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Review Article

# Challenges, opportunities and future directions in hydrogen sector development in Canada

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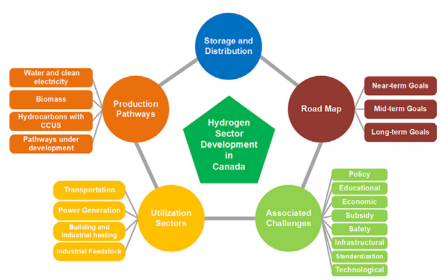
## HIGHLIGHTS

- Overview of Canada's global position with regards to hydrogen production.
- Overview of Canada's natural resources and infrastructural potential.
- Comprehensive discussion on hydrogen production pathways and end-use in Canada.
- Identification of several key challenges to achieve net-zero economy by 2050.

## GRAPHICAL ABSTRACT

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## ABSTRACT

Exploitation of fossil fuel sources in the power generation and transportation sector has been a major source of carbon dioxide emissions that contributes to global warming. Replacement of hydrocarbon-based fuel sources with cleaner fuels is imperative for environmental preservation at the global level. In this regard, hydrogen can be used as an effective non-carbonaceous fuel option as well as an energy carrier. Canada is currently one of the economically advanced countries in the world and aims at achieving a net-zero economy by 2050. However, fossil fuels are still largely utilized for both transportation and power generation purposes. Slightly less than a quarter of the total grid power in Canada is supplied through fossil fuel combustion including natural gas, coal, and petroleum. As a matter of fact, Canada, as one of the top ten global producers of hydrogen, exhibits a great potential of achieving the goal of sustainable development. Thus, this paper discusses the current status, challenges, and opportunities offered by the hydrogen sector and its development in the near- and long-term future in Canada. The potential methods of hydrogen production in Canada are described by categorizing them according to the energy and feedstock sources required for their realization. In addition, the status of hydrogen storage and distribution in Canada is also discussed. Various sectors consuming hydrogen

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as the end-users in Canada are categorized based on hydrogen use as a fuel, a heating source, and an industrial feedstock and are comprehensively discussed. Several challenges and the necessary line-of-actions to establish a hydrogen economy in Canada in the long-term future are also discussed, and a road map for accomplishing the net-zero economy by 2050 is further explained based on achieving certain near-term, mid-term, and long-term goals. Moreover, the job creation opportunities in Canada are discussed by considering numerous critical sectors.



## Contents



## Introduction

A significant increase in the global energy demands is estimated in the upcoming years as a consequence of exponential growth in the human population and industrial development activities. A fundamental challenge in this context appears to balance the demand and supply of energy that requires novel and innovative approaches for providing energy. Thus, energy serves as a crucial factor in the formulation of economic and environmental policies around the world. It is extremely essential to generate, transform, transport, and utilize both the sources and the systems of energy in a manner that ensures better service to the societies, their economies, and most importantly the environment [1]. The primary sources of energy generation at the global scale have always been fossil fuels, such as natural gas, crude oil, and coal. The basic reason for this over-dependence on fossil fuel sources for power generation is their capability of producing energy at higher efficiencies. However, despite being extremely efficient, the consistent utilization of these carbonaceous energy sources is deemed to cause an increase in the global carbon footprint at a swift rate due to the associated greenhouse gas (GHG) emissions. In the near future, there exists a remarkable uncertainty towards mitigation and adaptation to climate change due to the response of the climate system in addition to a vast range of economic and technological factors [2]. In addition to their environmental implications, these fossil fuel sources are limited in nature and are thus not sustainable. Therefore, their continuous exploitation depletes them which would eventually make us run out of them. As a consequence, the concerns regarding the security of energy supply are constantly increasing causing an increase in the energy carrier prices. Petroleum products are a major source of concern in this regard since they hold a share of more than one-third of global energy consumption with the transport sector accumulating almost 95% of it. Moreover, the detrimental implications of coal mining coupled with the huge contribution of coal utilization towards the global GHG emissions are among the factors of concern. Thus, proactive research efforts have been carried out by the scientific community globally in an attempt to minimize GHG emissions and to meet the projected energy demands of the future. Due to the anticipated increase in global energy demands and climate change, a shift from fossil fuels to renewable energy sources is expected. Renewable energy sources carry the potential to exponentially fulfill the global energy demands [3]. However, a major challenge towards the large-scale implementation of renewable sources such as solar and wind energy is their intermittent availability.

In such a scenario, alternate non-carbonaceous fuels like hydrogen are considered to be a long-term carbon-free solution to tackle the issues of climate change and energy sustainability [4]. Hydrogen appears to be an excellent energy carrier with a huge potential of providing a promising solution to the intermittency issue of renewable sources. It is anticipated by several researchers that hydrogen, in the longer run, will substitute petroleum products in the transportation sector thereby reducing the reliance on petroleum. In addition, it is abundantly utilized as a commodity in several industrial sectors including plastics, food processing, petrochemical, and agriculture [5]. A few advantages of hydrogen include higher energy density compared with most of the conventional carbonaceous fuels, higher energy conversion efficiencies, abundance, transportable over long distances, various forms of storage (liquid, gaseous, or together with metal hydrides), the convenience of conversion to other energy forms, and production utilizing water with zero emissions. Because of these various advantages of hydrogen, it is becoming a vital part of future global energy policies. According to the Hydrogen Council [6], it is projected that by 2050, nearly 18% of the global demand for energy can be met by hydrogen.

Canada fulfills all the requirements of developing a sustainable hydrogen economy including sufficient feedstocks for hydrogen production, a powerful energy industry, and extensive international relationships. For over 40 years, Canada has been a global leader in fuel cell technology and has played a crucial part in the development of equipment related to the production, distribution, and storage of hydrogen. In addition, Canada is amongst the top 10 producers of hydrogen in the world annually generating 3 Mts of hydrogen that is over 4% of hydrogen globally produced [7]. A large percentage of hydrogen in Canada is obtained by the oil and gas sector along with the chemical industry utilizing hydrocarbons. However, alternate cleaner pathways are also being explored by commercial consumers of hydrogen such as water electrolysis or steam methane reforming (SMR) incorporated with carbon dioxide capturing and sequestration technology. Thus, the enormous resources and production potential puts Canada in a distinct position to be able to establish a clean hydrogen economy. Subject to fully exploiting its position and advantages, Canadians are expected to generate a domestic revenue of over $50 billion by 2050 [7].

With regards to Canada's potential for a hydrogen economy, it possesses the world's lowest carbon intensity electricity supply systems, an ideal carbon dioxide ($CO_2$) storage geology, an abundance of fossil fuel and freshwater resources, and a huge supply of biomass. All these resources are capable of supporting the production of hydrogen. Canada possesses one-third of the world's largest reserves of oil. Moreover, it has one of the largest reserves of natural gas that are estimated to last for the next 300 years at the present consumption rate [8]. In the context of $CO_2$ capturing, one-fifth of the world's large-scale carbon capture and storage projects are implemented and operated in Canada. Moreover, Canada is also rich in renewable forest biomass with provinces including Ontario, British Columbia, Quebec, New Brunswick, and Alberta capable of the huge biomass capacity. Furthermore, Canada has almost a total of 7% of the global freshwater resources which is essential to the generation of green hydrogen. Due to the technologies developed recently, there have been options to produce hydrogen out of brakish and waste waters.

Canada is also amongst the world leaders in fuel cell and hydrogen technology. Over 100 hydrogen and fuel cell companies were established in Canada up until 2017 employing over 2100 people resulting in a revenue generation of over $200 million [7]. Quebec, Ontario, and British Columbia are amongst the provinces hosting the biggest group of companies that develop and deploy hydrogen solutions throughout Canada. As far as the export opportunities are concerned, over 50% of the globally deployed fuel cell buses comprise the fuel cell powertrain technology that is the intellectual property of Canadian companies. With regards to renewable energy systems, Canadian technologies pertaining to products such as advanced storage materials and electrolyzers offer a great deal on a global scale. Canada has a vast network of pipelines for the transmission and distribution of natural gas which is capable of supporting the long-term distribution of hydrogen. Canada is also rich in storage resources like salt caverns and exhausted wells etc. that could potentially serve as hydrogen and $CO_2$ storage.

Canada is amongst the global giants in terms of establishing international collaborations and has been a founding member of numerous initiatives and strategic partnerships that have strengthened the global collaboration on hydrogen over the past 30 years. For example, initiatives such as International Energy Agency (IEA) Hydrogen and Advanced Fuel Cell that transformed into the present Technology Collaboration Programs, were co-founded by Canada. The objective of these programs is to manage the researchers from public and private sectors to accelerate research and development on a global scale. The International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE) is also co-founded by Canada, in addition to being its important partner. Recently, a memorandum of understanding (MOU) was signed between the Australian Hydrogen Council (AHC) and Canadian Hydrogen and Fuel Cell Association (CHFCA) to support the commercial implementation of fuel cell and hydrogen technologies by bolstering the cooperation between the two countries.

Hydrogen can play a significant role in decarbonizing energy systems which makes its adoption extremely essential. Canada, as per the Paris agreement, pledged to minimize the GHG emissions by 30% lower than 2005 by 2030 with a target to achieve 511 Mt [7]. It has been announced by the Canadian government to accomplish the target of net-zero emissions by 2050. However, achieving this milestone is a much greater challenge in reality as the factors such as economic and population growth are the biggest obstacles in the way of attaining the objective of decarbonization. Transportation, electricity, buildings, heavy industry, and oil and gas sectors are the major contributors to the GHG emissions in Canada as shown in Fig. 1. Substantial efforts are required to accomplish the net-zero emissions objective by 2050 and low carbon intensity hydrogen can greatly contribute in this regard capable of serving applications like transportation, heat for residential

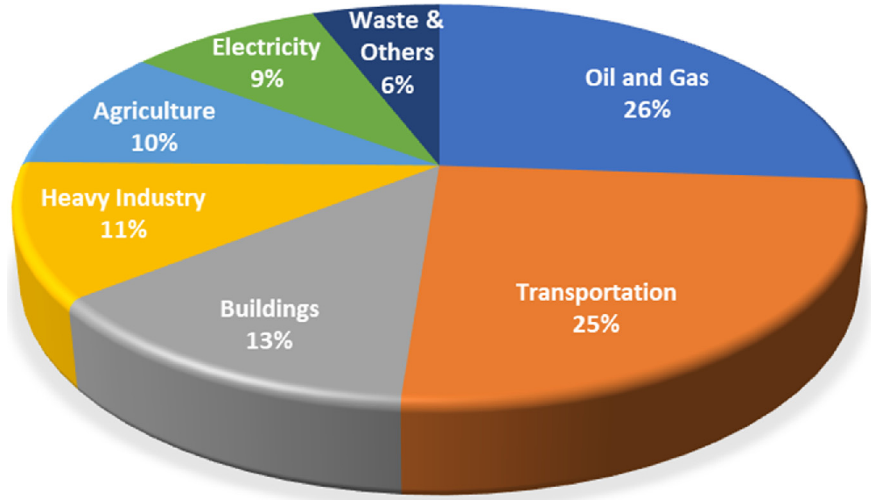


**Fig. 1 – Sector-wise distribution of GHG emissions in Canada in 2017 (data from Ref. [9]).**

and commercial buildings and industry, and utilization as an industrial feedstock. In this study, the present status of the hydrogen sector's development in Canada is comprehensively discussed by considering the production and distribution opportunities, end-use technologies of hydrogen, and the associated challenges and potential solutions for achieving a sustainable hydrogen economy. Several investigations reported in the open literature with specific regard to hydrogen production in Canada are also summarized.

## Hydrogen production pathways in Canada

There are several methods available for hydrogen production. Some of those methods are used commercially for large-scale generation of hydrogen, some of them are only capable of producing hydrogen for small-scale consumption, and a few others are in the experimental stages requiring further research and infrastructural development for their commercial implementation. The hydrogen rainbow categorizes the hydrogen obtained through various feedstock materials at a basic level. The most common form is *Grey* hydrogen which is obtained using natural gas (mostly comprising methane and ethane). *Brown* hydrogen utilizes lignite coal or oil while *black* hydrogen is obtained through bituminous coal which is a tar-like substance. *Blue* hydrogen is obtained through the same carbonaceous feedstock materials as the grey, brown, and black hydrogen. The only difference is that the emitted $CO_2$ is captured and stored underground in this case. Lastly, *Green* hydrogen is produced by utilizing electricity generated through renewable energy sources for splitting water into hydrogen and oxygen and is perhaps the cleanest way of producing hydrogen.

Fig. 2 shows the primary energy sources that can be utilized for producing hydrogen. In the specific context of Canada, hydrogen can be produced by employing the various Canadian feedstocks such as fossil fuels, renewable organic material, water via electricity generated through clean sources, and lastly as an industrial by-product (Fig. 2). As Canada is amongst the top ten global producers of hydrogen, most of it is obtained through SMR without incorporation of carbon capturing and storage technology which does not make it a low carbon intensity option. However, Canada has all the resources to produce low carbon intensity hydrogen in the coming future by exploiting cleaner routes of hydrogen production.

### *Water and electricity*

Canada is the third-largest generator of hydroelectricity worldwide and 67% of its overall power is generated using renewable sources [8] which puts it in a very comfortable position to produce green hydrogen through clean electricity via water electrolysis. During electrolysis, water undergoes electrochemical dissociation into hydrogen and oxygen. To produce one kg of hydrogen and 8 kg of oxygen through electrolysis, it takes about 9 L of water. The hydrogen obtained this way is extremely pure and can be directly employed for various applications whereas the obtained oxygen can also be utilized for a variety of purposes. Several technologies of electrolyzers are commercially available the two main types of which are the Solid Oxide Electrolysis Cells (SOEC) and the Proton Exchange Membrane (PEM) electrolyzer. The various cleaner electricity sources that can potentially be employed to supply the necessary electrical power for the electrolysis process include hydro, solar, wind, biomass, and nuclear.

As previously mentioned, a large percentage of Canada's electrical power demands are met through hydroelectricity. Fig. 3 provides an overview of the Canadian provinces with the highest percentages of hydroelectricity generation such as Manitoba, Quebec, Newfoundland and Labrador, Yukon, and British Columbia. The electricity utility suppliers of these provinces can play an instrumental part in the value chain of hydrogen. Moreover, independent electricity generating assets such as solar and wind power and run-of-river can also greatly contribute in this regard. The increased contribution of solar and wind in the overall energy sector of Canada can potentially improve the generation of clean hydrogen while at the same time causing a reduction in costs. Canada has the world's 9th most solar and wind energy installations.

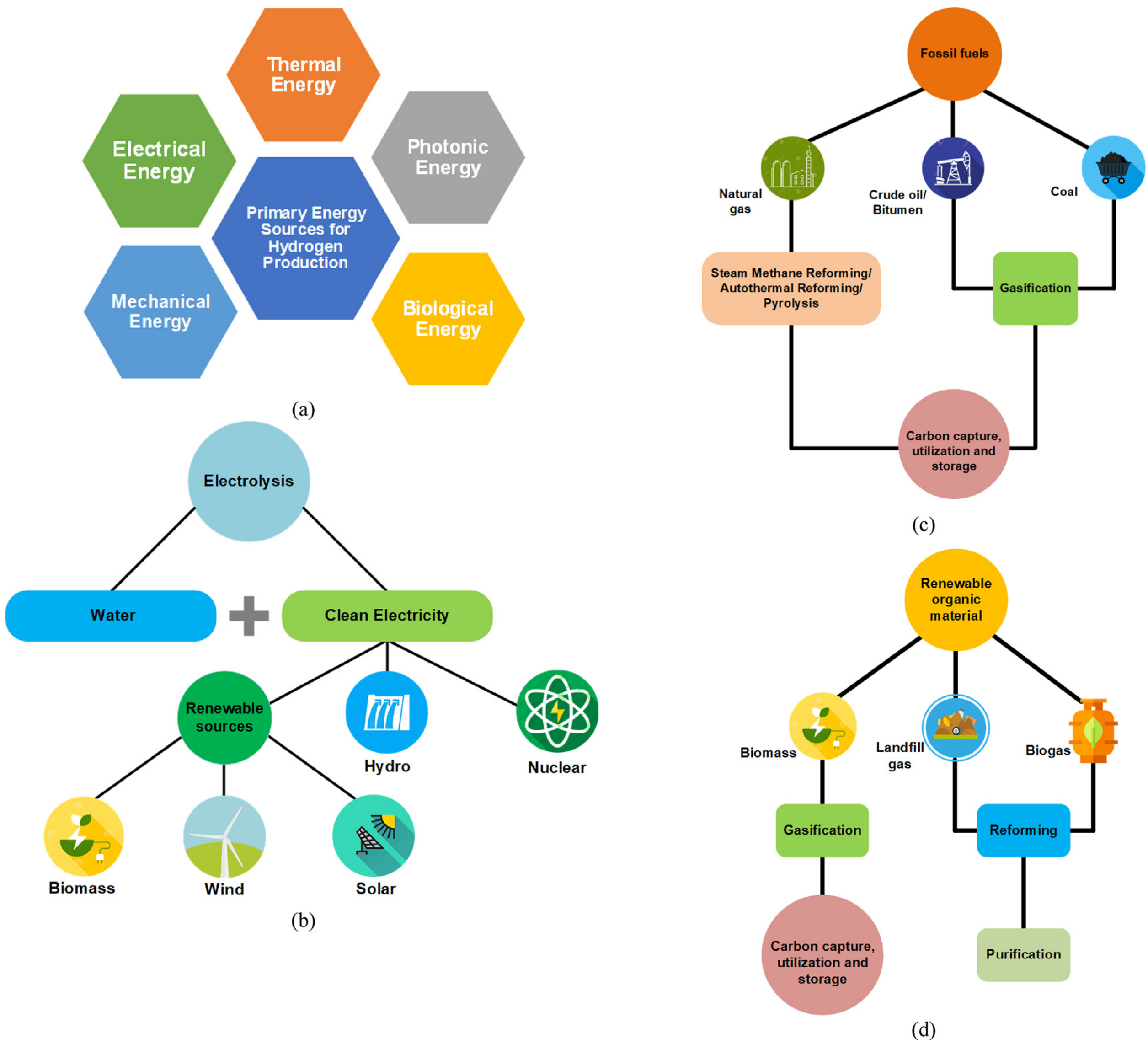


**Fig. 2 – (a) Primary energy sources available for hydrogen production, (b) water and clean electricity-based, (c) fossil fuel-based, and (d) renewable organic material-based low carbon intensity hydrogen production pathways in Canada.**

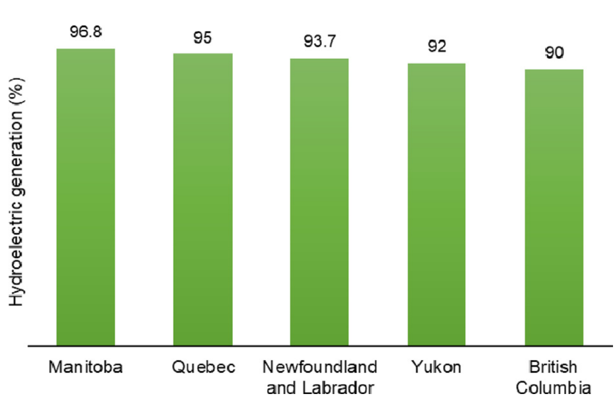


**Fig. 3 – Percentages of hydroelectricity generation in various Canadian provinces (data from Ref. [7]).**

Electricity generation from solar and wind energies was almost negligible in 2005 which grew to almost 5% of the overall power produced in 2018 with the solar and wind power capacities of 2.9 and 13 GW, respectively [7]. Ontario nests more than 98% of the solar installations in Canada while most of Canada's wind turbine installations are situated in Alberta, Ontario, and Quebec.

Nuclear energy can also significantly contribute to the generation of clean hydrogen since process heat and electricity are both obtained through nuclear reactors. Off-peak low-cost electricity generated through nuclear power plants can be utilized for water electrolysis to produce hydrogen. Ontario is the prime location for hydrogen production via nuclear energy since three of the four nuclear generation stations in Canada are located there. The heat dissipated through a nuclear reactor can also be utilized in a high-temperature electrolysis process to supply steam to the electrolyzer instead of liquid water which can decrease the electricity consumption during electrolysis thereby improving the process efficiencies. In the coming future, Canada may see an increased percentage of low carbon-intensive and sustainable hydrogen generation through better exploitation of nuclear energy.

### *Fossil fuels with carbon capture, utilization, and storage*

There are large reserves of fossil fuels in Canada such as crude oil, natural gas, and bitumen that can be exploited to produce low carbon intensity hydrogen with the incorporation of carbon capture, utilization, and storage technology. Apart from being a cleaner route, this is also the most cost-effective pathway of producing hydrogen on a large scale. Canada has considerable potential for development in terms of hydrogen generation and carbon capture, utilization, and storage that can significantly reduce GHG emissions. As far as natural gas is concerned, Canada ranks 6th and 4th in terms of exporting and producing natural gas, respectively around the world. Natural gas, which mainly constitutes methane, can be utilized for hydrogen production via the SMR process which results in higher GHG emissions. However, when SMR is coupled with the carbon capture, utilization, and storage technique, a nearly 90% decrease in the hydrogen's carbon intensity can be attained. This captured $CO_2$ can be employed in a variety of applications such as a feedstock for the industry as well as in enhanced oil recovery process in a way that does not result in emissions. Several investigations have been reported in the open literature that considered SMR in combination with carbon capture, utilization, and storage technique [10–13]. Apart from SMR, hydrogen can also be obtained through natural gas via Autothermal Reforming and Pyrolysis processes. However, Canada produces its majority of hydrogen via the SMR process which is expected to remain amongst the major pathways of hydrogen production in the near future. Canadian provinces of Alberta (69%), British Columbia (29%), and Saskatchewan (2%) possess sufficient reserves of natural gas as well as high storage potential of $CO_2$ [7] which puts them in an extremely favorable position for obtaining hydrogen using natural gas with carbon capture, utilization, and storage.

Apart from natural gas, Canada also has an abundance of crude oil, coal, and bitumen reserves in British Columbia, Saskatchewan, and Alberta. These resources can be utilized to produce hydrogen through the gasification process where they are reacted in the presence of oxygen and steam at higher temperatures to obtain a gas mixture commonly termed as "SYNGAS" from which hydrogen can be separated along with $CO_2$. Carbon capture, utilization, and storage technology needs to be combined with the gasification process to make it a low carbon intensity hydrogen pathway. At present, gasification is being implemented as a developing technique in Saskatchewan and Alberta utilizing bitumen and crude oil where the process occurs deep beneath the earth's surface, and membranes are employed for filtration and extraction of hydrogen. This makes the process cost-effective and less complicated since the generated $CO_2$ is already underground.

By 2050, the entire hydrogen produced in Canada needs to be low carbon intensity to accomplish the goal of a net-zero economy. Compared to the hydrogen obtained via electrolysis, fossil fuel-based hydrogen with carbon capture, utilization, and storage is more competitive in Canada in terms of the overall production cost due to being self-sufficient in large natural gas reserves [14]. With regards to carbon capture, utilization, and storage, Canada is in a favorable position due to its ideal geological topography to store $CO_2$ (Western Canada in particular), capability in the oil and gas industry that can be transferrable, and growing market interest in $CO_2$ exploitation. To encourage a reduction in emissions in several industries including chemicals, cement, oil and gas, iron and steel, and power generation, several opportunities are being explored for the carbon capture, utilization, and storage sector by Natural Resources Canada that will help Canada take maximum advantage of its resources. Based on a study recently conducted by Transition Accelerator (a non-profit organization in Canada), it is expected that by 2050, Canada will be producing eight times the hydrogen locally generated at present for which the carbon capture, utilization, and storage needs would be almost 203 Mt of $CO_2$/year which is currently standing at 4 Mt of $CO_2$/year projecting a huge increment [15]. The Shell Quest Project is a notable initiative entailing SMR with carbon capture, utilization, and storage and is currently under operation in Alberta annually capturing almost 1.2 Mt of $CO_2$.

### *Biomass*

Biomass gasification is a practically viable and renewable process of producing hydrogen for which the feedstock can be any organic means that mainly constitute oxygen, carbon, and hydrogen. In this process, biomass is broken down into hydrogen and some more products by reacting oxygen with steam at temperatures above 700 °C. In Canada, there is a large requirement of agricultural biomass for synthesizing renewable natural gas, biofuels, and for application in petroleum refineries. An uninterrupted and large feedstock supply is required for biomass gasification as the main route of hydrogen production and the integration of present forest resources into the hydrogen infrastructure can further bolster its position. Several investigations have been reported in the open literature considering the biomass gasification process for hydrogen production in the specific context of Canada [16–18]. An alternate source of obtaining hydrogen through biomass is the methane gas that is obtained as a consequence of the organic material's breakdown that is usually found in the form of waste such as sewage treatment and agricultural waste facilities and landfills. Hydrogen can be obtained using this methane via SMR and Autothermal Reforming pathways. However, with an increased need for renewable natural gas, these resources are expected to be utilized as methane instead of a hydrogen generation source.

### *Hydrogen production pathways in development*

Along with the exploitation of pathways including fossil fuels, water electrolysis via clean electricity, and renewable organic material to obtain hydrogen at a large scale in Canada, certain other processes are in the research and development phase.

These include thermal cracking of water via high-grade heat sources, thermochemical water-splitting, photoelectrolysis, and biophotolysis, etc. During thermal cracking, water is thermally dissociated into hydrogen and oxygen for which solar energy is an excellent option for providing the required process heat. Thermochemical water-splitting also constitutes dissociation of water into hydrogen and oxygen via a series of chemical reactions however requiring low or moderate grade heat sources. Copper-chlorine, magnesium-chlorine, sulfur-iodine, and hybrid sulfur cycles are a few notable examples of thermochemical processes. Photoelectrolysis exploits the photonic energy of the sun for dissociating water into hydrogen and oxygen via photon bombardment. Biophotolysis utilizes the biological source of energy for producing hydrogen via microorganisms through photosynthetic reactions. All these processes are capable of producing low carbon intensity sustainable hydrogen. However, there are certain challenges associated with each of these processes for large-scale commercial implementation. Yet, with consistent investments for research and development in these pathways, they can certainly be commercialized in the long-term future and contribute to achieving the net-zero economy goal of Canada by 2050.

## Hydrogen storage and distribution in Canada

There are several options to store and transport the hydrogen from the production source to the end-user. The overall GHG lifecycle emissions and cost of the delivered hydrogen are affected by this segment of hydrogen's value chain due to its substantial economic and environmental consequences. The low volumetric energy density of hydrogen makes its storage more challenging. The point of hydrogen's eventual utilization significantly dictates the approach through which it is to be stored. Storage approaches are broadly classified into two categories: (i) chemical, and (ii) physical storage. In the physical storage category, hydrogen storage is carried out either in the liquid or gaseous phase. As a gas, it is compressed and stored in high-pressure cylinders and as a liquid, it is stored in the cryogenic form in dedicated insulated containers. Vehicles that use hydrogen on-board usually utilize hydrogen gas stored in pressurized tanks (350–700 bar) however, liquid hydrogen is also expected to be considered for on-board vehicle utilization in the future. For stationary applications, hydrogen is stored both above and underground as a compressed gas in tanks, in natural gas pipelines, and exhausted wells as well as salt caverns. Hydrogen gas storage in salt caverns is practically demonstrated mostly in Europe. In Canada, salt caverns, that are specifically engineered, are exploited in different provinces to store natural gas. Compressed hydrogen can also be effectively stored for longer durations in such caverns. In addition, exhausted wells are also considered as a viable option for storing hydrogen at a large scale as a consequence of increased global hydrogen demand. Apart from compressed gas, several hydrogen liquefaction facilities are available in Ontario and Quebec that are under the ownership and operation of gas companies. Even though transporting liquid hydrogen is more cost-effective, it requires stringent storage conditions since it needs to be stored as a cryogenic liquid in specially insulated tanks to prevent its vaporization. There are a few emerging technologies that store hydrogen as chemical compounds for example ammonia and methylcyclohexane. These liquid chemical carriers can be conveniently managed and can comprise large amounts of hydrogen by volume.

With regards to the distribution of hydrogen, it is mainly transported in tube trailer trucks as pressurized gas (180–200 bar) [7]. In Canada, the Transport of Dangerous Goods regulations governs hydrogen gas transport. Currently, tube trailers made of steel are often used to transport hydrogen gas however, each truck can carry a certain weight as per the regulations which is why several companies are now utilizing composite material trucks to be able to carry more hydrogen per truck in an attempt to minimize emissions and costs associated with hydrogen transportation. Also, trucks with cryogenic tankers are employed for transporting liquid hydrogen. In the absence of pipelines carrying hydrogen, transporting liquid hydrogen is the most cost-effective option for hydrogen distribution in reasonable quantities at longer distances. The final cost of a given fuel after its delivery can be substantially influenced by the method of distribution. According to the British Columbia Hydrogen Study [19], hydrogen's delivery cost is significantly impacted by the total distance over which it is to be transported in a gaseous or liquid state via truck however, this impacts the cost of compressed gas much more than liquid hydrogen (Fig. 4). Mixtures of hydrogen and natural gas can be distributed via natural gas pipelines that can be utilized in several applications instead of purely natural gas however, separation of hydrogen from natural gas, once mixed, is complicated at present. Moreover, the implementation of special hydrogen pipelines can be an appealing option for applications requiring 100% hydrogen as an economical distribution route of hydrogen.

## Hydrogen utilizing sectors in Canada

There is a diverse use of hydrogen in Canada and it is targeted to be adopted in applications and sectors that are energy-intensive offering benefits compared to low-carbon alternate options. This involves hydrogen utilization in the form of fuel for both transportation and electricity generation, for supplying heat for residential and commercial buildings and industry, and lastly as an important feedstock material for industrial activities as shown in Fig. 5.

### *For transportation*

Hydrogen, as a fuel, can be directly utilized in fuel cell electric vehicles (FCEVs) that are twice as efficient as combustion engines and result in zero GHG emissions. Currently, light-duty fuel cell-based passenger vehicles and transit buses are commercially available worldwide and employed in Canada in small numbers. There is a great potential of hydrogen FCEVs for long-distance heavy-duty trucking applications where the batteries have demonstrated certain limitations. The zero-emission truck regulation, that is recently approved in California, is causing substantial activity by vehicle original

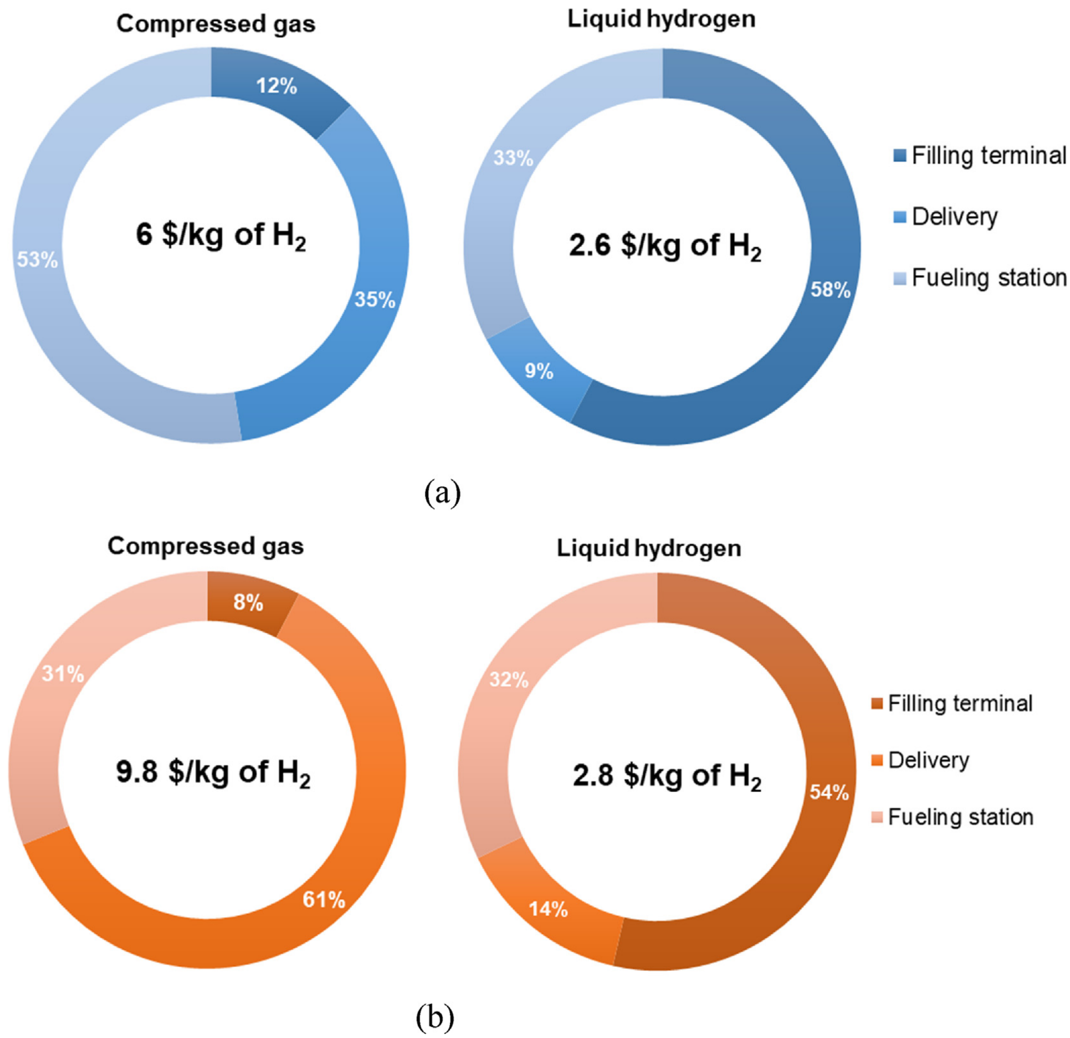


**Fig. 4 – Comparison of hydrogen's delivery and dispensing cost between gaseous and liquid hydrogen for a delivery distance of (a) 100 km, and (b) 500 km (data from Ref. [19]).**

equipment manufacturers (OEMs), fuel cell developers, and tier 1 engine suppliers [20]. The main objective is to swiftly move beyond the present phase of pilot demonstration and develop trucks (both medium and heavy-duty) to be commercially available to the market in North America soon. Trains, specialty industrial vehicles, aviation, and marine applications are currently in the phase of pilot demonstration and exhibit long-term potential since these applications demand high energy. FCEVs in Canada can potentially influence the Indigenous and remote communities in extreme cold weather conditions where a negative impact on battery chemistry is usually observed. Compared with batteries, the performance of fuel cells does not degrade in cold environments. Moreover, the waste heat dissipating from fuel cells can be utilized for cabin heating purposes.

Apart from being directly employed as a fuel in FCEVs, hydrogen can facilitate large amounts of renewable gas in supply networks of natural gas providing fuel for vehicles driven by compressed natural gas (CNG). For instance, under the *CleanBC* goal, efforts are underway in British Columbia to identify hydrogen as a suitable renewable gas to attain 15% renewable natural gas (RNG) in the distribution system of natural gas by 2030 [7]. There is a high demand from the CNG fleet operators to employ renewable gas and that demand can be effectively met through the use of hydrogen. Technical challenges such as $NO_x$ emissions and tank embrittlement in older tank types can arise in certain vehicles using $CNG/H_2$ blend. Nevertheless, emissions of CNG vehicles can be minimized with the incorporation of proper materials and engineering a $CNG/H_2$ blend as exhibited in various pilot projects. Subject to the technological maturity of hydrogen separation and abundant availability of hydrogen over a vast portion of the natural gas network, fueling stations may have the potential to supply both hydrogen and CNG such that both these fuels are separable where they are to be eventually utilized.

Additionally, hydrogen can be utilized in combination with diesel in internal combustion (IC) engine trucks via co-combustion technology. This technology provides the benefit of lower entry costs for end-users since the current diesel engines can be retrofitted. Nonetheless, these engines are unable to provide the efficiency advantages offered by fuel cells. Further, they can cause a reduction in tailpipe emissions nearly in proportion to the amount of hydrogen injected which is estimated to achieve levels of up to 30%. Also,

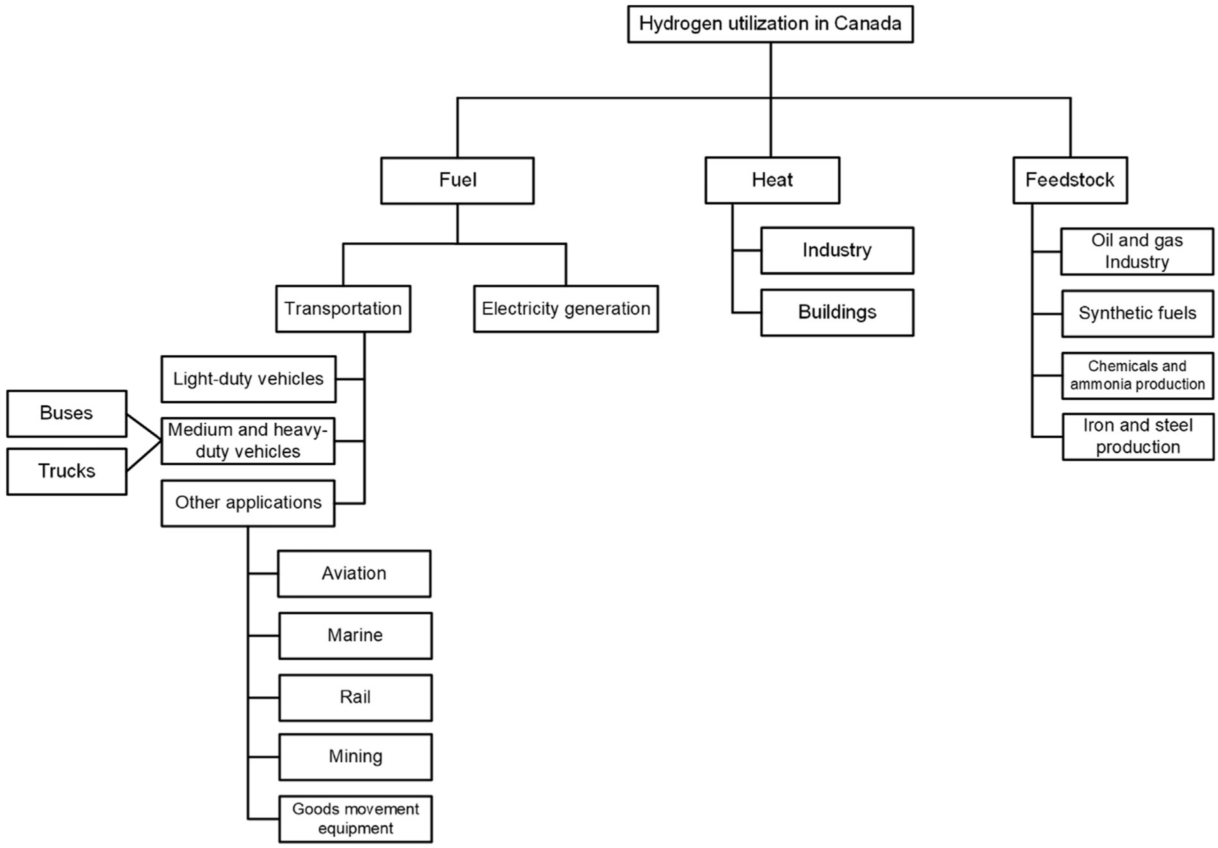


**Fig. 5 – Categorization of hydrogen utilization in various sectors in Canada.**

hydrogen combustion can result in increased $NO_x$ emissions. Thus, the co-combustion technology is considered as an intermediate step to transition towards FCEVs and can significantly contribute to fulfilling hydrogen demand in the near future which could assist in building out infrastructure for hydrogen fueling compatible with heavy-duty FCEV trucks.

a) **Light-duty vehicles**

Hydrogen is expected to play a significant part in a shift to zero-emission light-duty vehicles along with electrification. Federal targets for zero-emission vehicles (ZEVs) for the next twenty years have been set by the Canadian government to attain specific sales per year of light-duty vehicles. In this regard, a 10% sales per year is targeted to be achieved by 2025 increasing to 30% by the end of the following five years leading up to 100% by 2040 [7]. The ZEVs considered in Canada include FCEVs, plug-in hybrid electric vehicles (PHEVs), and battery electric vehicles (BEVs). Among the various provinces in Canada, Quebec and British Columbia have been leading in adopting ZEV sales policies and purchase incentives. Also, the deployment of the FCEVs and hydrogen fueling infrastructure has begun in both these provinces in limited numbers. Till now, the total number of light-duty vehicles operating in Canada has reached 110 which are supported by one retail fueling station in Ontario, one in Quebec, and three in British Columbia. Moreover, there are four new stations in the development phase in British Columbia that are expected to represent a significant milestone since it is indicated by vehicle OEMs that around 7 to 8 stations are required in a certain region for coverage as well as redundancy to allow broader vehicle rollout. Funding for additional 10 new stations has also been announced by British Columbia in an effort to further develop the network. In the months to come, an additional 150 light-duty vehicles are estimated to be deployed as new stations are expected to come online [7].

FCEVs are probably going to be more preferable for drivers in the urban regions of Canada where a large portion of the population resides in multi-unit residential buildings such as apartments, townhouses with shared garages, and condominiums. The concept of home charging stations in such scenarios can get inconvenient and expensive due to strata bylaws provided they have better hydrogen fueling infrastructure. Moreover, people counting on-street parking may prefer FCEVs over BEVs in terms of convenience. With an increase in penetration rates of BEVs in the markets of urban centers, constraints such as increased demands of energy supply from the power grid may pose an added obstacle. An additional expenditure of setting up further electrical substations and distribution networks along with the unavailability of land are amongst some major issues in this regard. Thus, hydrogen fueling may serve as an essential opportunity for optimizing the infrastructure costs of ZEVs.

b) **Medium and heavy-duty vehicles: buses and trucks**

There is a global shift towards zero and low-emission vehicles by the public transport agencies. In this regard, the two options considered to be zero-emission are the Fuel Cell Electric Buses (FCEBs) and the Battery-Electric Buses (BEBs). Around 2000 FCEBs are estimated to be in service globally with nearly 50% of those being driven by heavy-duty fuel cell engine technology of Canada. FCEBs have demonstrated their promising performance through several million-kilometer service in a variety of extreme cold and warm environments with more than 15 years on the road. Ballard Power Systems, Dana TM4, Hydrogenics, and New Flyer Industries are amongst the companies of Canada that possess important positions in the value chain of the FCEB thus providing a genuine "Made-in-Canada" solution.

The performance of diesel buses can be matched by the FCEBs as the only zero-emission option that is also beneficial in comparison with BEBs on longer routes that result in much higher energy consumption. Unlike the longer charging durations required by BEBs, the FCEBs are capable of fast refueling and in a manner quite similar to CNG buses. Another advantage of FCEBs is their one-to-one substitution ratio such that more vehicles are not required to be bought by the transit organizations for providing the level of service same as diesel buses.

In addition to buses, trucking applications can also benefit from fuel cells due to the higher energy density of hydrogen along with the quick fueling process. In contrast to the limitations such as the large weight of batteries and longer charging times, fuel cell technology is expected to demonstrate substantial potential in trucking applications. However, they are currently in the phase of pilot demonstration and are not yet produced at the commercial level. In the recent past, there has been great interest in fuel cell-based class 8 long-haul trucks with several global automobile giants such as Hyundai and Toyota, etc. constantly striving to achieve this goal. In the Canadian context, Cummins Incorporated has taken over Hydrogenics Corporation of Canada and has made large investments for developing fuel cells dedicated to trucking applications. Several pilot demonstrations have been initiated and the Alberta Zero-Emissions Truck Electrification Collaboration is amongst the notable of those initiatives. According to this project, two class 8 long-haul trucks will undergo a trial run between Calgary and Edmonton by employing a fuel cell-based propulsion system entirely developed in Canada [21].

c) **Miscellaneous applications**

The aviation sector can significantly benefit from hydrogen as it can serve as an efficient aviation fuel. Moreover, the overall expenditure of jet fuel may also be minimized by powering the various onboard systems through fuel cells. Several pilot demonstrations in this regard have been initiated for different applications globally. In an attempt to develop a zero-emission aviation sector, lithium-ion batteries are the main alternative to hydrogen. However, hydrogen offers certain benefits over lithium-ion batteries such as low fueling times and high energy density. The aerospace industry of Canada offers more than 0.2 million jobs along with $25 billion to the Canadian economy per year [22]. However, there is enormous pressure on this sector for achieving and maintaining the net-zero emissions objective of Canada by addressing the issues including GHG emissions and severe industrial interruption due to COVID-19. In this regard, hydrogen combustion and fuel cells have been considered as potential alternatives for minimizing emissions.

Similar to the aviation sector, the rail industry can also benefit from hydrogen since hydrogen-based rail or hydrail can potentially serve as a cost-effective alternative for rail electrification compared to conventional catenary wires. Diesel trains are a major source of GHG emissions due to the carbonaceous nature of the fuel and also result in air pollution thereby deteriorating the quality of air in urban areas. Similar to the aviation industry, there is immense pressure on the rail industry as well for minimizing the GHG emissions however, the electrification of the rail industry needs significant infrastructural modifications and is an extremely costly option. An active role has been played by the companies in Canada in the value chain of hydrogen-based rail applications. The fuel cell systems for the first commercial hydrogen-based trains implemented in Germany were developed and supplied by Hydrogenics (Ontario). Ballard Power Systems (British Columbia) is proactively involved in the research and development of hydrogen-powered trains in China and Europe. Even though significant interest in investigating the practical feasibility of hydrail has been shown, Canada is yet to see hydrail deployment in its rail industry. However, with the employment of hydrails entailing the intellectual property of Canadian companies around the world, local deployment in the near future is greatly anticipated.

With regards to marine applications, Canada exhibits great potential for hydrogen implementation. Propulsion and auxiliary power systems of ships can potentially be powered through hydrogen fuel cells. In an attempt towards decarbonization of the shipping industry, hydrogen and ammonia have been identified as potential non-carbonaceous fuels by the International Maritime Organization (IMO). Hydrogen has not been deployed for marine applications at present in Canada however, Ontario and British Columbia have initiated several studies for assessing the practical viability of establishing a hydrogen energy-powered marine sector. Activities such as hydrogen-driven car ferries, that are currently in the development phase in Europe, can benefit Canada to consider its domestic implementation to attain net-zero emissions in the near future.

One of the world's largest mining industries is in Canada with a production of over 60 minerals and metals making it one of the top five manufacturers of various metals globally [23]. In this regard, there is a serious need to minimize emissions in mining activities in Canada by replacing diesel with hydrogen. Nearly 2 billion liters of diesel is annually consumed by the mining sector in Canada which is an indication of its heavy reliance on diesel. In this context, hydrogen can play an important role by minimizing this over-dependence on diesel by vehicles used for mining under and above ground. The exhaust emissions caused by the combustion of diesel through the mining equipment for underground operations can be significantly reduced or altogether eliminated via the application of fuel cells. Moreover, this can also sufficiently decrease the mines' ventilation requirements that normally account for more than one-fourth of the total operating cost of mines [24]. There is a great emphasis by the

Canadian Mineral and Metals Plan (CMMP) on the implementation of cleaner energy sources like hydrogen. In Canada, Hydrogen was first employed in the mining sector for energy storage for the stationary electricity production system in northern Quebec in 2015 in an effort to decrease diesel utilization. However, the adoption of hydrogen by the mining sector has been rather on the slow side and international partnerships and collaborative efforts can facilitate hydrogen's deployment in the mining sector in Canada.

The fifth and the last application of hydrogen as a fuel in Canada's transport sector is for the equipment required for the movement of goods. A large number of forklift trucks that are powered by hydrogen fuel cells are operating at a commercial scale in North America with most deployments in the US. However, subject to their commercial viability, their large-scale implementation in Canada is also anticipated in the near future. Heavy-duty diesel equipment is mostly under the use of seaports and there is immense pressure on these seaports to decrease GHG emissions leading to air pollution. Apart from being employed in goods movement equipment at ports, hydrogen fuel cell generators can also supply electrical power for stationary units at the harbor. Thus, Canada's goods movement equipment and ports can be seen to be a key player in supporting the net-zero emissions target by the implementation of hydrogen for various applications.

### *For electricity generation*

Utilization of hydrogen for power generation can be accomplished via direct combustion of hydrogen as a fuel in turbines or in the form of fuel cell power plants. At present, turbines capable of combusting a mixture of natural gas and hydrogen are available at the commercial level. Traditional natural gas turbines can potentially work with a hydrogen-natural gas blend such that hydrogen ranges between 10 - 15% by volume. The development of such turbines that may have the potential to combust 100% pure hydrogen is in progress and is anticipated to be available commercially by 2030. Nearly 17% of the total grid power of Canada is provided through hydrocarbon

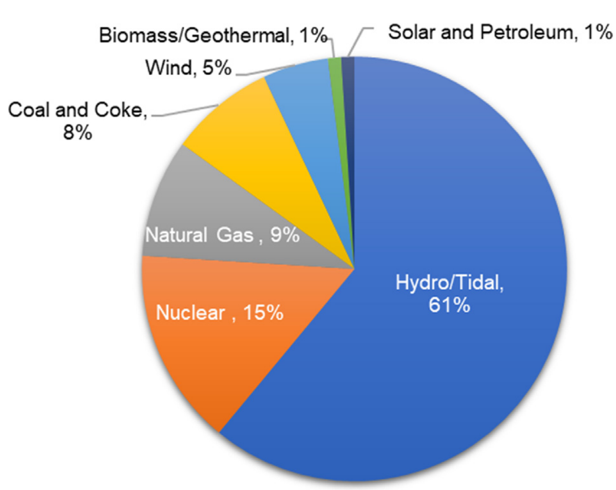


**Fig. 6 – Distribution of power production in Canada in 2018 through different fuel types (data from Ref. [25]).**

combustion [25]. Fig. 6 shows the distribution of electricity production by utilizing different types of fuel in Canada in 2018. Thus, to decrease emissions contributed by the electricity generation sector in Canada, the utilization of low carbon intensity hydrogen is essential [25]. The cost of electrical power generated via turbines combusting 100% hydrogen is anticipated to reduce and become comparable with traditional natural gas turbines by 2050.

Renewable energy sources like solar and wind can be used to supply electricity for hydrogen generation via electrolysis. This hydrogen can then be stored on-site to generate electrical power through a fuel cell or a turbine or can be utilized for decarbonizing natural gas. Power-to-gas (P2G) is a terminology used for such hydrogen that is obtained via utilizing excess renewable power through electrolysis and supplied to the natural gas network and a few of such initiatives are in progress in Canada. The installation of a PEM electrolyzer with a 2.5 MW capacity from Hydrogenics in 2018 was Canada's first P2G initiative. Numerous other similar programs are in progress throughout Canada up to nearly 150 MW of capacity. A few examples of some of the P2G projects in Canada include *Laboratory Plant HRI* (Quebec), *IRENE System* (British Columbia), *Wind-Hydrogen Village* (Prince Edward Island), and *Ramea Wind-Hydrogen-Diesel Project* (Newfoundland and Labrador), etc. [26].

### *For heating purposes in buildings and industry*

The utilization of hydrogen as a heating fuel is essential for supplying high-grade thermal energy since its combustion does not emit GHGs in contrast to fossil fuels. The industrial sector is heavily reliant on natural gas to provide the heat required for various processes such as steam generation. One of the prime sources of emissions in Canada is its oil and gas sector accounting for about 26% of the overall emissions in 2018 [27]. The Paper and cement manufacturing sectors of Canada are some of the other industries that utilize high-grade heat in large amounts. These sectors can largely contribute towards Canada's net-zero emissions goal by minimizing GHG emissions by considering the employment of natural gas-hydrogen mixtures or 100% hydrogen for the generation of thermal energy.

Due to the extremely cold climate in Canada, more than 60% of the energy being utilized for domestic purposes is accounted for space heating and more than 19% is consumed for water heating purposes [28]. For both these applications, natural gas is mostly used in various provinces. There is an increasing interest to employ hydrogen for these utilities subject to its production in large quantities as hydrogen can play an instrumental part in the decarbonization of heating applications for buildings. In this regard, the introduction of hydrogen into natural gas systems is already under consideration globally in an attempt to minimize the emissions related to domestic heating. However, certain technical aspects need to be addressed in this regard. Employment of mixtures of hydrogen-natural gas for the systems specifically designed for natural gas can adversely affect the pipelines, components associated with metering, and other appliances. Hence, efforts are needed to tackle such technical obstacles in the near future to allow such systems to accommodate hydrogen blends.

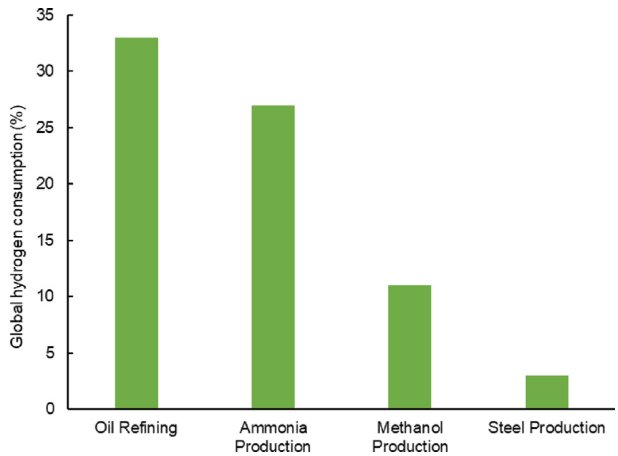


**Fig. 7 – Highest hydrogen consuming sectors as a feedstock worldwide (data from Ref. [29]).**

*As an industrial feedstock*

Hydrogen is mainly utilized in the largest quantities as an industrial feedstock in Canada as well as around the world. Fig. 7 shows the four sectors (oil and gas, ammonia and methanol synthesis, and steel production) with the highest consumption of hydrogen globally. SMR without carbon dioxide capturing and sequestration technology is primarily employed for the synthesis of this feedstock hydrogen. Regulations such as Clean Fuel Standards are anticipated to promote the need for clean hydrogen in the industrial sector. Hydrogen's prospective effectiveness for industrial consumption in the future is dependent upon the implementation of pathways for generating low-carbon intensity and low-cost hydrogen.

With regards to the oil and gas sector, hydrogen is mainly utilized in the processes of hydrocracking and hydrotreatment. An increment of almost 7% is projected in the hydrogen requirement in the oil and gas sector by IEA under current regulations [29]. A large percentage of hydrogen needed for oil refining purposes is generated on-site from methods that produce hydrogen as a primary product or as a by-product. Thus, hydrogen is mainly provided by reforming either naphtha or natural gas as a consequence of integrating refining infrastructure with hydrogen generation. As per the indications of IEA, the share of hydrogen utilization for oil refining purposes towards global emissions is nearly 20%. In the Canadian context, almost 4.5 T $CO_2$ per day is captured at present through the implementation of a carbon dioxide capturing and sequestration initiative in Alberta [30].

With regards to the hydrogen utilization in the chemical industry around the world, ammonia and methanol synthesis accounts for 31 Mt and 12 Mt of hydrogen on annual basis, respectively along with 3 Mt of hydrogen consumption per year [29] by miscellaneous applications including explosives, solvents, and plastics, etc. Ammonia is synthesized in large amounts in Canada for various fertilizers while methanol is utilized as an important industrial chemical. Ammonia and methanol synthesis results in significantly higher $CO_2$ emissions at the global level (630 Mt of $CO_2$ per year). It is anticipated that by 2030, there is going to be a substantial rise in hydrogen demand in the chemical industry which will consequently cause a huge increase in the associated $CO_2$ emissions. Hence, incorporation of a carbon dioxide capturing and sequestration technology to the existing fossil fuel-based hydrogen generation methods is essential to cut down these emissions or alternately, employment of cleaner routes of hydrogen production such as water electrolysis.

Hydrogen is utilized for iron and steel production at a rate of 4 Mt per year which is the fourth highest following oil refining and chemical industries [29]. Similar to the two aforementioned sectors, hydrogen is employed both as a fuel and a feedstock in iron and steel production industries most of which is obtained using hydrocarbon sources without incorporating carbon dioxide capturing and sequestration technology. IEA has projected that the demand for hydrogen in steel production is going to rise by more than two times by 2030 and could further increase up to 15 times by 2050. Steel production accounts for an average of 8% of $CO_2$ emissions globally and is amongst the largest sources of these emissions at present [31]. Steel production via direct reduction of iron-electric arc furnace could potentially be achieved through utilizing low carbon intensity hydrogen that could considerably reduce the associated process emissions. Figs. 8 and 9 show the contributions of transportation, heating, and industrial feedstock towards the demand for hydrogen and reduction in emissions, respectively according to the transformative scenario of 2050.

## Associated challenges and potential line-of-action

Even though Canada has plenty of natural resources and various advantages to implement a hydrogen economy in the long-term future, certain challenges are in the way of achieving the goal of a net-zero economy by 2050 and are essential to be addressed. The associated challenges are thus classified into eight main categories (Fig. 10). Due to the ever-increasing competition at the global level, these various challenges need to be considered separately and addressed simultaneously as well as quickly. In terms of the economic viewpoint, a major challenge faced at present is the cost

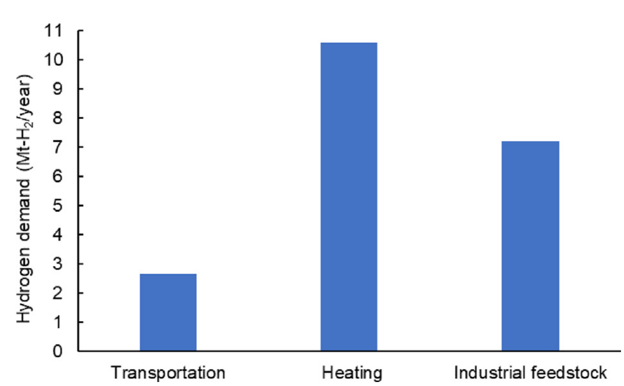


**Fig. 8 – Transportation, heating, and feedstocks contributions in 2050 transformative scenario for annual hydrogen demand (data from Ref. [7]).**

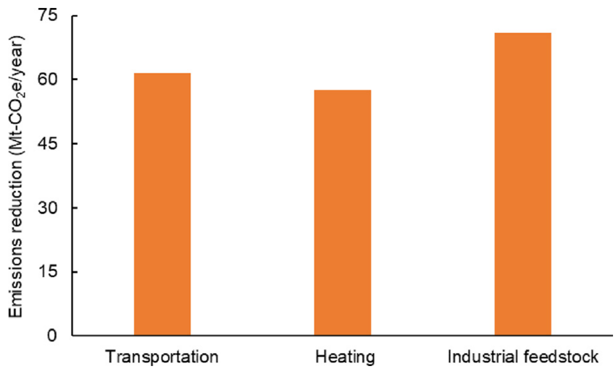


**Fig. 9 – Transportation, heating, and feedstocks contributions in 2050 transformative scenario for annual emissions reductions (data from Ref. [7]).**

competitiveness of hydrogen in comparison with traditional options of fuel available in the market since the cost of hydrogen is five times that of natural gas. Although, hydrogen can be one of the most cost-effective clean fuel options, yet the aspect of emissions is not indicated in the cost of conventional fuels in the global market. A significantly important move in this regard would be the establishment of carbon pricing at the federal level. In addition, the low carbon intensity hydrogen market is in the budding stages in Canada and a simultaneous relation needs to be established between the supply and demand of hydrogen in the Canadian market to ensure substantial investments for large-scale hydrogen production. Further, a hindrance in the way of demand and scale of hydrogen is its end-point utilization cost. For instance, the cost of FCEVs is much higher compared to PHEVs and BEVs since FCEVs are not produced at the bulk level. The cost of several components and materials associated with the manufacturing of FCEVs also needs to be reduced. To attain scale, investments are required in the manufacturing and research and development sectors. Efforts are also required in expanding the charging infrastructure of FCEVs for which large capital investments are essential. Thus, this sector needs provisional support in the coming future to ensure its eventual self-sustenance via investments in its different sub-sectors.

With regards to the challenge of policy formulation and implementation, the hydrogen sector in Canada lacks long-term policies that are necessary to support and strengthen the sector. Global clean hydrogen initiatives have mostly taken place in areas that possess such policies that regulate the use of low carbon intensity hydrogen production pathways to ensure reductions in GHG emissions. Although some policies are regulated in Canada to a certain extent, their implementation is not consistent across the country that slows down the adoption process. Thus, there is an urgent need for drastic changes in the energy sector in Canada if the long-term goals are to be accomplished. Several policies are essential to be implemented to promote the utilization of hydrogen technologies in Canada, such as the development of


**Fig. 10 – Main challenges to be addressed for achieving a net-zero economy in Canada.**

zones that are emission-free, carbon pricing, vehicle emissions, and clean fuel regulations.

Another challenge associated with hydrogen sector development is technological. Even though certain hydrogen-related technologies are commercially mature and ready, there is a need to put further efforts to ensure cost reduction of these technologies which demand consistent financial assistance for research and development. At present, research and development specific to the hydrogen sector is provided intermittent support through financial assistance programs on a short-term basis resulting in limited investment by the private sector. Hence, the lack of long-term support is critical to the large-scale development and implementation of the hydrogen sector in Canada. While most of the developed nations have been investing more and more in this sector, Canada has not coped up with them and has been particularly behind with regard to hydrogen-related pilot initiatives. Consequently, various companies have shifted their businesses abroad where they found better assistance for technological development and innovation. Thus, the Canadian government must take necessary steps to avoid the loss of valuable intellectual property. Moreover, collaborations between academia and industry are extremely critical to tackling this challenge.

A very significant challenge related to the development of the hydrogen sector is infrastructural. The limited availability of low carbon intensity hydrogen at the domestic level in Canada is a major obstacle in the utilization of hydrogen-related applications at both pilot and commercial stages. Storage and transportation of hydrogen from the source to the user is extremely important for certain applications including the infrastructure of fueling stations for transportation purposes. Thus, there is an urgent need for the rapid development of the storage and distribution system of hydrogen simultaneously with an increase in its demand. In addition, there is a massive need for developing carbon storage infrastructure since the natural storage capability of Canada (e.g., exhausted wells) is limited to some specific provinces and areas. With a gradual increase in the local production and demand of hydrogen, dedicated pipelines and hydrogen liquefaction facilities will be required and their development in due time is imperative for delivering cost-effective and low carbon intensity hydrogen to the users both locally and internationally.

Awareness regarding the opportunities for hydrogen is lacking within the government, the industry, and the public in general which is another challenge to be tackled. There is an utmost need for educating the general public, the people who are directly involved in the industrial sector, and the government personnel who are responsible for policy formulation and implementation. A major cause of this lack of knowledge is due to limited deployments of hydrogen at the domestic level. Thus, it is extremely essential to educate people about the role and viability of hydrogen in decarbonization. Specialized nationwide educational campaigns are needed in this regard across all sectors that are direct stakeholders of hydrogen such as the industrial sector, energy sector, transportation sector, and academia. Additionally, educational efforts with regards to the career opportunities offered by the hydrogen sector to the skilled personnel with technical backgrounds are also essential.

Subsidization of the hydrogen sector is vital since it can play a critical role to expedite the transition to achieving decarbonization. Not only can the short and long-term subsidies encourage the preliminary acceptance of hydrogen energy systems but can also assist in their scale-up phase. Thus, it is imperative to provide subsidies to accelerate the transition to a hydrogen economy. A few examples of subsidies for strengthening the hydrogen sector include subsidies to consumers for direct purchasing energy systems that are powered by hydrogen, infrastructural subsidies, and taxation of $CO_2$-based vehicles, etc. Moreover, appropriate supervision and adaptation of the several subsidies can potentially reduce the likelihood of over and under-spending.

Standardization is another important issue to be addressed by developing the proper standards to appropriately cover the overall hydrogen spectrum that ranges from hydrogen production to its final utilization. This exercise is anticipated to influence the reliability, consistency, safety, and commercial feasibility of the hydrogen sector. The standards at the moment vary with location and significant modifications are often needed for them to be implemented at a different location. Minimization in the gaps with regards to the standards that are associated with various components of hydrogen infrastructure is also essential. Moreover, for the reliable and safe utilization of hydrogen in various sectors, there is a need for the standards and codes to be bolstered and coordinated at the international level. Thus, standardization is imperative for the development of an efficient hydrogen infrastructure.

An issue of significance when dealing with flammable fuels is the safety in their handling. Similar to conventional hydrocarbon fuels such as natural gas and gasoline, hydrogen is also flammable and can therefore act dangerously under certain conditions and is needed to be managed responsibly. Due to hydrogen's volatility, various challenges arise regarding its safety such as requirements of maintaining specific working temperatures and pressures which becomes extremely significant when the general public is involved in its utilization such as at hydrogen fueling stations. In addition, special safety measures need to be considered during the design phase of pipeline networks for delivering hydrogen over longer distances. A safe delivery infrastructure is essential for the successful commercialization of hydrogen to be utilized in various sectors and applications.

The road map to achieve the net-zero economy by 2050 in Canada is based on accomplishing certain near-term, mid-term, and long-term goals. Each of the objectives to be attained in one term paves a way for achieving the subsequent term's goals. In this regard, the near-term goals consider laying the groundwork for a hydrogen economy, the mid-term goals consider the development and expansion of the sector, and the long-term goals consider the swift expansion of hydrogen's market in Canada [7] as shown in Fig. 11. Fig. 12a shows the province-wise distribution of the number of job opportunities in the clean energy sector in Canada projected to be created by 2030. Fig. 12b shows the sub-sector-wise distribution of the number of job opportunities in the clean energy sector in Canada expected to be created by 2030.

Table 1 shows the details of the employment sub-sectors in the energy sector in Canada, the number of employees in each of those sub-sectors in 2019, and four different scenarios for

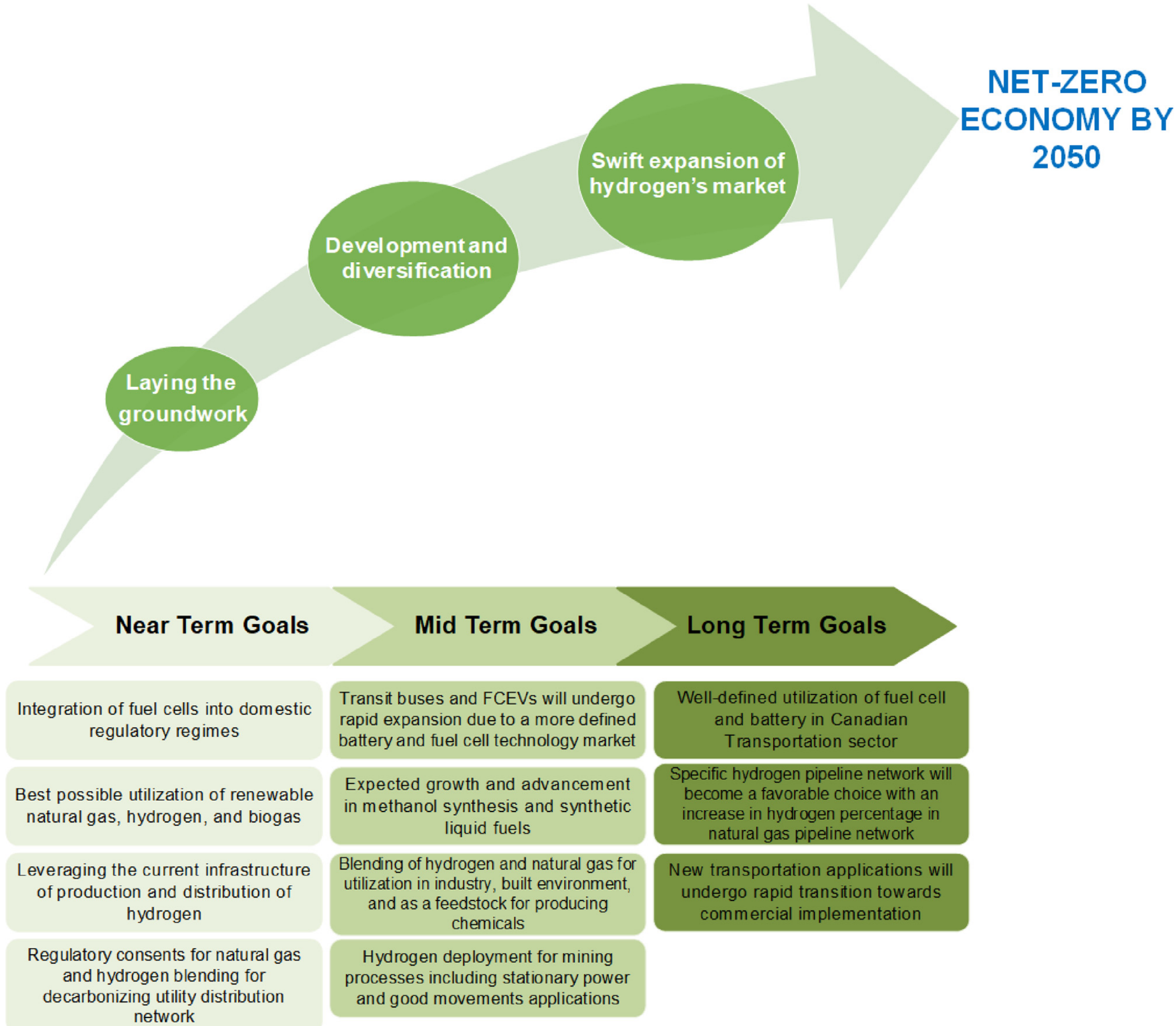


**Fig. 11 – Near, mid, and long-term goals to accomplish the net-zero economy in Canada by 2050.**

the estimated reduction in the number of employees in each sub-sector by 2030. The four scenarios are based on the trend in percentage reduction of employees as provided in Ref. [33] indicating the fluctuations in the number of employees in each of the sub-sectors between 2001 and 2019. The four scenarios include a 5, 6.5, 8, and 9.5% reduction in the number of employees by 2030. According to Ref. [34], 13.7% of employees working in the energy sector in Alberta are 55 years of age and above. Assuming that the same percentage is applicable to the employees in the energy sector in entire Canada, a further reduction in employees is also estimated by 2030. Table 2 shows the estimated number of employees shifting from each of the sub-sectors of energy sector in Canada to the hydrogen sector as part of the creation of employment opportunities in the sector. Three sub-scenarios are considered in this regard based on the percentage of employees shifting to hydrogen sector ranging from 10 to 30%. The shifting process is subject to the dedicated training of those employees to effectively serve in the hydrogen sector.

## Recently published literature specific to hydrogen in Canada

During the past decade, several investigations have been conducted and published in the open literature that are specific to hydrogen production in Canada. In this regard, Olateju and Kumar [35] developed a comprehensive techno-economic model for the evaluation of wind energy-based hydrogen generation by considering the pathway of water electrolysis. The proposed wind energy-based hydrogen plant considers the expansion of a currently operating wind farm in Alberta, Canada such that each wind turbine has a power generation capacity of 1.8 MW. They considered a constant flow rate electrolyzer (240 kW at 50 $Nm^3/h$) and a variable flow rate electrolyzer (360 kW at 90 $Nm^3/h$). These two sizes for the electrolyzers resulted in a minimum unit cost of hydrogen of 10.15 $/kg for the constant flow rate electrolyzer and 7.55 $/kg for the variable flow rate electrolyzer. For the baseline

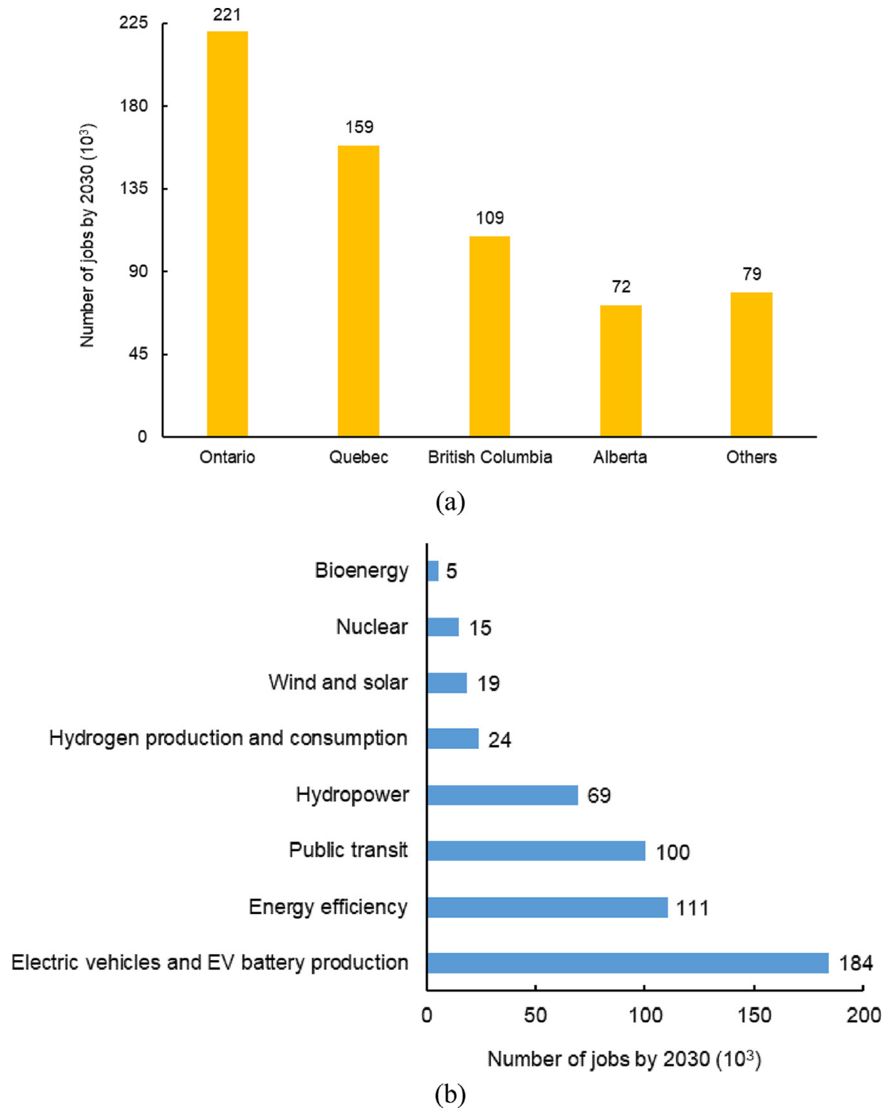


**Fig. 12 – (a) Distribution of the expected job opportunities in Canada's clean energy sector by 2030 for various provinces (data from Ref. [32]) and (b) distribution of the expected job opportunities in Canada's clean energy sector by 2030 for various sub-sectors (data from Ref. [32]).**

**Table 1 – Estimated number of employees in energy sector in Canada in 2019 and the estimated reduction in employees by 2030 based on [33,34].**

| Sub-sectors in energy sector in Canada | No. of employees in 2019 | Estimated reduction in employees by 2030 | | | | Estimated reduction in employees after retirement by 2030 | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Scenario A (5%) | Scenario B (6.5%) | Scenario C (8%) | Scenario D (9.5%) | Scenario A (5%) | Scenario B (6.5%) | Scenario C (8%) | Scenario D (9.5%) |
| Oil and gas extraction | 50,000 | 47,500 | 46,750 | 46,000 | 45,250 | 40,992 | 40,345 | 39,698 | 39,051 |
| Support activities for mining and oil & gas extraction | 125,000 | 118,750 | 116,875 | 115,000 | 113,125 | 102,481 | 100,863 | 99,245 | 97,627 |
| Natural gas distribution | 140,000 | 133,000 | 130,900 | 128,800 | 126,700 | 114,779 | 112,967 | 111,154 | 109,342 |
| Petroleum and coal product manufacturing | 160,000 | 152,000 | 149,600 | 147,200 | 144,800 | 131,176 | 129,105 | 127,034 | 124,962 |
| Petroleum and petroleum products wholesalers | 175,000 | 166,250 | 163,625 | 161,000 | 158,375 | 143,474 | 141,208 | 138,943 | 136,678 |
| Gasoline stations | 260,000 | 247,000 | 243,100 | 239,200 | 235,300 | 213,161 | 209,795 | 206,430 | 203,064 |
| Total | 910,000 | 864,500 | 850,850 | 837,200 | 823,550 | 746,063 | 734,283 | 722,504 | 710,724 |

**Table 2 – Estimated number of employees shifting from energy sector to hydrogen sector by 2030 based on various scenarios.**

| Sub-sectors in energy sector in Canada | Estimated employees joining hydrogen sector after training by 2030 | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Scenario A1 (10%) | Scenario A2 (20%) | Scenario A3 (30%) | Scenario B1 (10%) | Scenario B2 (20%) | Scenario B3 (30%) | Scenario C1 (10%) | Scenario C2 (20%) | Scenario C3 (30%) | Scenario D1 (10%) | Scenario D2 (20%) | Scenario D3 (30%) |
| Oil and gas extraction | 4099 | 8198 | 12,298 | 4034 | 8069 | 12,103 | 3970 | 7940 | 11,909 | 3905 | 7810 | 11,715 |
| Support activities for mining and oil & gas extraction | 10,248 | 20,496 | 30,744 | 10,086 | 20,173 | 30,259 | 9924 | 19,849 | 29,773 | 9762 | 19,525 | 29,288 |
| Natural gas distribution | 11,478 | 22,955 | 34,434 | 11,297 | 22,593 | 33,890 | 11,115 | 22,231 | 33,346 | 10,934 | 21,868 | 32,803 |
| Petroleum and coal product manufacturing | 13,118 | 26,235 | 39,353 | 12,911 | 25,821 | 38,731 | 12,703 | 25,407 | 38,110 | 12,496 | 24,992 | 37,489 |
| Petroleum and petroleum products wholesalers | 14,347 | 28,695 | 43,042 | 14,121 | 28,242 | 42,362 | 13,894 | 27,789 | 41,683 | 13,668 | 27,335 | 41,003 |
| Gasoline stations | 21,316 | 42,632 | 63,948 | 20,979 | 41,959 | 62,939 | 20,643 | 41,286 | 61,929 | 20,306 | 40,613 | 60,919 |
| Total | 74,606 | 149,213 | 223,819 | 73,428 | 146,857 | 220,285 | 72,250 | 144,501 | 21,675 | 71,072 | 142,145 | 213,217 |

conditions considered in their study, they reported a minimum delivery cost of hydrogen of 4.96 $/kg. In another study, Cuda et al. [36] assessed and compared the emissions resulting from the numerous modes of transportation utilizing hydrogen in Ontario, Canada. The purpose of their study was to examine which mode of transportation could benefit the most from hydrogen conversion. They considered three different scenarios based on hydrogen production via water electrolysis, thermochemical water-splitting through the copper-chlorine (Cu–Cl) cycle, and SMR. In the first scenario, the breakdown of hydrogen production through SMR, Cu–Cl cycle, and electrolysis was considered as 90%, 5%, and 5%, respectively. In the second scenario, this distribution was changed to 80%, 10%, and 10%, respectively and in the third scenario, a 70%, 20%, and 10% distribution was considered, respectively. According to their results, they reported a 9.8% reduction in $CO_2$ emissions while employing thermochemical hydrogen at a fraction of 20% for road vehicles weighing less than 4500 kg in comparison with hydrogen that is entirely obtained via SMR or other fossil fuel-based pathways. Moreover, they observed comparable trends for other modes of transportation including marine, air, and rail. Olateju and Kumar [37] evaluated the techno-economic feasibility of hydrogen generation through underground coal gasification (UCG) in Western Canada (Alberta) for bitumen upgrading. The inherent advantages of Western Canada such as abundant coal reserves and geological suitability for $CO_2$ sequestration make it an ideal location for obtaining cost-competitive sustainable hydrogen via UCG. They developed techno-economic models for UCG and SMR with and without incorporation carbon capture and sequestration to evaluate the hydrogen generation cost with delivery to bitumen upgrader. They considered seven different scenarios based on SMR with/without carbon capture and sequestration and UCG with/without carbon capture and sequestration. For SMR, hydrogen production was centered at Fort Saskatchewan, Alberta while $CO_2$ sequestration was carried out at either Thorhild, Alberta, or Swan Hills, Alberta. For UCG, hydrogen production was centered at Swan Hills, Alberta with hydrogen delivery to Fort Saskatchewan, Alberta while $CO_2$ sequestration was carried out at either Thorhild, Alberta, or within a 10 km radius of the UCG plant. Based on their analysis, they reported the unit costs of hydrogen for UCG and SMR without $CO_2$ sequestration to be 1.78 and 1.73 $/kg, respectively while with sequestration in place for both processes, the unit hydrogen cost ranged between 2.1 and 2.7 $/kg for UCG and between 2.14 and 2.41 $/kg for SMR. In another study, Olateju et al. [38] techno-economically evaluated wind energy-based hydrogen production with energy storage in Alberta. Through their developed model, they determined the optimal electrolyzer size, the number of electrolyzer units, and the capacity of the battery for energy storage by utilizing the real-time wind energy data to obtain a minimum production cost of hydrogen. According to the plant's optimal design, it constituted a total of 81 electrolyzer units with a capacity of almost 3500 kW and 60 battery units with a capacity of 360 MWh. The minimum unit cost of hydrogen was evaluated to be 9 $/kg which was claimed to be reduced to 3.37 $/kg subject to utilizing the existing farm resources. Moreover, they concluded that this unit hydrogen cost was not competitive with that of SMR which ranges between 1.9 and 2.6 $/kg. Ghandehariun and Kumar [39] conducted the life cycle assessment of wind energy-based hydrogen generation in Alberta in which they evaluated the environmental impact of hydrogen obtained via water electrolysis based on electricity supplied through wind energy. They performed a life cycle assessment to ascertain the GHG emissions per unit mass for the obtained hydrogen by accounting for the emissions beginning from the point of wind energy extraction to the point of hydrogen generation. They reported the overall GHG emissions for the plant to be approximately 0.68 kg of $CO_2$ eq. per kg of $H_2$ which was estimated to be 94% less than the emissions resulting through SMR. Mukherjee et al. [40] proposed a detailed design of a renewable hydrogen-based microgrid capable of supplying backup electricity to a community in Cornwall, Ontario in case of interruption from the power grid. The various components of the system included fuel cells, FCEVs, wind turbines, solar panels, electrolyzers, and hydrogen tanks to supply electricity throughout the community. The community's peak energy demand of nearly 5400 kW was estimated for which 1600 kW and 400 kW of energy would be provided through a wind turbine and solar panels, respectively. An additional 3000 kW was also supplied via the fuel cell generation system as a backup in case of a total blackout for two days. Moreover, 38 Toyota Mirai were also utilized to supply vehicle-to-grid service. It was concluded that more economic provisions need to be provided for clean microgrid power generation systems to allow for a positive net present value at the end of the project's life. Most recently, Aydin et al. [41] investigated the development of a prospective hydrogen hub in Oshawa (Ontario), Canada. Several key conclusions were drawn based on their obtained results. They reported that an increase in the demand for hydrogen generation technologies, fueling stations, and FCEBs is expected to cause a reduction in their costs. Moreover, the overall emissions could potentially be decreased by nearly 60% subject to the gradual increase and corresponding decrease in the FCEBs and diesel buses, respectively since the FCEBs emit 89% fewer pollutants. They also concluded that for hydrogen to be competitive with fossil fuels, incentives from the government are essential for the implementation of large-scale projects. In another most recent study, Karaca and Dincer [42] provided a comprehensive overview of research and development activities associated with hydrogen in Canada during the past 50 years. In their study, they comparatively assessed the contributions from research centers and academic organizations in Canada towards research and innovation activities in specific relation to hydrogen. Based on their findings, they reported that nearly 112,500 publications in total were contributed by Canadian institutes towards hydrogen research during the considered period. Moreover, Ontario Tech University, which is a considerably young academic institution in Canada, has accounted for 11% of research articles to hydrogen research which is the highest contribution in this area from a Canadian organization.

## Conclusions

This paper provides a comprehensive overview of the development of the hydrogen sector in the near and long-term future in Canada. The various opportunities of hydrogen utilization in several sectors and the challenges in the way of large-scale adoption of hydrogen for numerous purposes in Canada are also discussed. In this regard, being the third largest producer of hydroelectricity in the world, Canada can most certainly adopt the water electrolysis pathway with hydroelectricity as the clean electricity source for obtaining large-scale low carbon intensity sustainable hydrogen. In the context of the public transport sector, FCEBs can potentially replace the diesel buses as an environment-friendly option while at the same time not compromising over efficiency for both inter and intra city transportation in Canada. Further, hydrogen can replace fossil fuels for space and process heating purposes in buildings and industry in Canada to ensure reductions in emissions. The domination of hydrogen as a clean fuel in the wider spectrum of transportation sectors such as marine, aviation, rail, mining, and goods movement equipment is also not a distant reality in the Canadian context. For a net-zero economy to be achieved by Canada by 2050, numerous infrastructural, technological, policy, and economic challenges are needed to be tackled and overcome. An inherent advantage to Canada in this regard is its abundance of natural resources and the required technological capacity. And, with the implementation of the necessary policies and all the other steps taken in the right direction, Canada has the potential to become one of the global giants in the context of achieving a hydrogen economy in the long-term future.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Nomenclature

| | |
|---|---|
| AHC | Australian hydrogen council |
| BEB | battery electric bus |
| BEV | battery electric vehicle |
| CHFCA | Canadian hydrogen and fuel cell association |
| CMMP | Canadian mineral and metals plan |
| CNG | compressed natural gas |
| $CO_2$ | carbon dioxide |
| Cu−Cl | copper chlorine |
| FCEB | fuel cell electric bus |
| FCEV | fuel cell electric vehicle |
| GHG | greenhouse gas |
| IC | internal combustion |
| IEA | international energy agency |
| IMO | international maritime organization |
| IPHE | international partnership for hydrogen and fuel cell economy |
| MOU | memorandum of understanding |
| OEM | original equipment manufacturer |
| PEM | proton exchange membrane |
| PHEV | plug-in hybrid electric vehicle |
| P2G | power-to-gas |
| RNG | renewable natural gas |
| SMR | steam methane reforming |
| SOEC | solid oxide electrolysis cell |
| UCG | underground coal gasification |
| ZEV | zero-emission vehicles |

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