

STANDARDS RESEARCH

Hydrogen Production using Nuclear Energy

March 2024

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Acknowledgment

This research report is made possible by a financial contribution from Natural Resources Canada.

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Executive Summary

As recognized in the Hydrogen Strategy for Canada, hydrogen may be expected to play an important role in Canada's future energy mix. Across Canada and around the world, a number of projects are currently underway to establish hydrogen production from clean energy sources as a means to achieve climate objectives.

The goal of this research report is to help identify gaps and needs for standards-based solutions related to the production of hydrogen using nuclear energy, particularly the interface between nuclear power plants (NPPs) and hydrogen facilities. The report provides an overview of hydrogen production technologies and their compatibility with nuclear reactor technologies that are currently in operation or proposed for deployment in Canada. It also reviews policies, regulations, and standards currently available to establish the framework for hydrogen production at nuclear facilities.

The research conducted for this report included a review of scientific literature, technical studies, governmental agency reports, and relevant codes and standards. In addition, select relevant parties and specialists were interviewed to help identify areas where modified or new standards could support the development of hydrogen production from nuclear energy.

To manage the complexity of the study, a subset of potentially available nuclear reactor technologies was considered, including CANDU NPPs currently operating in Canada and a range of small modular reactors that are in an advanced stage of development and licensing in Canada. This report describes various plausible combinations of hydrogen production facilities and NPPs for the production of hydrogen.

The findings suggest that a number of CSA standards could be further assessed for potential updating to address aspects related to the production of hydrogen using nuclear energy, particularly for topics related to safety analysis. In addition, new standards might be considered to further address the areas of interfacing of NPPs and hydrogen production facilities, and the siting of hydrogen production and storage facilities with respect to NPPs.



"With a strong and well-established nuclear sector, and with the anticipated deployment of new small modular reactor designs, Canada appears to be well positioned to produce clean hydrogen using nuclear power as an energy source."

1 Introduction

Hydrogen may be expected to play an important role in Canada's future energy mix, as recognized in the Hydrogen Strategy for Canada [1], which was released in 2020. Across Canada and around the world, projects for hydrogen production from clean energy sources are currently underway as a means to facilitate energy storage and transport while respecting climate objectives. These projects aim to reduce dependency on fossil fuels and demonstrate how the challenges for storage and transport of alternative energy sources can be addressed. For example, a project in Bruce County, Ontario might provide insight on the use of low-temperature electrolyzers for the production of hydrogen from nuclear power, as well as information on existing guidelines and standards [2].

With a strong and well-established nuclear sector, and with the anticipated deployment of new small modular reactor designs, Canada appears to be well positioned to produce clean hydrogen using nuclear power as an energy source.

An assessment of standards applicable to nuclear energy and hydrogen production can help determine whether further standardization is required to address the interface between these technologies and to support the implementation of technological solutions, thereby helping to provide guidance for more efficient hydrogen production while helping ensure continued safety for the protection of people, property, and the environment.

The objective of this research report is to help identify gaps and needs for standardization related to the production of hydrogen using nuclear energy, particularly the interface between nuclear power plants (NPPs) and hydrogen production facilities. This report provides an overview of current and emerging scenarios for integrating hydrogen production with nuclear facilities. It also reviews relevant existing standards for nuclear facilities and for hydrogen production, and identifies gaps and needs for scenarios where hydrogen is produced using nuclear energy.

This report focuses on the technical and safety aspects of hydrogen production from NPPs and is based on a representative set of scenarios that consider a matrix of nuclear generation alternatives and appropriate hydrogen production technologies.

2 Methodology

The research conducted for this report included a review of recent scientific literature, technical studies, governmental technical agency reports, and relevant codes and standards. To gain insight on the latest developments and challenges faced by industry, the literature review was augmented by interviews with select relevant parties and specialists currently working in this area.

The literature search was based primarily on online and university library searches using key search terms related to hydrogen, hydrogen production, and

nuclear power and hydrogen. The literature review encompassed publicly available information on the potential of hydrogen production using energy from existing NPPs in Canada, as well as from a range of small modular reactor designs that are going through the Canadian regulatory (licensing) process at the time of writing this report. The review considered technologies that are expected to be technically and commercially viable in the near future, as well as emerging methods that are still in the research and development stages. Relevant European Union and other global guidelines and criteria for hydrogen from nuclear power were also examined. The reviewed information was then used to create a representative range of scenarios for the production of hydrogen from NPPs, which was mapped in a matrix to identify applicable hydrogen production options for each category of NPP.

The literature review and the matrix of hydrogen production with nuclear power formed the basis for interviews with parties to determine whether there is a need to develop new or update existing standards and guidelines that might support the integration of hydrogen production facilities with NPPs. The interviews were conducted to obtain input on the latest, dynamic, and fast-changing considerations facing hydrogen production at nuclear facilities.

Several representatives were contacted from each of the key relevant parties including potential and current operators of nuclear or hydrogen facilities, power utility representatives, regulators, industry associations, and university researchers. While emphasis remained on Canada and North America, international representatives were also interviewed to gain a broader perspective, especially on advanced European Union hydrogen projects.

Interviews were conducted via phone calls and video meetings. The outreach was tailored to the backgrounds of participants, but generally focused on gathering information to conduct the following:

- An analysis of policy and regulatory issues to identify potential gaps that could be addressed by standards-based solutions, such as areas where harmonization of potentially overlapping regulatory jurisdictions or clarified operational boundaries of facilities might advance the development of hydrogen production using nuclear energy.
- An analysis of existing standards, guidelines, and practices to identify gaps and potential needs for harmonization of requirements or to clarify interfaces between different standards. Standards used for Canadian facilities were the primary focus.

The high level analysis of the obtained information was performed with a goal to:

- Identify and prioritize standardization needs considering factors such as technology readiness level (TRL), regulatory and industry initiatives, implementation timelines, and the potential significance of identified gaps; and
- Recommend considerations for potential standardization approaches to address the identified gaps, opportunities for harmonization, and opportunities for collaboration, as they relate to existing standards and practices, including international standards and standards from other jurisdictions.

3 Results

3.1 Methods of Producing Hydrogen

3.1.1 Hydrogen Use

Historically, hydrogen has primarily been used in ammonia production, oil refining, and methanol production [3], [4]. The demand for hydrogen has increased steadily over time, with a sharp increase since 2000. It is expected that the demand for hydrogen will increase even more rapidly in the near future [5], as the global demand for energy obtained from primary energy sources increases to between 600 and 1000 EJ (10^{18} J) by 2050 [3], [6]. Because fossil fuels currently dominate the global primary energy demand and there is pressure to decarbonize the transportation and energy sectors, hydrogen is expected to play a critical role during the energy transition to net zero emissions and the fulfillment of increased energy demand.

3.1.2 Hydrogen Production

A variety of raw materials can be used as a feedstock for hydrogen production through conversion by heat, typically via steam reforming of a hydrocarbon. Low molecular weight hydrocarbons (e.g., natural gas composed mainly of methane) are the primary feedstock for hydrogen production, although other hydrocarbon fuels (e.g., biomass and coal) are also used. It is estimated that approximately 96% of hydrogen produced worldwide is obtained from hydrocarbons: 30% from naphtha reforming, 48% from steam reforming of natural gas, and 18% from coal gasification [3], [7].

Hydrogen produced from hydrocarbons has the highest carbon emissions intensity [8]. Coupling carbon capture and storage technologies to the process can reduce carbon intensity. However, hydrogen production through electrolysis of water using non-emitting sources of electricity, such as wind and solar, or nuclear energy, has zero carbon intensity [1]. Hydrogen produced using nuclear energy is broadly accepted as supportive of decarbonization and sustainable development efforts [9].

A colour coding classification system for hydrogen has been commonly used to identify the source and process of hydrogen production [10]. However, a CSA Group report found that the colour coding system may not present a comprehensive measure of the carbon intensity associated with hydrogen production, and other means of classifying hydrogen production are under development globally [11]. Going forward, hydrogen classification is expected to adopt an approach that is based on carbon intensity to better communicate the relative impacts of different hydrogen production methods [11].

3.1.3 Hydrogen Production Using Nuclear Energy

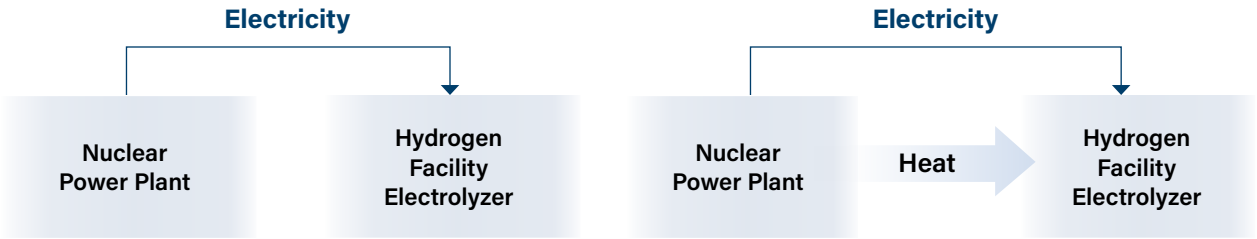
Historically, the primary application of nuclear energy has been electricity production. As the landscape in the energy sector evolves, nuclear energy is already being used in hydrogen production processes, and small modular reactors are being considered for off-grid applications and for co-generation (electricity and heat) applications, such as for industrial sites and chemical facilities [1].

The energy market for hydrogen is growing rapidly and may exceed the capacity of electricity generation facilities. If the push for decarbonization and zero emission sectors limits the consumption of fossil fuels, hydrogen and hydrogen-derived fuels are poised to be a first choice to replace fossil fuels [12], [13]. This suggests that hydrogen production from nuclear energy could make up a large portion of future nuclear energy use [14].

In general, hydrogen production uses electricity or thermal energy. NPPs are increasingly being considered for both sources of energy, as shown in Figure 1, for the following key reasons [15]:

- Nuclear energy has much lower life-cycle carbon intensity compared with conventional fossil fuels; and
- Nuclear energy is adaptable to large-scale production.

Figure 1. Example connections between nuclear power plants and electrolyzers for hydrogen production.



The use of electricity from a nuclear reactor is a well-established practice for water electrolysis production of hydrogen. While feasible, nuclear thermal energy is still not widely adopted in thermal hydrogen production processes, such as steam reforming or pyrolysis, or high-temperature electrolysis [3]. High-temperature gas reactors and molten salt reactors are capable of providing both electricity and high-temperature heat (over 600 °C) that could be used in high-temperature hydrogen production technologies. Pressurized heavy water reactors and boiling water reactors without heat recuperation can only supply thermal energy up to 340 °C [16], [17], which is not sufficiently hot for high-temperature hydrogen production technologies using heat from NPPs. However, one interviewee stated that steam temperature as low as 150 °C has been used for high-temperature electrolysis by taking advantage of heat recuperation. At the high voltage and power, high-temperature electrolysis can sustain its operating temperature (i.e., 600–900 °C) exothermally, allowing the input streams to be provided at much lower temperatures. This operation can allow steam at 150 to 200 °C to be the input stream to the high-temperature steam electrolysis plant, which enables coupling with currently operating nuclear reactors [18].

Examples of hydrogen production processes that can use nuclear energy include the following:

- Low-temperature water electrolysis:
  - Alkaline water electrolysis (AWE)
  - Proton exchange membrane (PEM) water electrolysis
  - Anion exchange membrane (AEM) water electrolysis
- High-temperature solid oxide electrolysis
- Photolysis of water
- Thermolysis of water
- Thermochemical water splitting
- Steam reforming of hydrocarbons
- Partial oxidation of hydrocarbons
- Autothermal reforming of hydrocarbons
- Pyrolysis of hydrocarbons
- Coal and biomass gasification
- Plasma arc decomposition of hydrocarbons

Albeit at different TRLs, these technologies are advancing rapidly, and their associated TRLs are therefore dynamic. As such, the TRLs discussed in Sections 3.3.3.1 through 3.1.3.11 are based on the Government of Canada's TRL assessment tool [19], and should be considered provisional.

Low-Temperature Water Electrolysis

Water electrolysis is a method of hydrogen production that involves the dissociation of water molecules to oxygen and hydrogen using direct current passing through an electrolyte [3], [15], [20], [21], [22], as shown in Equation 1.

Equation 1

$$H_2O \rightarrow H_2 + 1/2O_2$$

Various technologies can be used for water electrolysis, including alkaline water electrolysis (AWE, proton exchange membranes (PEMs) electrolysis, and anion exchange membranes (AEMs) electrolysis, which are described in Sections 3.1.3.1.1 through 3.1.3.1.3. These three technologies operate with the same principle, but use different processes under different conditions [3], [23]. The main difference between an AWE and an AEM electrolyzer is the replacement of the anion exchange membrane with a conventional diaphragm, which reduces the gas crossover and the need for pressure difference operation between the anode and cathode [24]. The key distinction between an AWE and a PEM is the type of ion that diffuses between the anode and cathode sides of the cell. In an AWE, alkaline OH^- ions diffuse, while in a PEM, protons (H+ ions) are the ones that diffuse. While PEM cells have membranes that conduct protons in an acidic environment, AEM cells conduct hydroxide ions in an alkaline environment [25].

Low-temperature electrolysis is at an intermediate to advanced stage of development (TRL 7–9), with commercially available systems in operation. Commercial adoption is progressing as the technology matures, and various industries are exploring these systems for hydrogen production. Technology suppliers are continuously working to develop larger capacity equipment for potential future deployment to reduce capital and production costs [26]. The production capacity of AWE industrial electrolysers ranges between 5 and 670 $m^3 H_2/h$ [27].



Alkaline Water Electrolysis

The AWE process uses an alkaline solution, such as potassium or sodium hydroxide, as an electrolyte and non-platinum electrodes, such as nickel and iron. A diaphragm membrane is used to separate the products, provide electrical insulation between electrodes, and conduct ions [3], [15]. AWE is seen as a technology that is reliable for hydrogen production up to the megawatt scale [28], [29]. AWE is also a mature, well-established technology [30] that is widely used in various industrial applications [1].

Proton Exchange Membrane Water Electrolysis

In the PEM electrolysis process, water is decomposed into hydrogen proton, electron, and oxygen at the anode [3]. The proton then moves to the cathode through the PEM, where recombination with an electron occurs to form hydrogen [31]. Iridium in the anode accounts for much of the platinum group metal content, but platinum is also present in the cathode. The TRL for PEM electrolysis is between 7 and 8 [1], [30].

Anion Exchange Membrane Water Electrolysis

The AEM electrolysis process integrates the advantages of AWE and PEM electrolysis [3]. It consists of an AEM that is hydrocarbon-based and uses two transition metals (e.g., platinum or iridium) as catalyst-based electrodes [32]. Water is passed through the cathode side of the electrolyzer, which produces hydrogen and hydroxyl ion. The hydroxyl ions pass through the AEM to reach the anode, where they lose an electron to form oxygen and water. The TRL for AEM electrolysis is 7 [33].

High-Temperature Solid Oxide Water Electrolysis

High-temperature solid oxide water electrolysis uses both thermal energy and electrical current to split water or steam at temperatures that range from 600 to 1000 °C in solid oxide electrolysis cells [3], [15], [34], [35]. This high-temperature electrolysis process has both thermodynamic and kinetic advantages over low-temperature PEM and alkaline electrolysis processes with higher efficiency [34], [35], [36]. It should be noted that this process is different from self-sustainable protonic ceramic electrochemical cells, which is a newer technology using a triple conducting electrode for hydrogen and power production [37] that was not considered in this report.

The solid oxide electrolysis cell is a solid-state electrochemical device consisting of an oxygen-ion conducting electrolyte (e.g., yttria- or scandia-stabilized zirconia) with porous electrodes deposited on either side of the electrolyte [36]. Steam is supplied to the cathode, and then water is reduced to yield hydrogen [3], as shown in Equation 2.

Equation 2

$$H_2O(g) + 2e^- \rightarrow H_2(g) + O^{2-}$$

The oxide anions produced at the cathode go through the solid electrolyte to the anode, and then they recombine to form oxygen and close the circuit with the electrons released [3], as shown in Equation 3.

Equation 3

$O^{2-} \rightarrow ½\ O_2\ (g) + 2e^-$

Unlike the PEM and alkaline electrolysis processes, in high-temperature solid oxide water electrolysis, the electrochemical reactions at the electrodes occur in vapour phase. This makes it challenging to maximize the interfacial contact area between the gaseous chemical species and the electrodes. This technology is in the research and development stage [30]. The Idaho National Laboratory assessed the feasibility of using solid oxide based electrolysis cell technology for high-temperature electrolysis of steam for large-scale hydrogen production and concluded that the technology has the potential for large-scale commercial applications [38], [39]. Given that high-temperature solid oxide water electrolysis is still under development, its TRL is between 4 and 6 [40].

Photolysis of Water

The dissociation of the H-O bond in water molecules can be achieved by exposing water to high energy, 190-nm UV photons at an energy consumption of about 285.57 kJ/mole of water [3]. This process is called photolysis [41]. The energy required for UV radiation can be produced by an NPP. The photolysis process needs chemical catalysts such as zirconium dioxide (ZrO_2), tin oxide (SnO), zinc oxide (ZnO), and other semiconductor sulfur oxides [42].

While photolysis of water is in the early research and development stage, ongoing research and advancements continue to shape the potential for solar water splitting technologies to contribute to hydrogen production. The TRL for photolysis of water is between 1 and 3 [3].

Thermolysis of Water

Equation 4 shows the chemical reaction for the thermal dissociation of water [3], [15], [20].

Equation 4

$H_2O + \text{heat} \rightarrow H_2 + ½\ O_2$

When water is heated above 2000 °C, it starts to decompose without the need for a catalyst. The higher the temperature, the higher the level of dissociation. For example, the level of dissociation is 64% at 2727 °C and 0.1 MPa [43]. Operation of thermolysis reactors at this temperature is technically and financially challenging due to the extremely high temperature, so different catalytic processes have been proposed to lower the thermolysis temperature. For example, Kasai and Bishop [44] proposed zeolite catalysis to lower the thermolysis temperature to 400 °C [45], and Hsu proposed the use of a nickel plate reactor (10% aluminum and 90% nickel), which functions as a catalytic surface to lower the thermolysis temperature to below 400 °C [42].

The readiness level of thermolysis of water varies among the different methods, and research is ongoing to address challenges and explore opportunities for practical applications. While some technologies are in the early stages of development, others have progressed to more advanced stages. Overall, the TRL for high-temperature water thermolysis ranges between 2 and 5 [15].

Thermochemical Water Splitting

In thermochemical water splitting, endothermic chemical reactions are used to split water into hydrogen and oxygen [22], [34], [46]. A total of 115 thermochemical water splitting cycles have been identified [47], [48], [49], [50], [51], [52], including copper–chlorine [34], [53], zinc–zinc oxide, nickel–manganese ferrite, magnesium–chloride, hybrid S, calcium–barium [53], hybrid–sulphuric acid [54], vanadium–chlorine [55], and the sulphur–iodine [30], [47], [53], [54], [55]. Of these, the copper–chlorine (Cu–Cl) cycle is an attractive process for hydrogen production due to its relatively low temperature (below 530 °C) [34].

Cu–Cl thermochemical cycles involve a series of chemical reactions that include between two and five



steps [34], [46]. The three main Cu–Cl cycles consist of three-, four-, and five-step processes, respectively [34]. The five-step cycle consists of the following steps:

1. HCl (g) production
2. O_2 production
3. Cu production
4. Drying
5. H_2 production

The four-step Cu–Cl cycle combines steps 3 and 4, whereas the three-step cycle combines steps 3, 4, and 5 [34]. The chemical reactions involved in each of the five steps are shown in equations 5 through 9.

Equation 5

$2\ CuCl_2\ (s) + H_2O\ (g) \rightarrow Cu_2OCl_2\ (s) + 2\ HCl\ (g)$

Equation 6

$Cu_2OCl_2\ (s) \rightarrow 2CuCl\ (l) + ½\ O_2$

Equation 7

$4\ CuCl\ (aq) \rightarrow 2\ CuCl2\ (aq) + 2\ Cu\ (s)$

Equation 8

$2\ CuCl_2\ (aq) \rightarrow 2\ CuCl_2\ (s)$

Equation 9

$2\ Cu\ (s) + 2\ HCl\ (g) \rightarrow 2\ CuCl_2\ (l) + H_2\ (g)$

Similar to thermolysis of water, the readiness level of thermochemical water splitting varies among the different methods. This technology has garnered more attention than thermolysis and photolysis of water, primarily due to the inclusion of chemical reactions and the potential for lower temperature operation.

Consequently, thermochemical water splitting technologies generally exhibit a higher TRL. Overall, the TRL for thermochemical water splitting ranges between 3 and 7.

Steam Reforming of Hydrocarbons

The steam reforming of hydrocarbons or biomass yields hydrogen-rich gases and hydrogen [3] through intermediate production of synthesis gas, which is a mixture of mainly H_2 and CO [56]. Generally, lower hydrocarbons, and natural gas in particular, are used as the feedstock, but heavier hydrocarbons up to naphtha can be reformed as well.

Steam reforming of low molecular weight hydrocarbons (e.g., methane) is a thermochemical reaction that is currently the most common and least expensive method of producing hydrogen [21], [22], [30], [34]. Steam methane reforming involves the following three steps.

1. High-temperature catalytic reforming of methane, which produces a syngas. Nickel catalyst is generally used for the reforming reaction, as shown in Equation 10.

Equation 10

$C_nH_m + nH_2O \rightarrow nCO + (n+ m)\ H_2$

2. More hydrogen is produced through the water–gas shift reaction, as shown in Equation 11, which takes place at high and low temperature phases.

Equation 11

$CO + H_2O \rightarrow CO_2 + H_2$

3. Purification of hydrogen using a pressure swing adsorption unit [57].

Steam methane reforming is an endothermic (heat absorbing) catalytic process performed in the temperature range of 700 to 900 °C, at a pressure up to 3.5 MPa [41]. Developments in catalysis technology, including nickel-based, noble metal-based, and bimetallic catalysts, have made it possible to perform methane steam reforming at a low reaction temperature (550 °C) [58].

One disadvantage of steam reforming processes is that the production of hydrogen is accompanied by the emission of large quantities of CO_2 into the atmosphere because it uses fossil fuels in both the manufacturing process and as the heat source [41]. However, if the steam reforming process is combined with carbon capture and storage technology, carbon emissions can be significantly reduced. Steam reforming is a well-established, commercialized process, and the technology is widely used in various industrial applications [31], [43], [59].

Partial Oxidation

The partial oxidation of low molecular weight hydrocarbons is another thermochemical process used for hydrogen production [30] [21]. It produces syngas through the reaction shown in Equation 12.

Equation 12

$$C_nH_m + n/2\ O_2 \rightarrow nCO + m/2\ H_2$$

In partial oxidation, the syngas is sent to the water–gas shift reactor, and then hydrogen is purified using a suitable method, such as pressure swing adsorption. Compared with the steam reforming process, the efficiency of the partial oxidation process is low, and the operating cost is high because it requires large quantities of pure oxygen [30]. As such, this commercialized process is not widely used for hydrogen production.

Autothermal Reforming

Autothermal reforming is a combination of steam reforming and partial oxidation of low molecular weight hydrocarbons [21], [30], [60]. The autothermal reforming process, when combined with water–gas shift and carbon capture technology, is one of the most cost-effective solutions to produce low-carbon hydrogen at scale [21]. Autothermal reforming is generally performed in the temperature range of 950 to 1050 °C, at a pressure of 3.0 to 5.0 MPa [43], [61]. The autothermal reforming process is also commercialized [30], [31].

Pyrolysis of Hydrocarbons

The pyrolysis or co-pyrolysis process yields carbon black (solid carbon) as a by-product of hydrogen production instead of carbon monoxide and carbon dioxide, which means it does not contribute to greenhouse gas emissions [3], [30], [21]. In this process, decomposition of hydrocarbons occurs in the temperature range of 500 to 900 °C, at a pressure of 0.1 to 0.5 MPa [21], [62] in the absence of air and oxygen. The reaction for this process is shown in Equation 13 [21].

Equation 13

$$C_nH_m + \text{heat} \rightarrow nC + 0.5mH_2$$

Pyrolysis can be grouped into high (over 800 °C), medium (500–800 °C), and low temperatures (up to 500 °C).

Although pyrolysis technologies have reached commercial adoption in various industries, particularly in the treatment of biomass and organic waste, the TRL for pyrolysis of hydrocarbons ranges between 5 and 7, and efforts to optimize the technology are ongoing.[63]. As such, the adoption of hydrocarbon pyrolysis for hydrogen production is likely to increase as technologies mature.

Biomass and Coal Gasification

Gasification is a high-temperature partial oxidation process where coal or biomass is transformed into a gaseous mixture using gasifying agents [3], [30], [21]. Biomass gasification's performance is affected by at least 20 operational parameters pertaining to the feedstock and gasifier, which include the gasifier's geometrical configuration, flow rate, type of gasifying agent, reaction time, pressure and temperature of the gasification, and the gasifying agent to biomass ratios

[64], [65]. The product distribution and the composition of gas depends on several factors, including the reactor type and the temperature of the gasification.

Biomass gasification normally occurs within a temperature range between 700 and 1200 °C, using oxygen, air, steam, or their combination as a gasifying agent. Steam enhances the formation of H_2 and produces a high heating value gas without nitrogen.

The readiness level of biomass gasification technologies vary among the different methods. Some biomass gasification technologies are at TRLs between 4 and 7, where prototypes and pilot-scale implementations have proven functionality and performance [66]. Although there are challenges in terms of scale-up, efficiency, and cost-effectiveness, especially for large-scale commercial applications, ongoing research and development are working to address these challenges and elevate the TRL of advanced biomass gasification technologies 66].

Coal gasification technologies have a more established history and higher TRLs compared to biomass gasification. Some coal gasification technologies have been deployed at commercial scale.

Plasma Arc Decomposition of Hydrocarbons

Plasma is an ionized state of matter comprising atomic species and electrons in an excited state at the same thermodynamic temperature of >2000 °C [21]. Because of the existence of electrically charged particles, plasma can be used as medium for high voltage electric current discharge [15], [30]. Under the action of thermal plasma, natural gas can be decomposed to hydrogen and carbon black, which can be collected at the bottom of the vessel while the hydrogen remains in the gas phase [15], [30].

Plasma arc decomposition of hydrocarbons is at the experimental and technology development stage, with ongoing efforts to improve efficiency, address challenges, and explore practical applications [15]. The TRL for plasma arc decomposition of hydrocarbons ranges between 4 and 5.

3.2 Scenarios for Hydrogen Production from Nuclear Power

In broad terms, there are two modes of nuclear power that can be used for hydrogen production:

1. Use of surplus (off-peak) electricity, or electricity from a dedicated nuclear facility, for water electrolysis; and
2. Use of heat and steam from a NPP for any thermal treatment.

At the time of writing, the Canadian nuclear power industry includes 19 operating CANDU reactors and several advanced small modular reactors that are under regulatory review. Nuclear reactor types that may be considered representative in Canada include:

- Pressurized heavy water reactors (e.g., CANDU 6);
- Boiling water reactors (e.g., GE Hitachi BWRX-300);
- High-temperature gas reactors and modular helium reactors (e.g., X-energy Xe-100, Ultra Safe Nuclear Corporation MMR);
- Liquid metal cooled reactor (e.g., ARC-100);
- Molten salt reactors (e.g., Terrestrial IMSR400, Moltex SSR-W); and
- Heat pipe reactors (e.g., Westinghouse eVinci).

Table 1 provides a summary of the key considerations for hydrogen production paired to the NPPs considered in this study. All reactor types listed in the table can provide electricity or thermal energy to hydrogen production facilities, but the technical viability and feasibility of using high temperature and steam to support the production of hydrogen varies by reactor type.

It should be noted that the compatibility of nuclear reactors with hydrogen production technologies shown in Table 1 is based on the literature and has not been validated with nuclear reactor or hydrogen production technology vendors.

Table 1. Hydrogen Production Technology Mapped to Compatible Nuclear Power Technology

Nuclear Power Technology	Pressurized Heavy Water Reactor	Boiling Water Reactor	Liquid Metal Cooled Reactor	High-Temperature Gas Reactor	High-Temperature Gas Reactor	Molten Salt Reactor	Molten Salt Reactor	Heat Pipe Reactor
Hydrogen Production Technology and Operating Requirements								
Low-Temperature Water Electrolysis *DC current:* Yes *Process operating temperature:* 60–70 °C *Steam requirements:* No	x	x	x	x	x	x	x	x
High-Temperature Water Electrolysis *DC current:* Yes *Process operating temperature:* 600–980 °C *Steam requirements:* No	x		x	x	x	x	x	x
Photolysis of Water *DC current:* No *Process operating temperature:* >2300 °C *Steam requirements:* Yes	x	x	x	x	x	x	x	x
Thermochemical Water Decomposition *DC current:* No *Process operating temperature:* 500–900 °C *Steam requirements:* No			x	x	x	x	x	
Steam Reforming DC *current:* No *Process operating temperature:* 800–1100 °C *Steam requirements:* Yes			x	x		x	x	
Partial Oxidation *DC current:* No *Process operating temperature:* 590 °C *Steam requirements:* Yes			x	x		x	x	
Autothermal Reforming *DC current:* No *Process operating temperature:* 800–1050 °C *Steam requirements:* Yes			x	x		x	x	
Pyrolysis *DC current:* No *Process operating temperature:* 500–800 °C *Steam requirements:* Yes			x	x	x	x	x	x
Biomass Gasification *DC current:* No *Process operating temperature:* 700–1800 °C *Steam requirements:* No			x	x	x	x	x	x
Plasma Arc Decomposition DC *current:* No *Process operating temperature:* >2,000 °C *Steam requirements:* No	x	x	x	x	x	x	x	x

3.2.1 Proposed Scenarios for Hydrogen Production from Nuclear Power

There are several existing and proposed hydrogen production facilities using nuclear energy, both in Canada and internationally, including the following projects and feasibility studies:

- The province of Ontario is investing in a feasibility study on integrating hydrogen systems with NPPs, including hydrogen production using high-temperature water electrolysis [67], [68], [69].
- A proposed Green Energy Hub at the Port of Belledune in New Brunswick plans to include an ARC-100 reactor to provide energy for hydrogen production and other applications [70].
- The US Department of Energy (DOE) is funding several pilot projects at the Idaho National Laboratory, including two that will demonstrate hydrogen production using low- and high-temperature electrolysis powered by NPPs [71].
- In the UK, the new Sizewell C nuclear power station plans to commit 200 MWth per unit (400 MWth total) to the production of hydrogen and powering a Direct Air Capture system. Hydrogen production processes are being explored and are likely to involve the use of electrolysis combined with heat. The station has an approved design for extracting heat to support the hydrogen production facility [72].
- Shell Global Solutions has signed an agreement with NuScale Power to assess the feasibility of putting hydrogen production systems at small NPPs. The two companies plan to develop an integrated energy system that would produce hydrogen using electricity and waste heat from a NuScale VOYGR small modular reactor. Hydrogen would be used or stored as excess energy that could be used to balance the grid [73].
- The US DOE has announced funding for seven Regional Clean Hydrogen Hubs (H2Hubs), two of which will be powered in part by nuclear energy [74].
- The US DOE is sponsoring collaboration among the Idaho National Laboratory, the Argonne National Laboratory, the National Renewable Energy Laboratory, Exelon, and Fuel Cell Energy. The project will evaluate the potential of using existing NPPs to produce hydrogen via high-temperature steam electrolysis in parallel with grid electricity [75].

3.3 Existing Policies and Regulations

The regulatory and licensing requirements for a stand-alone hydrogen facility are typical of an industrial facility. While the requirements vary across provinces, they generally fall into similar categories and would be applicable to a hydrogen facility using nuclear energy that is located outside the area of an NPP.
The following noncomprehensive list summarizes the types of potential permits, registrations, or l icences that would be applicable for such a hydrogen production facility:

- Air emissions
- Wastewater discharge
- Subject and hazardous waste
- Site redevelopment
- Zoning amendments
- Dangerous goods
- Emergency plans
- Building permits and electrical connections

Where a hydrogen facility is integrated into a regulated nuclear site, Canada's federal nuclear regulator, the Canadian Nuclear Safety Commission (CNSC), would apply federal legislation. Under the Nuclear Safety and Control Act [76], two key regulations are applicable to NPPs in the context of hydrogen production:

- Class I Nuclear Facilities Regulations [77]; and
- Radiation Protection Regulations [78].

Requirements for existing nuclear facilities are generally consolidated with site operating licences and the licence conditions handbook for individual stations. Modifications to a nuclear site, such as the addition of a hydrogen production facility, could be considered in light of typical site licence requirements.

The following CNSC regulatory documents could be applicable to newly constructed NPPs, including small modular reactors, that are integrated with hydrogen production:

- *Site Evaluation and Site Preparation for New Reactor Facilities*, REGDOC-1.1.1 [79];
- *Licence Application Guide: Licence to Operate a Nuclear Power Plant*, REGDOC-1.1.3 [80];
- *Supplemental Information for Small Modular Reactor Proponents*, REGDOC-1.1.5 [81]; and
- *Design of Reactor Facilities*, REGDOC-2.5.2 [82].

It is anticipated that an on-site hydrogen production facility could be evaluated and regulated by the CNSC, while an off-site hydrogen production facility could be seen as an external hazard to be considered in safety analysis.

3.4 Existing Standards and Industry Practices

Codes and standards governing hydrogen systems may be classified under two categories:

1. ***General codes and standards.*** These documents could be applicable to all structures in a hydrogen production facility, such as building construction, fire protection, electrical installations, pressure vessels, and piping.
2. ***Hydrogen production-specific codes and standards.*** These documents could be applicable to any activities related to hydrogen production and storage and their equipment and components, such as hydrogen piping and vent installation, electrolyzer design and performance, and hydrogen handling.

For NPPs, the CNSC references standards within the regulatory framework and in licensing requirements. This includes various CSA standards relevant to the operation of NPPs, safety systems, quality management, and environmental management. These CSA standards provide requirements and guidance that should be considered when evaluating an existing or proposed NPP in conjunction with a hydrogen production facility, as detailed in Section 4.1.

3.5 Technical Considerations for Hydrogen Production at Nuclear Power Plants

The integration of a hydrogen production facility with an NPP poses potential hazards and consequent risks to people, site infrastructure, and safety of both the NPP and the hydrogen production facility. Many factors can contribute to these hazards and risks, including the specifics of the hydrogen production facility, such as method and rate of hydrogen production (e.g., electrolysis or thermal process); hydrogen storage requirements; and characteristics of the NPP and supporting infrastructure, including switchyards, used fuel dry storage areas, and evacuation routes. The interviews with relevant parties revealed several key integration issues, which are analyzed and discussed in Sections 3.5.1 and 3.5.2. Several of the issues have common, overlapping themes. The two main themes that can be addressed through standardization are:

1. ***Siting of hydrogen production and storage facilities with respect to NPPs.*** This includes topics such as implications for NPP safety analysis; emergency planning; hydrogen storage location; safe distance to structures, systems, and components (SSCs); and other mitigation measures.
2. ***Interfacing of NPPs and hydrogen production facilities.*** This includes topics such as supplying electricity or thermal energy and its source within the NPP; nuclear safety aspects of extraction of energy; fluctuation of the thermal energy use; and potential for cross contamination of produced hydrogen.

3.5.1 Siting of Hydrogen Production and Storage Facilities with Respect to Nuclear Power Plants

The presence of hydrogen within the boundaries of NPPs is not a novel concept. Because of the high thermal conductivity, hydrogen is commonly supplied to NPPs and used for cooling turbogenerators. Hydrogen-cooled turbogenerators are the most common type of turbogenerator used in NPPs. According to the conducted interviews, many NPPs are considering installing hydrogen production units



within their facilities for the purpose of turbogenerator cooling. Hydrogen may also be produced for use beyond the NPP. In those cases, consideration will need to be given to matching production and uptake requirements and balancing with on-site storage, as large quantities of hydrogen may need to be stored on-site.

Safe operation of a hydrogen production facility is an important consideration with possible implications for the safe operation of a nearby NPP, and the integration of hydrogen production could likely trigger an update of the NPP's safety analysis and licensing. The CNSC's REGDOC 2.4.2 [83] requires a probabilistic safety assessment, which is conducted according to methodology provided in CSA N290.17 [84], and REGDOC 2.4.1 [85] requires a deterministic safety analysis. These analyses should consider safety issues possibly arising from the existence of a hydrogen production facility, hydrogen transmission pipelines, and a hydrogen storage facility, even though they are not part of the NPP. The potential effects of a hydrogen explosion on an NPP's SSCs should be assessed, particularly for SSCs that are important for nuclear safety and the ability to achieve safe shutdown of a reactor in the event of a serious nuclear accident. The assessed SSCs may include switchyard components and auxiliary transformers. The effects of a hydrogen explosion on a used nuclear fuel dry storage facility should also be assessed.

Provincial emergency response planning, a structured framework of instructions and information created to help ensure an effective and coordinated response in the event of a nuclear emergency, would also likely need to be reviewed. The goal of emergency response planning is to limit off-site consequences, such as radiation exposure and contamination to people and the environment. For the purpose of evacuation, it includes information on public alerting, locations of worker centers, evacuation and shelter locations, distribution of potassium iodide, tritium responses, and regional transportation instructions to help manage traffic.

Given the variety of possible combinations of NPPs and hydrogen production facilities, emergency planning zones, the areas around the systems for which necessary responses to an accident are planned, should be assessed case-by-case, based on the location and characteristics of each NPP. As discussed with several interviewees, this is true given the anticipated future role of small modular reactors and consideration of a graded approach to developing emergency planning zone requirements based on the individual characteristics of the nuclear reactor under consideration. The proposed hydrogen production technology should ideally be assessed on a graded, risk-informed basis.

The separation distance between an NPP and a hydrogen production and storage facility may be considered critical and may depend on several factors, including hydrogen fire or explosion risks to the NPP and sensitive infrastructure, such as SSCs that are important for nuclear safety. In particular, the safety of SSCs located outside the reactor building should be considered when assessing the hazards arising from on-site hydrogen production. CNSC REGDOC 1.1.1 [79] requires that external human-induced hazards, including fire and explosions, be considered and evaluated in the site evaluation and preparation

assessments. Fire or explosions that could arise from hydrogen leaks and potential accidents should be considered in the context of the distance between the NPP, SSCs that are external to the NPP, and hydrogen and other chemicals production and storage facilities, as well as the quantity of stored products, (i.e., the size of storage facility). The size of an on-site hydrogen storage facility may depend on requirements to balance hydrogen production and uptake.

Distance requirements between an NPP and SSCs containing hydrogen could depend on each combination of nuclear reactor and hydrogen production facility, but would likely be risk-informed following a standard safety assessment protocol. The safe distance accounts for many distances between the hydrogen and NPP facilities components, such as power plant switchyards, circuit breakers, communication towers, and auxiliary transformers. There are a number of factors to consider in such an assessment, including specific location of hydrogen production and storage in relation to the NPP site, as well as safety architecture of the NPP and the hydrogen production facilities. Other mitigation measures, such as physical barriers (e.g., berms, blast walls), may also be considered in determining separation requirements based on the specific safety assessment.

Due to hydrogen's low volumetric energy intensity, low molecular weight, and very low liquefaction temperature, hydrogen production facilities may store hydrogen on-site in large, high-pressure storage vessels, or ship it off-site for storage or use. Hydrogen on-site storage presents potential fire and explosion hazards. Even in the case of the continuous off-site shipment, hydrogen poses risks of explosion in the production facility and associated piping. Additionally, hydrogen production is often coupled with production of other chemicals, such as ammonia, methanol, and synthetic fuel, and the risks and safe operation of these facilities must also be considered, both for impacts to NPP safety analysis and licensing, as well as for compliance of the industrial facilities with relevant regulatory requirements.

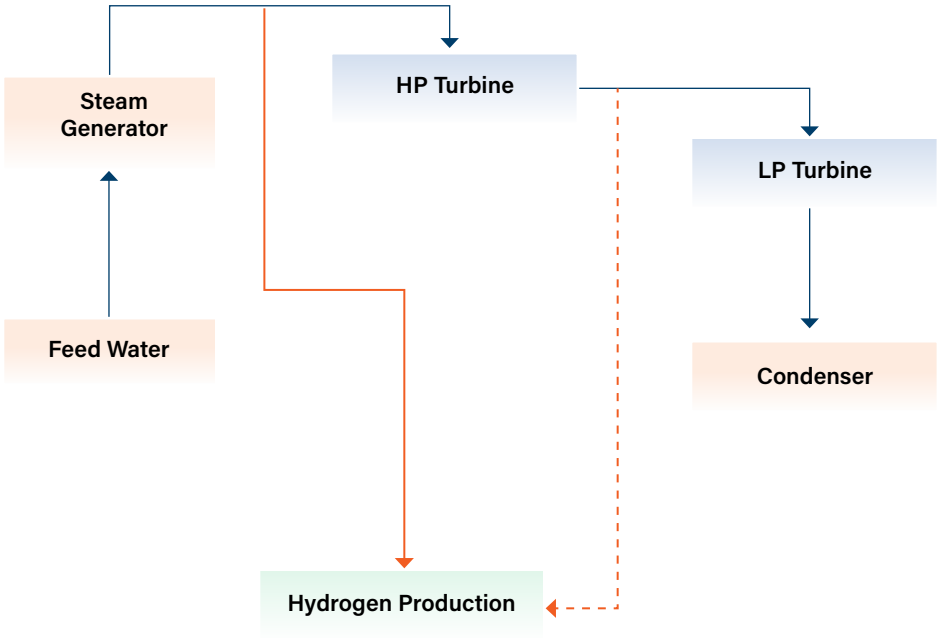
Hydrogen storage requirements may depend on uptake requirements and the on-demand needs of uptakers. One of the interviewees discussed a recent risk assessment of potential damage from a hydrogen production facility co-located at an NPP. Even with continuous off-site shipment of hydrogen, hydrogen explosions within a production facility and associated piping could potentially lead to overpressures, which could affect the safety of workers; the integrity of ancillary facilities such as switchyards, used fuel dry storage, and other facilities; as well as the operation of safety systems. It is not currently common practice in NPPs to use hydrogen monitors for regular operations and design basis accidents. However, in some cases, hydrogen monitors have been installed to address the potential for hydrogen production during accidents and malfunctions related to beyond design basis accident scenarios. The installation of real-time hydrogen sensors in both the hydrogen production and hydrogen storage areas could provide early indication of a hydrogen release and may be a mitigation measure for consideration. For hydrogen production facilities in which steam electrolyzers produce oxygen at high temperatures, the oxygen might also need to be considered as a safety hazard.

3.5.2 Interfacing of Nuclear Power Plants and Hydrogen Production Facilities

For integrated hydrogen and NPP facilities, an NPP supplies electricity to a hydrogen facility via the switchyard. Cold electrolyzers can be located anywhere that electricity can be delivered, since they rely only on the transmitted electricity and not on any other outputs or systems at the NPP.

Hydrogen production facilities that require thermal energy from NPPs could require special consideration. Thermal energy can be supplied in many forms and in different ways depending on the type of nuclear reactor. For water-cooled nuclear reactor technologies, thermal energy can be supplied to hydrogen production facilities in the form of steam directly from an NPP reactor's primary or secondary cooling systems, or in the form of hot water produced from the steam in a utility plant. Figure 2 illustrates the concept of thermal energy extraction in the form of steam upstream and downstream of the high-pressure turbine. When steam is extracted from the nuclear reactor cooling system, the implications with respect to

Figure 2. Alternative locations of thermal energy extraction for hydrogen production (HP = high pressure; LP = low pressure).



nuclear safety and designs should be evaluated to help ensure SSCs are protected and safe shutdown can be achieved in the event of an emergency, since change in the thermal load of nuclear reactors could affect safe performance. Any process changes in an NPP requires that the safety assessments (both probabilistic and deterministic, as well as the safety case) be updated to include the required changes and to support relicensing. Water heating to provide steam, although more expensive, is considered a safer option than steam extraction from the reactor cooling system.

For nuclear reactor technologies that use molten salt thermal storage, thermal energy could be extracted from the molten salt heat storage, which could alleviate the impact of loss of heat extraction from the NPP.

Considerations related to the potential contamination of the hydrogen facility with radionuclides include the need to monitor thermal energy sources (i.e., steam, hot water, or molten salt) for radioactive contamination and to identify intervention measures and possible courses of action for cases of contamination. According to one hydrogen production facility manufacturer, ensuring low levels of radioactive contamination requires consideration of:

- Occupational health and safety at the hydrogen production facility; and
- Radiation contamination of the produced hydrogen, which may potentially have implications for end uses and consequently, for public exposure.

This may be particularly relevant for thermal energy supplied from boiling water reactors, because water that passes through the reactor pressure vessel is also used as the steam source in turbogenerators. As confirmed through the interviews, in case of potential leaks and in the absence of an intermediate heat exchanger system, steam in direct contact with fuel channels could become contaminated with radioactivity and potentially contaminate the hydrogen production system. In integrated systems that have multiple barriers between the primary coolant and the ultimate heat sink, it can be anticipated that there may be a requirement for an intermediate heat exchanger to isolate the nuclear side from the hydrogen production. Tritium may require special consideration in this regard.

4 Standardization Recommendations for Nuclear Power Plant and Hydrogen Production Facility Integration

The focus of this report is to help identify areas where revisions of existing standards or development of new standards might support the integration of a hydrogen production facility and an NPP, including consideration of the associated infrastructure for both the hydrogen production facility and the NPP.

The findings, which are outlined in Section 3.5, predominantly identified challenges associated with the impact of a hydrogen production facility on an NPP. Consequently, the recommendations and considerations discussed in this Section focus on standardization needs to support safety of the NPP. The discussion provides a high level summary of standards and topics that should be considered for further research and assessment to identify gaps and opportunities for harmonization of existing standards and practices, as well as considerations for possible solutions to overcome identified gaps. It should be noted that although there are other general standardization needs associated with hydrogen production facilities, these fall outside the scope of this report.

4.1 Standards Recommended for Review

This Section presents a brief overview of CSA standards that should be considered for review to address the integration of a hydrogen production plant with an NPP. Given the discussion in Section 3.5.1 regarding implications on the NPP safety analysis, standards that relate to safety assessments are expected to be most impacted and should be reviewed in further detail. This includes the following:

- CSA N286, *Management system requirements for nuclear facilities* [86], applies to the senior management with overall accountability for the nuclear facility, and integrates the management system requirements for health, safety, environment, security, economics, and quality. The integration of a hydrogen production facility and an NPP may introduce additional health, safety, and environmental requirements that should be considered in this standard.
- CSA N290 series addresses many topics related to safety systems and safety analysis. Of specific relevance are:
  - CSA N290.1, *Requirements for the shutdown systems of nuclear power plants* [87];
  - CSA N290.11, *Requirements for reactor heat removal capability during outage of nuclear power plants* [88];
  - CSA N290.15, *Requirements for the safe operating envelope of nuclear power plants* [89];
  - CSA N290.17, *Probabilistic safety assessment for nuclear power plants* [84]; and
  - CSA N290.19, *Risk-informed decision making for nuclear power plants* [90].
  - These standards merit review, particularly in cases of nuclear thermal energy extraction for hydrogen production. Furthermore, because the probabilistic safety assessment provides input to various NPP programs, including operational programs, accident management procedures, and emergency planning, review of CSA N290.17 could support a subsequent review of other related standards.
- CSA N293, *Fire protection for nuclear power plants* [91], provides the minimum fire protection requirements for the design, construction, commissioning, operation, and decommissioning of NPPs and small modular reactors. The integration of a hydrogen production facility with an NPP introduces potential additional fire hazards, and this standard could also be reviewed to assess the need for additional guidance or requirements for unique aspects associated with hazards related to hydrogen production facilities.
- CSA N1600, *General requirements for nuclear emergency management programs* [92], provides requirements for a comprehensive nuclear emergency management program. The integration of a hydrogen production facility with an NPP, the extraction of electrical and thermal energy from the NPP, and the potential for a flammable and explosive



hydrogen-rich atmosphere near the NPP, introduce additional hazards that could be addressed in the emergency response program. CSA N1600 should be reviewed to assess the need for additional guidance or requirements for unique emergency management aspects associated with hazards related to hydrogen production facilities.

4.2 Considerations for Requirements and Guidance

Based on the findings presented in this report, there may be a need for the development of additional requirements and guidance to address the two main themes that were discussed in Section 3.5:

- Siting of hydrogen production and storage facilities with respect to NPPs; and
- Interfacing of NPPs and hydrogen production facilities.

Evaluation of the need for further standardization for the siting of hydrogen production and storage facilities with respect to NPPs should consider:

- The potential for fire and explosions originating from the hydrogen production facility, including guidance on:
  - Assessment of the hazard's potential;
  - Determination of appropriate separation distances between the hydrogen plant and the NPP based on the hazards potential assessment; and
  - Evaluation of the potential impact on the reactor containment structure and the critical SSCs.
- Guidance on the use of physical structures, such as blast wall or berm to mitigate impacts and protect sensitive components.

Review of the need for additional requirements and guidance specific to the interfacing of a hydrogen production facility and an NPP should include assessment of:

- The need for the development of provisions to address the potential contamination of the hydrogen facility with radionuclides, such as:
  - Monitoring any steam, hot water, or molten salt that flows from the NPP into the hydrogen production facility to detect any radioactive contamination;
  - Determining intervention measures and possible courses of action if such contamination is detected; and
  - Assessing the reliability of these monitors.
- The need for additional specific guidance related to the implications of the use of NPP thermal energy (heat) for NPP safety analysis and the SSCs important for reactor safety, such as guidance on the application of relevant existing standards (e.g., considering the hydrogen production plant as an external hazard in the probabilistic safety assessment, and the implications of the loss of heat sink on NPP safety when the hydrogen production plant needs to be taken offline); and
- The need for the development of provisions to address installation and reliability of hydrogen monitors within and around the hydrogen production facility, and proximate to the interface with the NPP, to detect potential hydrogen releases from the hydrogen production facility, pipelines, and storage.

5 Conclusions

Overall, of the potential combinations of hydrogen production from nuclear energy, the integration of low-temperature electrolyzers and NPPs for hydrogen production has been assessed to be the least complex in terms of interactions between the two facilities, because the electrolyzer can be sized to scale and located within the exclusion zone or at some distance from the NPP.

Due to proximity and interconnection limitations, hydrogen production facilities relying on heat energy supply from NPPs would likely need to be on the nuclear regulated site and would likely thus be subject to licensing requirements imposed by the CNSC. Hydrogen production facilities located outside the nuclear regulated site boundaries would need to be considered as an additional external hazard in a safety assessment for the specific combination of NPP and hydrogen production (and storage) facility.

This report's findings suggest that, at a minimum, existing nuclear standards applicable to management systems, safety analysis, fire protection, and emergency management could be reviewed and considered for potential updates.

The development of new standards or guidance documents could also be considered to address potential contamination of the hydrogen facility with radionuclides, implications of the use of NPP thermal energy, and hydrogen monitoring. Finally, further standardization to address siting of hydrogen production and storage facilities with respect to an NPP could be considered, including the potential for fire and explosions originating from the hydrogen production facility, mitigation measures such as use of physical structures, and assessment of land use with respect to NPP–hydrogen plant interactions.

References

[1] Natural Resources Canada, "Hydrogen strategy for Canada: Seizing the opportunities for hydrogen," Natural Resources Canada, Ottawa, ON, Canada, 2020. Accessed: Mar. 2, 2023. [Online]. Available: https://natural-resources.canada.ca/sites/nrcan/files/environment/hydrogen/NRCan_Hydrogen-Strategy-Canada-na-en-v3.pdf

[2] Bruce County. "Bruce Innovates – Foundational Hydrogen Infrastructure Project." [Online]. Available: https://www.brucecounty.on.ca/business/bruce-innovates-foundational-hydrogen-infrastructure-project

[3] E. B. Agyekum, C. Nutakor, A. M. Agwa, and S. Kamel, "A critical review of renewable hydrogen production methods: Factors affecting their scale-up and its role in future energy generation," *Membranes,* vol. 12, no. 2, 2022, Art. no. 173, https://doi.org/10.3390/membranes12020173.

[4] R. Y. Kannah, S. Kavitha, O. P. Karthikeyan, G. Kumar, N. V. Dai-Viet, and J. Rajesh Banu, "Techno-economic assessment of various hydrogen production methods – A review," *Bioresour. Technol.,* vol. 319, 2021, Art. no. 124175, https://doi.org/10.1016/j.biortech.2020.124175.

[5] J. Nowotny and T. N. Veziroglu, "Impact of hydrogen on the environment," *Int. J. Hydrogen Energy,* vol. 36, pp. 13218–13224, 2011, https://doi.org/10.1016/j.ijhydene.2011.07.071.

[6] E. M. W. Smeets, A. P. C. Faaij, I. M. Lewandowski, and W. C. Turkenburg, "A bottom-up assessment and review of global bio-energy potentials to 2050," *Prog. Energy Combust. Sci.,* vol. 33, pp. 56–106, 2007, https://doi.org/10.1016/j.pecs.2006.08.001.

[7] T. da Silva Veras, T. S. Mozer, D. da Costa Rubim Messeder dos Santos, and A. da Silva César, "Hydrogen: Trends, production and characterization of the main process worldwide," *Int. J. Hydrogen Energy,* vol. 42, pp. 2018–2033, 2017, https://doi.org/10.1016/j.ijhydene.2016.08.219.

[8] International Energy Agency. "Comparison of the emissions intensity of different hydrogen production routes, 2021." Accessed: Nov. 27, 2023. [Online]. Available: https://www.iea.org/data-and-statistics/charts/comparison-of-the-emissions-intensity-of-different-hydrogen-production-routes-2021

[9] M. Platonova, "Decarbonizing steel production with nuclear hydrogen," *IAEA Bulletin*, vol. 64, no. 3, Sep. 2023. [Online]. Available: https://www.iaea.org/bulletin/decarbonizing-steel-production-with-nuclear-hydrogen

[10] International Renewable Energy Agency, "Green hydrogen: A guide to policy making," International Renewable Energy Agency, Abu Dhabi, United Arab Emirates, 2020. [Online]. Available: https://www.irena.org/publications/2020/Nov/Green-hydrogen

[11] B. Oliver, A. Davidson, and G. K. Punia, "Advanced classification of hydrogen: Life cycle assessment and beyond," Canadian Standards Association, Toronto, ON, Canada, 2023. [Online]. Available: https://www.csagroup.org/article/research/advanced-classification-of-hydrogen/

[12] B. Page. "Energy transition: Hydrogen isn't the fuel of the future. It's already here." Accessed: Nov. 21, 2023. [Online]. Available: https://www.weforum.org/agenda/2019/06/the-clean-energy-of-the-future-is-already-here/

[13] Geoscience Australia. "Hydrogen." Accessed: Nov. 21, 2023. [Online]. Available: https://www.ga.gov.au/scientific-topics/energy/resources/hydrogen

[14] C. W. Forsberg, "Is hydrogen the future of nuclear energy?" *Nuclear Technology,* vol. 166, no. 1, pp. 3–10, 2009, https://doi.org/10.13182/NT09-A6962.

[15] I. Dincer, "Green methods for hydrogen production," *International Journal of Hydrogen Energy,* vol. 37, no. 2, pp. 1954–1971, 2012, https://doi.org/10.1016/j.ijhydene.2011.03.173.

[16] F. Reisch, "High pressure boiling water reactor," International Atomic Energy Agency, Vienna, Austria, Rep. IAEA-CN-164-5S02, 2009. [Online]. Available: https://www-pub.iaea.org/MTCD/publications/PDF/P1500_CD_Web/htm/pdf/topic5/5S02_F.%20Reisch.pdf

[17] P. Breeze, "Nuclear power," in *Power Generation Technologies*, 3rd ed., Oxford, United Kingdom: Newnes, 2019, pp. 399–429, https://doi.org/10.1016/B978-0-08-102631-1.00017-1.

[18] J. E. O'Brien, M. G. McKellar, C. M. Stoots, J. S. Herring, and G. L. Hawkes, "Parametric study of large-scale production of syngas via high-temperature co-electrolysis," *International Journal of Hydrogen Energy,* vol. 34, no. 9, pp. 4216–4226, 2009, https://doi.org/10.1016/j.ijhydene.2008.12.021.

[19] Innovation, Science and Economic Development Canada, "Technology Readiness Level (TRL) assessment tool," Innovation, Science and Economic Development Canada, Ottawa, ON, Canada, Mar. 25, 2021. [Online]. Available: https://ised-isde.canada.ca/site/clean-growth-hub/sites/default/files/attachments/TRL-e.pdf

[20] Z. Wang, R. R. Roberts, G. F. Naterer, and K. S. Gabriel, "Comparison of thermochemical, electrolytic, photoelectrolytic and photochemical solar-to-hydrogen production technologies," *International Journal of Hydrogen Energy,* vol. 37, no. 21, pp. 16287–16301, 2012, https://doi.org/10.1016/j.ijhydene.2012.03.057.

[21] C. M. Kalamaras and A. M. Efstathiou, "Hydrogen production technologies: current state and future developments," *Conference Papers in Science,* vol. 2013, 2013, Art. no. 690627, https://doi.org/10.1155/2013/690627.

[22] C. W. Forsberg, "Hydrogen, nuclear energy, and the advanced high-temperature reactor," *International Journal of Hydrogen Energy,* vol. 28, no. 10, pp. 1073–1081, 2003, https://doi.org/10.1016/S0360-3199(02)00232-X.

[23] J. Chi and H. Yu, "Water electrolysis based on renewable energy for hydrogen production," *Chin. J. Catal.,* vol. 39, no. 3, pp. 390–394, 2018, https://doi.org/10.1016/S1872-2067(17)62949-8.

[24] F. Moradi Nafchi, E. Afshari, and E. Baniasadi, "Anion exchange membrane water electrolysis: Numerical modeling and electrochemical performance analysis," *International Journal of Hydrogen Energy*, vol. 52, pt. D, pp. 306–321, 2024, https://doi.org/10.1016/j.ijhydene.2023.05.173.

[25] M. Riemer, S. Duval-Dachary, and T. M. Bachmann, "Environmental implications of reducing the platinum group metal loading in fuel cells and electrolysers: Anion exchange membrane versus proton exchange membrane cells," *Sustainable Energy Technologies and Assessments*, vol. 56, 2023, Art. no. 103086, 2023, https://doi.org/10.1016/j.seta.2023.103086.

[26] Electric Power Research Institute, "Program on technology innovation: prospects for large-scale production of hydrogen by water electrolysis," Electric Power Research Institute, Palo Alto, CA, United States, Rep. no. 3002014766, Feb. 2019. [Online]. Available: https://www.epri.com/research/products/000000003002014766

[27] R. M. Navarro, R. Guil, and J. L. G. Fierro, "Introduction to hydrogen production," in *Compendium of Hydrogen Energy, vol. 1, Hydrogen Production and Purification*, V. Subramani, A. Basile, and T. Nejat Veziroğlu, Eds., Sawston, United Kingdom: Woodhead Publishing, 2015, pp. 21–61, https://doi.org/10.1016/B978-1-78242-361-4.00002-9.

[28] A. Ursua, L. M. Gandia, and P. Sanchis, "Hydrogen production from water electrolysis: Current status and future trends," *Proc. IEEE,* vol. 100, no. 2, pp. 410–426, 2012, https://doi.org/10.1109/JPROC.2011.2156750.

[29] C. Li and J.-B. Baek, "The promise of hydrogen production from alkaline anion exchange membrane electrolyzers," *Nano Energy,* vol. 87, 2021, Art. no. 106162, https://doi.org/10.1016/j.nanoen.2021.106162.

[30] M. El-Shafie, S. Kambara, and Y. Hayakawa, "Hydrogen production technologies overview," *Journal of Power and Energy Engineering,* vol. 7, pp. 107–154, 2019, https://doi.org/10.4236/jpee.2019.71007.

[31] J. D. Holladay, J. Hu, D. L. King, and Y. Wang, "An overview of hydrogen production technologies," *Catal. Today,* vol. 139, no. 4, pp. 244–260, 2009, https://doi.org/10.1016/j.cattod.2008.08.039.

[32] Z. Zhou, O. Zholobko, X.-F. Wu, T. Aulich, J. Thakare, and J. Hurley, "Polybenzimidazole-based polymer electrolyte membranes for high-temperature fuel cells: Current status and prospects," *Energies,* vol. 14, no. 1, 2021, Art. no. 135, https://doi.org/10.3390/en14010135.

[33] S. Charnock, M. Temminghoff, V. Srinivasan, N. Burke, C. Munnings, and P. Hartley, "National hydrogen research, development and demonstration (RD&D): Technical repository," Commonwealth Scientific and Industrial Research Organisation, Canberra, Australia, 2019. [Online]. Available: https://publications.csiro.au/rpr/download?pid=csiro:EP20068&dsid=DS1

[34] A. Ozbilen, I. Dincer, and M. A. Rosen, "Comparative environmental impact and efficiency assessment of selected hydrogen production methods," *Environmental Impact Assessment Review,* vol. 42, pp. 1–9, 2013, https://doi.org/10.1016/j.eiar.2013.03.003.

[35] K. W. Harrison, R. Remick, G.D. Martin, and A. Hoskin, "Hydrogen production: Fundamentals and case study summaries," National Renewable Energy Laboratory, Golden, CO, United States, Rep. NREL/CP-550-47302, 2010. [Online]. Available: https://www.nrel.gov/docs/fy10osti/47302.pdf

[36] J. E. O'Brien et al., "High temperature electrolysis for hydrogen production from nuclear energy – Technology summary," Idaho National Laboratory, Idaho Falls, ID, United States, Rep. INL/EXT-09-16140, 2010. [Online]. Available: https://inldigitallibrary.inl.gov/sites/sti/sti/4480292.pdf

[37] H. Ding et al., "Self-sustainable protonic ceramic electrochemical cells using a triple conducting electrode for hydrogen and power production," *Nature Communications*, vol. 11, 2020, Art. no. 1907, https://doi.org/10.1038/s41467-020-15677-z.

[38] C. M. Stoots, J. E. O'Brien, K. G. Condie, and J. J. Hartvigsen, "High-temperature electrolysis for large-scale hydrogen production from nuclear energy – Experimental investigations," *International Journal of Hydrogen Energy,* vol. 35, no. 10, pp. 4861–4870, 2010, https://doi.org/10.1016/j.ijhydene.2009.10.045.

[39] J. E. O'Brien, M. G. McKellar, E. A. Harvego, and C. M. Stoots, "High-temperature electrolysis for large-scale hydrogen and syngas production from nuclear energy – Summary of system simulation and economic analyses," *International Journal of Hydrogen Energy,* vol. 35, no. 10, pp. 4808–4819, 2010, https://doi.org/10.1016/j.ijhydene.2009.09.009.

[40] H. Lange, A. Klose, W. Lippmann, and L. Urbas, "Technical evaluation of the flexibility of water electrolysis systems to increase energy flexibility: A review," *International Journal of Hydrogen Energy,* vol. 48, no. 42, pp. 15771–15783, 2023, https://doi.org/10.1016/j.ijhydene.2023.01.044.

[41] R. Kothari, D. Buddhi, and R. L. Sawhney, "Comparison of environmental and economic aspects of various hydrogen production methods," *Renew. Sustain. Energy Rev. 2008,* vol. 12, no. 2, p. 553–563, 2008, https://doi.org/10.1016/j.rser.2006.07.012.

[42] W. J. Martinez-Burgos et al., "Hydrogen: Current advances and patented technologies of its renewable production," *J. Clean. Prod.,* vol. 286, 2021, Art. no. 124970, https://doi.org/10.1016/j.jclepro.2020.124970.

[43] I. Dincer and C. Acar, "Review and evaluation of hydrogen production methods for better sustainability," *Int. J. Hydrogen Energy,* vol. 40, no. 34, pp. 11094–11111, 2015, https://doi.org/10.1016/j.ijhydene.2014.12.035.

[44] P. H. Kasai and R. J. Bishop Jr., "Thermolysis of water in contact with zeolite masses," United States Patent 3963830, Jun. 16, 1976. [Online]. Available: https://patents.google.com/patent/US3963830A/en

[45] K.-T. Hsu, "Cold chemical water-splitting hydrogen generation system," United States Patent 20070017154 A1, Jul. 25, 2005. [Online]. Available: https://patents.google.com/patent/US20070017154A1/en

[46] G. F. Naterer, I. Dincer, and C. Zamfirescu, *Hydrogen Production from Nuclear Energy*, London, United Kingdom: Springer, 2013, https://doi.org/10.1007/978-1-4471-4938-5.

[47] K. R. Schultz, L. C. Brown, G. E. Besenburch, and C. J. Hamilton, "Large-scale production of hydrogen by nuclear energy for hydrogen economy," General Atomics, San Diego, CA, United States, Tech. rep. GA-A24265, 2003. [Online]. Available: https://www.osti.gov/servlets/purl/814028.

[48] National Research Council and National Academy of Engineering, *The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs*, Washington DC, United States: The National Academies Press, 2004, https://doi.org/10.17226/10922.

[49] United States Department of Energy, "Hydrogen, Fuel Cells and Infrastructure Technologies Program: Multi-year research, development and demonstration plan," United States Department of Energy, Washington, DC, United States, 2007, Rep. DOE/GO-102007-2430. [Online]. Available: https://www.nrel.gov/docs/fy08osti/39146.pdf.

[50] M. A. Lewis, M. Serban, and J. K. Basco, "Hydrogen production at <550°C using a low temperature thermochemical cycle," in *Nuclear Production of Hydrogen: Second Information Exchange Meeting — Argonne, Illinois, USA 2-3 October 2003*, Paris, France: OECD Publishing, 2004, https://doi.org/10.1787/9789264107717-12-en.

[51] J. Turner et al., "Renewable hydrogen production," *International Journal of Energy Research*, vol. 32, no. 5, pp. 379–407, 2008, https://doi.org/10.1002/er.1372.

[52] M. F. Orhan, I. Dincer, and M. A. Rosen, "Investigation of an integrated hydrogen production system based on nuclear and renewable energy sources: A new approach for sustainable hydrogen production via copper–chlorine thermochemical cycles," *International Journal of Energy Research*, vol. 36, no. 15, pp. 1388–1394, 2012, https://doi.org/10.1002/er.1926.

[53] R. S. El-Emam, H. Ozcan, and C. Zamfirescu, „Updates on promising thermochemical cycles for clean hydrogen production using nuclear energy," *Journal of Cleaner Production,* vol. 262, p. 121424, 2020, https://doi.org/10.1016/j.jclepro.2020.121424.

[54] S. Yalçin, "A review of nuclear hydrogen production," *Int. J. Hydrogen Energy,* vol. 14, no. 8, pp. 551–561, 1989, https://doi.org/10.1016/0360-3199(89)90113-4.

[55] J. Nowotny et al., "Towards sustainable energy. Generation of hydrogen fuel using nuclear energy," *International Journal of Hydrogen Energy,* vol. 41, no. 30, pp. 12812–12825, 2016, https://doi.org/10.1016/j.ijhydene.2016.05.054.

[56] S. Fremaux, S.-M. Beheshti, H. Ghassemi, and R. Shahsavan-Markadeh, "An experimental study on hydrogen-rich gas production via steam gasification of biomass in a research-scale fluidized bed," *Energy Convers. Manag.*, vol. 91, pp. 427–432, 2015, https://doi.org/10.1016/j.enconman.2014.12.048.

[57] P. L. Spath and M. K. Mann, "Life cycle assessment of hydrogen production via natural gas steam reforming," National Renewable Energy Laboratory, Golden, CO, United States, Rep. NREL/TP-570-27637, 2001. [Online]. Available: https://doi.org/10.2172/764485

[58] S. D. Angeli, G. Monteleone, A. Giaconia, and A. A. Lemonidou, "State-of-the-art catalysts for CH_4 steam reforming at low temperature," *International Journal of Hydrogen Energy,* vol. 39, no. 5, pp. 1979–1997, 2014, https://doi.org/10.1016/j.ijhydene.2013.12.001.

[59] N.Z. Muradov, T.N. Veziroğlu. 2005. "From hydrocarbon to hydrogen–carbon to hydrogen economy," *International Journal of Hydrogen Energy*, vol. 30, no. 3, pp. 225-237, 2005, https://www.sciencedirect.com/science/article/abs/pii/S0360319904001685

[60] J. J. Lamb et al., "Traditional routes for hydrogen production and carbon conversion," in *Hydrogen, Biomass and Bioenergy: Integration Pathways for Renewable Energy Applications*, J. J. Lamb and B. G. Pollet, Eds., Cambridge, MA, United States: Academic Press, 2020, pp. 21–53, https://doi.org/10.1016/B978-0-08-102629-8.00003-7.

[61] F. Suleman, I. Dincer, and M. Agelin-Chaab, "Environmental impact assessment and comparison of some hydrogen production options," *International Journal of Hydrogen Energy,* vol. 40, no. 21, pp. 6976–6987, 2015, https://doi.org/10.1016/j.ijhydene.2015.03.123.

[62] N. Muradov, "Emission-free fuel reformers for mobile and portable fuel cell applications," *J. Power Sources,* vol. 118, no. 1–2, pp. 320–324, 2003, https://doi.org/10.1016/S0378-7753(03)00078-8.

[63] S.R. Patlolla, K.Katsu, A. Sharafian, K. Wei, O.E. Herrera, W. Mérida. 2023. "A review of methane pyrolysis technologies for hydrogen production," *Renewable and Sustainable Energy Reviews,* vol. 181, p. 113323, 2023, https://www.sciencedirect.com/science/article/abs/pii/S136403212300179X

[64] T. Y. Ahmed, M. M. Ahmad, S. Yusup, A. Inayat, and Z. Khan, "Mathematical and computational approaches for design of biomass gasification for hydrogen production: A review," *Renew. Sustain. Energy Rev,* vol. 16, no. 4, pp. 2304–2315, 2012, https://doi.org/10.1016/j.rser.2012.01.035.

[65] G. Chen, J. Andries, Z. Luo, and H. Spliethoff, "Biomass pyrolysis/gasification for product gas production: the overall investigation of parametric effects," *Energy Convers. Manag.,* vol. 44, no. 11, pp. 1875–1884, 2003, https://doi.org/10.1016/S0196-8904(02)00188-7.

[66] S. Heyne, T. Liliedahl, and M. Marklund, "Biomass gasification – A synthesis of technical barriers and current research issues for deployment at large scale," The Swedish Knowledge Centre for Renewable Transportation Fuels, Göteborg, Sweden, 2013. [Online]. Available: https://f3centre.se/app/uploads/f3_report_2013-5_gasification_technology_status_130517.pdf

[67] Government of Ontario, "Ontario's low-carbon hydrogen strategy, A path forward," Government of Ontario, Toronto, ON, Canada, Apr. 2022. Accessed: Feb. 6, 2024. [Online]. Available: https://www.ontario.ca/files/2022-04/energy-ontarios-low-carbon-hydrogen-strategy-en-2022-04-11.pdf

[68] Independent Electricity System Operator. "Market assessment: Overview." Accessed: Feb. 6, 2024. [Online]. Available: https://www.ieso.ca/sector-participants/market-oversight/market-assessment/market-assessment-overview

[69] Bruce Power. "Bruce Power supports study exploring potential to produce hydrogen through nuclear." Accessed: Feb. 6, 2024. [Online]. Available: https://www.brucepower.com/2023/10/12/bruce-power-supports-study-exploring-potential-to-produce-hydrogen-through-nuclear/

[70] Port of Belledune. "Belledune Port authority to pursue an ARC Clean Technology aSMR project with Cross River Infrastructure Partners at planned Green Energy Hub." Accessed: Feb. 6, 2024. [Online]. Available: https://portbelledune.ca/belledune-port-authority-to-pursue-an-arc-clean-technology-asmr-project-with-cross-river-infrastructure-partners-at-planned-green-energy-hub/

[71] Idaho National Laboratory. "Pilot projects test a path to hydrogen economy." Accessed: Feb. 6, 2024. [Online]. Available: https://inl.gov/integrated-energy/pilot-projects-test-a-path-to-hydrogen-economy/

[72] Sizewell C. "Hydrogen and nuclear: Why does Sizewell C want to produce hydrogen?" Accessed: Feb. 6, 2024. [Online]. Available: https://www.sizewellc.com/environment/szc-energy-hub/hydrogen/

[73] Business Wire. "NuScale Power signs research collaboration agreement for clean hydrogen production." Accessed: Feb. 6, 2024. [Online]. Available: https://www.businesswire.com/news/home/20221201005239/en/NuScale-Power-Signs-Research-Collaboration-Agreement-for-Clean-Hydrogen-Production

[74] Office of Clean Energy Demonstrations. "Regional clean hydrogen hubs." Energy.gov. Accessed: Feb. 6, 2024. [Online]. Available: https://www.energy.gov/oced/regional-clean-hydrogen-hubs-0

[75] S. M. Bragg-Sitton, "DOE Office of Nuclear Energy Integrated Energy Systems: Program overview," Idaho National Laboratory, Idaho Falls, ID, United States, Apr. 2022. Accessed: Feb. 6, 2024. [Online]. Available: https://inldigitallibrary.inl.gov/sites/sti/sti/Sort_58528.pdf

[76] Government of Canada, 1997. *Nuclear Safety and Control Act, S.C. 1997, c. 9*. [Online]. Available: https://laws.justice.gc.ca/eng/acts/N-28.3/

[77] Government of Canada, 2000. *Class I Nuclear Facilities Regulations, SOR/2000-204*. [Online]. Available: https://laws.justice.gc.ca/eng/regulations/SOR-2000-204/

[78] Government of Canada, 2000. *Radiation Protection Regulations, SOR/2000-203*. [Online]. Available: https://laws.justice.gc.ca/eng/regulations/SOR-2000-203/

[79] *Site Evaluation and Site Preparation for New Reactor Facilities*, REGDOC-1.1.1, Canadian Nuclear Safety Commission, Ottawa, ON, Canada, Jul. 2022. [Online]. Available: https://www.cnsc-ccsn.gc.ca/eng/acts-and-regulations/regulatory-documents/published/html/regdoc1-1-1-v1-2/

[80] *License Application Guide: License to Operate a Nuclear Power Plant*, REGDOC-1.1.3, Canadian Nuclear Safety Commission, Ottawa, ON, Canada, Jul. 2022. [Online]. Available: https://www.nuclearsafety.gc.ca/eng/acts-and-regulations/regulatory-documents/published/html/regdoc1-1-3-v1-1/

[81] *Supplemental Information for Small Modular Reactor Proponents*, REGDOC-1.1.5, Canadian Nuclear Safety Commission, Ottawa, ON, Canada, Aug. 2019. [Online]. Available: https://www.cnsc-ccsn.gc.ca/eng/acts-and-regulations/regulatory-documents/published/html/regdoc1-1-5/

[82] *Design of Reactor Facilities*, REGDOC-2.5.2, Canadian Nuclear Safety Commission, Ottawa, ON, Canada, Aug. 2019. [Online]. Available: https://www.cnsc-ccsn.gc.ca/eng/acts-and-regulations/regulatory-documents/published/html/regdoc2-5-2-v2-1/

[83] *Probabilistic Safety Assessment (PSA) for Reactor Facilities*, REGDOC-2.4.2, Canadian Nuclear Safety Commission, Ottawa, ON, Canada, May 2022. [Online]. Available: https://www.cnsc-ccsn.gc.ca/eng/acts-and-regulations/regulatory-documents/published/html/regdoc2-4-2-v2/

[84] *Probabilistic Safety Assessment for Nuclear Power Plants*, CSA N290.17, Canadian Standards Association, Toronto, ON, Canada, 2022. [Online]. Available: https://www.csagroup.org/store/product/2704178/

[85] *Deterministic Safety Analysis*, REGDOC-2.4.1, Canadian Nuclear Safety Commission, Ottawa, ON, Canada, May 2014. [Online]. Available: https://www.cnsc-ccsn.gc.ca/eng/acts-and-regulations/regulatory-documents/published/html/regdoc2-4-1/

[86] *Management System Requirements for Nuclear Facilities*, CSA N286, Canadian Standards Association, Toronto, ON, Canada, 2022. [Online]. Available: https://www.csagroup.org/store/product/N286-12/

[87] *Requirements for the Shutdown Systems of Nuclear Power Plants*, CSA N290.1, Canadian Standards Association, Toronto, ON, Canada, 2023. [Online]. Available: https://www.csagroup.org/store/product/2430884/

[88] *Requirements for Reactor Heat Removal Capability During Outage of Nuclear Power Plants*, CSA N290.11, Canadian Standards Association, Toronto, ON, Canada, 2021. [Online]. Available: https://www.csagroup.org/store/product/2703601/

[89] *Requirements for the Safe Operating Envelope of Nuclear Power Plants*, CSA N290.15, Canadian Standards Association, Toronto, ON, Canada, 2019. [Online]. Available: https://www.csagroup.org/store/product/2703089/

[90] *Risk-Informed Decision Making for Nuclear Power Plants*, CSA N290.19, Canadian Standards Association, Toronto, ON, Canada, 2018. [Online]. Available: https://www.csagroup.org/store/product/2704530/

[91] *Fire Protection for Nuclear Power Plants*, CSA N293, Canadian Standards Association, Toronto, ON, Canada, 2022. [Online]. Available: https://www.csagroup.org/store/product/2700227/

[92] *General Requirements for Nuclear Emergency Management Programs*, CSA N1600, Canadian Standards Association, Toronto, ON, Canada, 2021. [Online]. Available: https://www.csagroup.org/store/product/2703669/

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