Journal of Fusion Energy, https://www.researchsquare.com/article/rs-1732661/v1

74 UKAEA, 2020, "Government Investment in Fusion Energy Boosts British Economy by £1.4 billion", https://www.gov.uk/government/news/government-investment-in-fusion-energy-boosts-british-economy-by-14-billion

75 Federal Ministry of Education and Research, 2023, "Positionspapier Fusionsforschung", https://www.bmbf.de/SharedDocs/Publikationen/de/bmbf/7/775804_Positionspapier_Fusionsforschung.pdf?__blob=publicationFile&v=2

76 Tony Blair Institute for Global Change, 2022, "Gaining More Bang for Fusion's Buck with Pivot-support Programs", https://www.institute.global/insights/tech-and-digitalisation/gaining-more-bang-fusions-buck-pivot-support-programmes

77 W.R. Meier, 2014, Tritium Breeding Blanket for a Commercial Fusion Power Plant – A System Engineering Assessment", Lawrence Livermore National Laboratories, LLNL-TR-652984, https://www.osti.gov/servlets/purl/1305833

78 T, Giegerich, K. Battes, J.C. Schwenzer, et al., 2019, "Development of a Viable Route for Lithium-6 Supply of DEMO and Future Fusion Power Plants", Fusion Engineering and Design, Vol 149

79 D. Clery, 2022, "Out of Gas: A shortage of tritium fuel may leave fusion energy with an empty tank", Science, https://www.science.org/content/article/fusion-power-may-run-fuel-even-gets-started