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Hydrogen Hub Potential

A FEASIBILITY STUDY FOR THE REGINA-MOOSE JAW INDUSTRIAL CORRIDOR

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The Transition Accelerator
L'Accélérateur de transition

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EXECUTIVE SUMMARY

Energy transition. Over the last two centuries our global energy mix has continuously shifted. From the burning of biomass for heating, to the use of coal through the Industrial Revolution, to the adoption of oil and gas from the mid-1900s to present day. These transitions were driven predominantly by **population growth, economic development, innovation, energy density,** and **resource availability**. While those elements still apply today, concerns are mounting over global climate change, dominated by the atmospheric accumulation of human-produced greenhouse gases (GHGs), including carbon dioxide (CO_2) and methane (CH_4).

Canada is one of 90 countries in the world that have committed to achieve net-zero GHG emissions by mid-century. While the province of Saskatchewan has not signed on to the national commitment, their climate change strategy does include a plan to achieve significant emissions reductions in the coming decades.

Since more than 70% of Canada's GHG emissions are associated with the production and distributed combustion of four energy carriers (gasoline, diesel, jet fuel and natural gas), achieving major reductions in emissions necessitates finding zero-emission alternatives to those that are carbon intense. The options are limited and include biofuels, electricity, hydrogen, and ammonia, all of which must be produced with minimal or no GHGs.

Electricity produced from hydropower, wind, solar, nuclear, or fossil fuels coupled with carbon capture and storage (CCS) is widely seen as the most promising zero-emission energy carrier for the future. However, challenges associated with its production, storage, distribution, and use makes electricity a poor solution for sectors such as heavy-duty, long-distance, or off-grid mobility, space heating in cold climates, or industrial process heat demand.

Hydrogen has long been an industrial feedstock for petroleum refining and the production of ammonia, which is essential to produce nitrogen fertilizer for agriculture. However, in recent years, the drive for climate change solutions has countries around the world investing in projects that would use hydrogen and ammonia as energy carriers.

This report explores the potential for Saskatchewan's **Regina-Moose Jaw Industrial Corridor (RMJIC)** to produce, use, and export low GHG hydrogen, thereby reducing emissions and contributing to the economy of the province. A 'hydrogen hub' in the RMJIC could build on the existing refinery that currently produces and uses hydrogen, the proven CO_2 storage in the region, the wind and solar potential of southern Saskatchewan, and the province's vast uranium resource. All of these assets point to the potential for the RMJIC to produce low cost, low GHG hydrogen as an energy carrier and industrial feedstock for domestic and export markets.

This report explores the potential for Saskatchewan's **Regina-Moose Jaw Industrial Corridor (RMJIC)** to produce, use, and export low GHG hydrogen, thereby reducing emissions and contributing to the economy of the province.

While the region has good potential for successful hub development, there are challenges that would have to be addressed to ensure a robust hydrogen economy for the RMJIC, including the development of **infrastructure for CCUS and pure hydrogen transport and storage**. With the production of low-carbon "blue" hydrogen from natural gas, comes the need for CCUS pipeline infrastructure. Hydrogen would also require low-cost transport for future large-scale adoption. Fortunately, there is interest in the future of dedicated pipelines from industries within the RMJIC and there are federal government incentives which could support CCUS and clean hydrogen projects in the region. The Carbon Capture, Utilization, and Storage Investment Tax Credit, which supports projects tied to dedicated geological storage and storage in concrete, expanded in 2023 to include a broad range of equipment. The Clean Hydrogen Investment Tax Credit provides subsidies from 15% to 40% of eligible costs for clean hydrogen projects [1,2]. Each of these ITCs could be key to attracting investment in CCUS and a hydrogen hub for the RMJIC.

There are challenges that would have to be addressed to ensure a robust hydrogen economy for the RMJIC, including the development of **infrastructure for CCUS and pure hydrogen transport and storage**.

Hydrogen Price Targets. On an equal basis of energy units (C$/$GJ_{HHV}$), Western Canadians pay significantly more for transportation fuels (C$25 to C$45/GJ) than for space heating from natural gas (C$8 to C$13/GJ). As such, the total retail cost of hydrogen would have to be C$5 to C$8/kg when used for transportation and C$2 to C$3/kg when used to provide heat and power for homes and buildings, to be cost competitive against legacy fuel sources. The lowest cost currently which includes the sum of production from natural gas, processing and delivery, and refuelling is C$5 to C$7/kg. This assumes hydrogen production from natural gas priced at C$4.20/GJ in Saskatchewan and hydrogen delivery over 5 km of dedicated pipeline to an 8 t H_2/day fuelling station.

Hydrogen Demand and Market Potential in the RMJIC. Early estimates based on the 2020 energy system yielded a total demand of 601 t H_2/d. An RMJIC-specific analysis applied regional sector specific activity and an energy use escalation (1.5% annually) for more accurate estimates of **691 t H_2/d by 2028** and **895 t H_2/d by 2035** in the following areas:

- ☐ **Industrial feedstock** demand could reach **749 t H_2/d** which represents ~84% (Figure ES1) of the total estimated hydrogen demand by 2035. Major industries in the RMJIC use feedstocks for petroleum refining and urea production. While these industries currently produce enough hydrogen on site to satisfy their feedstock needs, the demand for low-carbon hydrogen for fuel is expected to rise. In addition to feedstocks, a hydrogen hub could support near- to mid-term industrial process heat by blending hydrogen with natural gas.

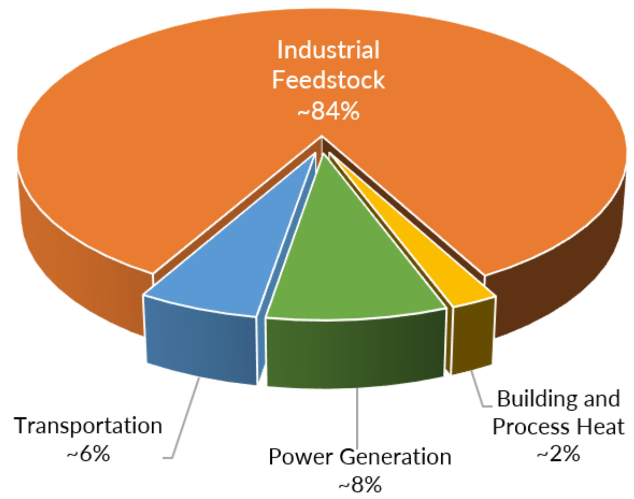

Figure ES1 Relative percentage of RMJIC hydrogen demand by market in 2035.

- ☐ **Transportation fuel** demand of nearly **51 t H_2/d** by 2035 is largely attributed to medium- and heavy-duty trucks (~56%) and freight rail (~23%). There could also be opportunities over the mid- to long-term for (motive) agriculture which comprises ~33% of all transportation energy use throughout the province of Saskatchewan.

- ☐ **Power Generation** demand of **76 t H_2/d** by 2035 assumes that hydrogen will be used to provide backup power and support the intermittency of renewable energy. Covering the industrial, commercial, and residential sectors, this estimate also accounts for cases where scale does not justify the adoption of CCUS technology.

- ☐ **Building and Process Heat** demand of **20 t H_2/d** assumes a 10% blending rate with natural gas by 2035, supporting space and water heating throughout the industrial, commercial, and residential sectors.

Projected RMJIC hydrogen market potential does not include the significant portion of existing hydrogen demand for industrial feedstocks. A net hydrogen demand of 146 t H_2/d by 2035 represents a market potential of C$133M/y at a wholesale price of C$2.50/kg H_2.

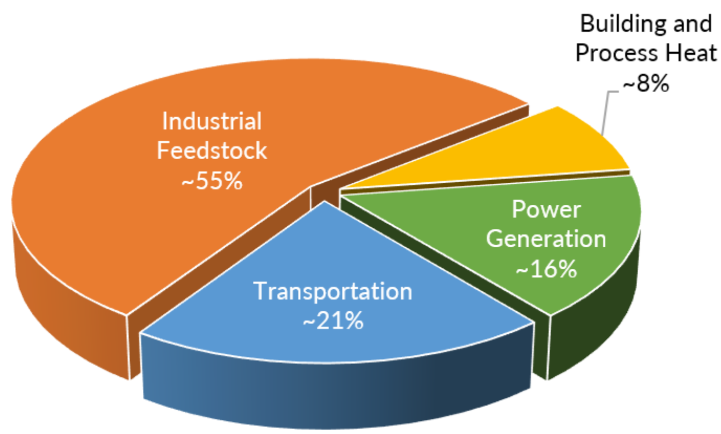

Figure ES2 Relative percentage of RMJIC hydrogen demand by market in a low-emissions future.

In an unconstrained supply scenario (Figure ES2), the **RMJIC hydrogen demand in a low-emissions future** would be much higher for a total of 1,719 t H_2/d. Transportation, power generation, and building and process heat would comprise ~45% of hydrogen demand throughout the RMJIC for a **total fuel demand of 776 t H_2/d** which represents **a market potential of C$708M/y.** Expand the low-emissions hydrogen potential to **the entire province of Saskatchewan**, served in part by the RMJIC, and the market value climbs to **C$2.7B/y**.

The RMJIC has opportunities (Figure ES3), interests, and unique qualities which favour a hydrogen hub and related CCUS infrastructure development for Saskatchewan, including:

- ☐ **Leveraging a regional CCUS hub to accelerate low-carbon hydrogen production.** Continued investment in CCUS will be critical for hydrogen hub development in the RMJIC. An existing CCUS hub in southern Saskatchewan, and a newly approved geologic storage project in the RMJIC, could be leveraged to accelerate the production of "blue" hydrogen and support future industrial carbon reduction initiatives throughout the region.

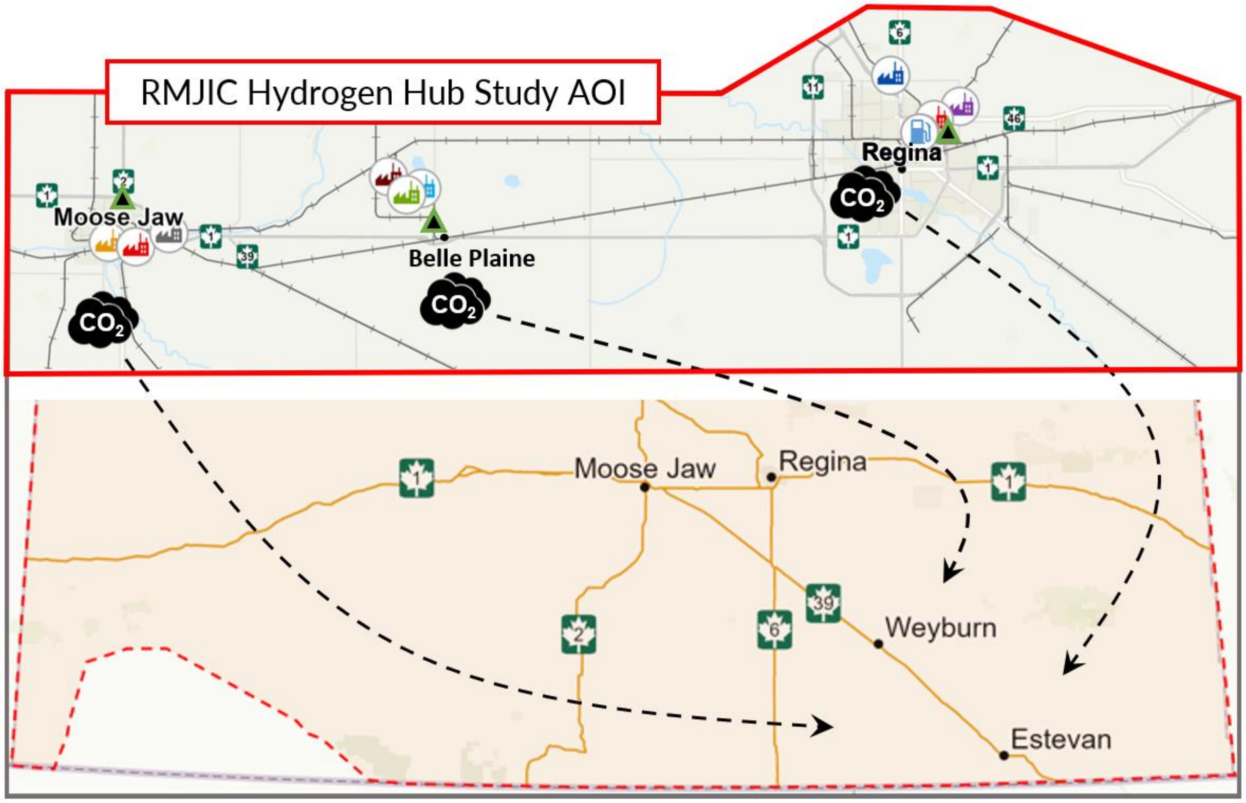

Figure ES3 General schematic depicting opportunities for hydrogen hub and CCUS development in the RMJIC.
Sources: EERC [5] and Esri Canada [3] (modified)

- ☐ **CO_2 Storage Potential.** Saskatchewan is estimated to have at least 3 gigatonnes (Gt) of regional CO_2 storage space in approved/operating geologic storage projects and EOR projects south of the RMJIC, and ~250 Gt of prospective CO_2 storage (P50) throughout the province [4,5]. Hydrogen production from natural gas reforming and coal/biomass gasification are among the lowest cost CCS technologies.

- ☐ **Hydrogen Storage Potential.** When developing hydrogen as an energy carrier, scale-up would require gas storage to buffer variations in supply and demand, as with "green" hydrogen production from renewables. Salt cavern storage (SCS) is among the favoured sub-surface options. The capital cost of SCS for hydrogen can range from C$127/kg H_2 to C$26/kg H_2 on a scale of 100 to 3,000 tonnes [126]. Annual storage costs range from approximately C$23/kg H_2 to C$4/kg H_2 over the same scale and would improve with increased cycling of hydrogen gas. The total levelized cost of SCS for hydrogen, which includes capital and storage, can be as low as C$3.40/kg H_2 for working gas capacities of 100,000 tonnes [127].

- ☐ **Medium- and heavy-duty road freight.** Trucks in provincial classes 5 through 13 account for nearly 40% of all transportation on Saskatchewan highways with over 1,000 units passing through the RMJIC daily. Assuming 8 t H_2/d per fuelling station, the RMJIC could support 3-4 fuelling stations by 2035 on trucking demand alone. Early planning for fuelling station development in the RMJIC should be considered along with leveraging existing pilot initiatives in British Columbia and Alberta such as Hydra (hydrogen-diesel dual-fuel or H2DF) and AZETEC (hydrogen fuel cell electric or HFCE).

- ☐ **Freight rail.** 97% of the diesel demand for rail transport in Saskatchewan is used to haul freight. HFCE trains are currently being piloted in Western Canada and RMJIC energy demand by 2035 would require 12 t H_2/d to support a 10% transition for freight rail. CPKC Limited's H20EL initiative should be leveraged to accelerate development in this area.

- ☐ **Dedicated pipelines.** Local steel manufacturing is interested in the development of safety codes and standards for pure hydrogen pipeline that would be designed to resist embrittlement. They are also working on projects tied to CO_2 pipeline and related projects in CCUS. [150]

- ☐ **Future low-carbon hydrogen production.** Saskatchewan has some of the best solar and wind resource potential in the country and plans for the development of new nuclear. Wind and solar generation can produce low-carbon hydrogen during times of peak production for use during off-peak periods. Nuclear can produce low-carbon hydrogen from electricity and/or heat via high-temperature electrolysis or thermolysis.

Challenges to be addressed for the development and scale-up of a hydrogen hub in the RMJIC. The following are key hydrogen hub related challenges either specific to Saskatchewan and the RMJIC or the hydrogen economy as a whole:

- ☐ **Economics.** Today's retail cost of "blue" hydrogen fuel in the RMJIC (C$5 to C$7/kg) would only be competitive in a transportation market. This assumes 5 km of dedicated pipeline from a natural gas production source to a fuelling station optimized to deliver 8 t H_2/day. The power generation and building and process heat markets would require a total retail cost of C$2 to C$3/kg H_2 to be competitive. Adding salt cavern storage for increased scalability would require a minimum C$12.7 million in capital with a minimum annual storage cost of C$2.3 million. [126]

- ☐ **Hydrogen properties and energy efficiency.** Efficiency losses from multiple energy transfers is especially challenging when using electrolytic H_2 for grid storage. Losses from production of electrolytic hydrogen and conversion from hydrogen back to electricity can range from 30% to 80% [16,17]. This is partly due to the unique physical and chemical properties of hydrogen. Hydrogen gas has a remarkably low volumetric energy density which requires considerable work for compression, significant space for storage, and energy for pipeline transport. Hydrogen also heats up when decompressed, unlike most real gases, adding to the cost of hydrogen fuelling stations.

- **Infrastructure.** The RMJIC would require significant infrastructure development to support hydrogen fuel markets. The transportation market would require 6 to 7 fuelling stations to satisfy transportation estimates of RMJIC hydrogen demand for 2035. Pure hydrogen markets for backup and renewable power and building and process heat would require dedicated pipelines and compressors, not to mention upgrades to end-use applications such as industrial and home heating systems. While hydrogen blending could be considered as a near- to mid-term strategy until such infrastructure is in place, the integrity of existing natural gas pipeline networks would have to be assessed for embrittlement potential and durability under various concentrations of hydrogen gas.

- **Hydrogen supply and demand.** Saskatchewan is also challenged in terms of natural gas production, from which "blue" hydrogen is manufactured. The province produced ~10 million m^3/d of natural gas in 2020, or ~2% of all gas in Western Canada. With natural gas production steadily declining in the province over the past decade [68], a regional hydrogen economy would require low-carbon hydrogen produced from coal, biomass, or imported natural gas to satisfy hydrogen demand estimates over the near- to mid-term and added production from sources such as renewables and nuclear over the mid- to long-term.

- **Investment Tax Credits.** The Clean Hydrogen ITC does not apply to projects with carbon intensities greater than or equal to 4 kg CO_2e/kg H_2, which would mean considerable investment into the development and deployment of CO_2 capture units in the RMJIC over the near- to mid-term. However, both The Clean Hydrogen and CCUS ITCs challenge the development of "blue" hydrogen in the region, as they exclude projects which utilize captured CO_2 for enhanced oil recovery (EOR) and therefore do not support the use of existing CCUS infrastructure to produce "blue" hydrogen from natural gas.

The following are suggested next steps for the RMJIC to capitalize on the hydrogen hub potential in the region:

- **Build a regional hydrogen hub consortium** to support a shared vision for hydrogen and develop a regional hub strategy. The consortia should be comprised of government and First Nations representatives, industry associations, companies representing the entire value chain, and universities and other research groups.

- **Develop a CCUS strategy for the RMJIC** to leverage and expand upon existing CCUS infrastructure in southern Saskatchewan for de-risked carbon sequestration and scale-up of "blue" hydrogen production. CCUS infrastructure growth could also support local industries with future CO_2 reduction initiatives and incentives.

- **Leverage existing pilot initiatives** for regional trials to garner public support and spur hydrogen hub investment, such as the Hydra (H2DF) and AZETEC (HFCE) truck projects and H20EL from CPKC Limited. New trials of farm equipment that can run on both diesel and hydrogen, such as H2 Dual Power tractors, should also be considered.

- **Pre-plan for the development of RMJIC hydrogen fuelling stations (HFS)** at the confluence of freight rail lines and Highway 1 in Regina's east end.

- **Initiate detailed studies into regional salt cavern storage potential.** Large volume gas storage will be essential for hydrogen to support the intermittency of wind and solar power and to be readily available for backup power generation.
- **Initiate the development of dedicated hydrogen pipelines** and respective safety codes and practices.
- **Accelerate the development of low-carbon hydrogen production** from sources in addition to natural gas such as renewables and new nuclear.

ABOUT THE TRANSITION ACCELERATOR

The Transition Accelerator (The Accelerator) exists to support Canada's transition to a net-zero future while solving societal challenges. Using our four-step methodology, The Accelerator works with innovative groups to create visions of what a socially and economically desirable net-zero future will look like and build out transition pathways that will enable Canada to get there. The Accelerator's role is that of an enabler, facilitator, and force multiplier that forms coalitions to take steps down these pathways and get change moving on the ground.

Our four-step approach is to understand, codevelop, analyze and advance credible and compelling transition pathways capable of achieving societal and economic objectives, including driving the country towards net-zero greenhouse gas emissions by 2050.

1 UNDERSTAND the system that is being transformed, including its strengths and weaknesses, and the technology, business model, and social innovations that are poised to disrupt the existing system by addressing one or more of its shortcomings.

2 CODEVELOP transformative visions and pathways in concert with key stakeholders and innovators drawn from industry, government, indigenous communities, academia, and other groups. This engagement process is informed by the insights gained in Stage 1.

3 ANALYZE and model the candidate pathways from Stage 2 to assess costs, benefits, trade-offs, public acceptability, barriers and bottlenecks. With these insights, the process then re-engages key players to revise the vision and pathway(s), so they are more credible, compelling and capable of achieving societal objectives that include major GHG emission reductions.

4 ADVANCE the most credible, compelling and capable transition pathways by informing innovation strategies, engaging partners and helping to launch consortia to take tangible steps along defined transition pathways.

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LIST OF ABBREVIATIONS

ABBREVIATION	DEFINITION
°C	Degrees Celsius
AOI	Area of Interest
ATR	Autothermal Reforming
Bcf	Billion Cubic Feet
Bcf/d	Billion Cubic Feet per Day
BEV	Battery Electric Vehicle
BTX	Benzene, Toluene, Xylene
Ca-Br	Calcium Bromide
Cao	Calcium Oxide
CCS	Carbon Capture and Storage
CCUS	Carbon Capture, Utilization, and Storage
CH_4	Methane
CHP	Combined Heat and Power
CMA	Census Metropolitan Area
CN	Canadian National (Railway)
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CO_2e	Carbon Dioxide Equivalent
CO_2e/y	Carbon Dioxide Equivalent per Year

CP	Canadian Pacific (Railway)
Cu-Cl	Copper-Chlorine
EOR	Enhanced Oil Recovery
EUP	Ebara Ube Process
FCL	Federated Co-operatives Ltd.
GHG	Greenhouse Gas
GJ	Gigajoule
Gt	Gigatonne
GTH	Global Transportation Hub
H_2	Hydrogen
H2DF	Hydrogen-Diesel Dual-Fuel
H20EL	Hydrogen Zero-Emission Locomotive
H_2S	Hydrogen Sulfide
HCl	Hydrochloric Acid
HCN	Hydrogen Cyanide
HFCE	Hydrogen Fuel Cell Electric
HFS	Hydrogen Fuelling Station
HHV	High heating value
HTSE	High Temperature Steam Electrolysis
ICE	Internal Combustion Engine
IEA	International Energy Agency
J	Joule

J/kg	Joule per Kilogram
kg	Kilogram
kg H_2/d	Kilogram of Hydrogen per Day
km	Kilometer
km^3	Cubic Kilometers
kt	Kilotonne
kt H_2/y	Kilotonnes of Hydrogen per Year
kW	Kilowatt
LCOH	Levelized Cost of Hydrogen
LCOT	Levelized Cost of Transport
LH_2	Liquid Hydrogen
LHV	Low Heating Value
LOHC	Liquid Organic Hydrogen Carrier
LOS	Lease of Space
m^3	Cubic Meter
m^3/d	Cubic Meters per Day
Mcf/d	Thousand Cubic Feet per Day
MCH	Methylcyclohexane
MJ/kg	Megajoule per Kilogram
MMcf	Million Cubic Feet
MPa	Megapascal
Mt	Megatonne
Mt CO_2e	Megatonnes of Carbon Dioxide Equivalent

MW	Megawatt
MWh	Megawatt Hour
NH_3	Ammonia
NOx	Nitrogen Oxide
PEM	Proton Exchange Membrane
PJ	Petajoule
PJ/y	Petajoule per Year
PSA	Pressure-Swing Adsorption
RM	Rural Municipality
RMJIC	Regina-Moose Jaw Industrial Corridor
S-I	Sulfur-Iodine
SMNR	Small Modular Nuclear Reactor
SMR	Steam Methane Reforming
SOEC	Solid Oxide Electrolytic Cells
t CO_2e/y	Tonnes of Carbon Dioxide Equivalent per Year
t H_2/d	Tonnes of Hydrogen per Day
TT	Tube Trucks
WGS	Water-Gas Shift

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1 INTRODUCTION

1.1 Why Hydrogen?

Canada is one of 90 countries in the world that have committed to achieve net-zero GHG emissions by mid-century. While the province of Saskatchewan has not signed on to the national commitment, their climate change strategy includes a plan to achieve significant reductions in GHG emissions in the coming decades.

Since the majority of Canada's GHG emissions are associated with the production and distributed combustion of four energy carriers (gasoline, diesel, jet fuel, and natural gas), achieving major reductions in GHGs necessitates finding zero-emission alternatives to these carbon intense energy carriers. The options are limited, and include biofuels, electricity, hydrogen, and ammonia, all of which must be produced with minimal or no GHG emissions.

Electricity produced from hydropower, wind, solar, nuclear, or fossil fuels coupled with carbon capture and storage (CCS) is widely seen as the most promising zero-emission energy carrier for the future. However, challenges associated with its production, storage, distribution, and use makes electricity a poor solution for sectors such as heavy-duty, long-distance, or off-grid mobility, space heating in cold climates, or industrial process heat demand.

Hydrogen has served local industry for decades as feedstock for petroleum refining and the production of fertilizers, and many organic and inorganic compounds such as methanol and ammonia. Hydrogen could also have a pivotal role in a future low-emissions energy system with potential end uses ranging from residential and industrial heat to transportation fuel. Annual global production of hydrogen is currently around 120 million tonnes with a tenfold increase expected over the next thirty years to satisfy global demand. [6,7]

As hydrogen is like electricity in its ability to move energy, its use could extend to applications where electrification is challenged, with the added benefit of energy storage for future use. It can be stored in competent caverns or tanks for delayed fuel combustion or converted to electricity using hydrogen fuel cells. A typical car with an internal combustion engine (ICE) operates at an efficiency of about 20%. Equipped with a fuel cell, that efficiency increases to 40%-60% depending on the vehicle, the driver, and the road conditions. The US Department of Energy (DOE) states that the efficiency of a proton exchange membrane (PEM) fuel cell is 60% based on the low heating value (LHV) of hydrogen [8].

Hydrogen, at nearly three times the specific energy of natural gas, gasoline, and diesel, has the most energy units per mass with low and high heating values of 120 and 142 MJ/kg, respectively [9]. However, it has very low energy output per unit volume in an ICE because the hydrogen displaces air significantly at the intake, de-rating the engine. In terms of space and water heating, studies have shown efficiency fluctuations as low as 1-2% when blending up to 30% hydrogen with natural gas [10,11]. Hydrogen is also extremely efficient at the molecular level, taking the same amount of energy to separate it from oxygen as is found within it. When used as an alternative fuel, hydrogen has some of the lowest carbon dioxide equivalent (CO_2e) emissions.

While hydrogen can be produced from almost any source of energy, including wind, solar, hydropower, nuclear, and biomass, approximately 95% of the world's commercial production is from natural gas through the process of steam-methane reforming (SMR). With annual increases in carbon pricing, alternatives to fossil fuels and the process of electrolysis and thermolysis for mass hydrogen production become increasingly cost competitive. Developments in hydrogen transport will also be key to being competitive. Current options for hydrogen transport include pipeline blending with natural gas and transport by truck, rail, or ship in either liquid or compressed gas form.

A renewed momentum

Interest in hydrogen fuel began in the 1970s with concerns over petroleum shortages and an awareness of the effects of vehicle emissions on ambient air quality. This led to the emergence of associations and projects in support of hydrogen as an alternative fuel[1,2]. Enthusiasm eventually waned with the discovery of abundant fossil fuels and alternative controls over air pollution, such as the introduction of the catalytic converter and US government regulations mandating its use in 1975 [12]. Fast-forward to the late 1990s and early 2000s, and there was renewed interest due to mounting concerns over global climate change. However, a surge in the development of hydrogen fuel cell vehicles and the introduction of public fuelling stations could not overcome the high cost of hydrogen production, technology, and infrastructure, and the lack of climate policy implementation. After five decades of research and development (R&D) and attempts to boost interest in commercial hydrogen, the latest wave of momentum comes with significant progress that could see us through to a thriving hydrogen economy. [13]

There has been considerable growth in applications for hydrogen use and research into a range of hydrogen production methods with cost and cleanliness in mind. Nations have also shown more interest in mitigating climate change through the development of greener global economies, especially in light of a changing geopolitical landscape [13]. Furthermore, the development of a hydrogen hub network through Western Canada, with connections to the northern US, could spur local investment and welcome energy export opportunities.

While battery electric vehicles (BEVs) have taken centre stage in the transition away from small ICEs, hydrogen offers solutions to medium- and heavy-duty transport not supported by the limited range and added weight of BEV technology. Progress and interest in hydrogen fuel cell electric (HFCE) technology has led to a 70% reduction in production cost since 2008 [14]. In 2017, nearly all HFCE vehicles were passenger cars. By 2021, nearly 20% were comprised of buses and trucks, as the global market grew more than sixfold to over 43,000 hydrogen vehicles [13]. In addition to HFCE trucks, hydrogen-diesel dual-fuel (H2DF)

[1] International Energy Agency Hydrogen and Fuel Cell Technology Collaboration Program
[2] International Journal of Hydrogen Energy

retrofits have emerged, offering the advantage of early adoption and the ability to use 100% diesel or a combination of diesel and up to 90% hydrogen [15].

The global renewable energy sector has grown considerably in recent years with a move towards energy diversity. With a greater share of renewables to come, hydrogen could offer energy storage solutions to offset the intermittency of these resources. As with any transfer of energy, however, there are efficiency losses to consider, which can range from 30% to 80% for hydrogen [16,17]. Despite such challenges, there were over 350 renewables-based hydrogen projects under development globally in 2021, while more were in the early stages. Among the pilot projects were the world's first production of fossil fuel-free steel in Sweden, and the production of renewables-based ammonia in Spain. [18,19]

It is important to note that even renewables-based hydrogen sources are not carbon-free, as they produce what is referred to as low-carbon hydrogen once life-cycle emissions and the entire process from minerals extraction to end-of-life is considered. Low-carbon hydrogen can also be produced from natural gas with the addition of carbon capture, utilization, and storage (CCUS) or from nuclear via electrolysis or thermochemical processes as published extensively in Canada and abroad over the past decade. [20-23]

1.2 Why Hydrogen Hubs?

According to the International Energy Agency (IEA), low-carbon hydrogen would have to account for 10% of global energy consumption by 2050 in a net-zero scenario [16]. The creation of hydrogen hub networks could support reduced emissions and drive market demand by aligning producers, consumers, and existing infrastructure for sustainable economic growth of low-carbon hydrogen in each of the respective hydrogen hub corridors. The identification of supply and demand synergies that exist within those concentrated areas of activity, such as the **RMJIC**, is key to a strong business case for hydrogen. In addition, the hub model could support the sharing of capital costs for new infrastructure and connections to R&D in commercial hydrogen technology and workforce capacity [24].

> [A hydrogen hub is] a **coordinated**, **synergistic**, **regional** initiative for economic development to create an **economically viable** hydrogen **value chain** where **low- or zero-emission hydrogen** is **used as a novel fuel or industrial feedstock**, thereby achieving **substantial reductions** in greenhouse gas emissions.

The definition of a hydrogen hub by Natural Resources Canada (NRCan) is "a coordinated, synergistic, regional initiative for economic development to create an economically viable hydrogen value chain where low- or zero-emission hydrogen is used as a novel fuel or industrial feedstock, thereby achieving substantial reductions in greenhouse gas emissions". For a hub to be successful, it must satisfy the requirements for regional, feedstock, and end-use diversity [25]. Canada has diverse feedstocks to support many types of low-carbon hydrogen production - from fossil fuels and growth in CCUS and the renewable energy sector to large-scale biomass supply and the emerging development of new nuclear, all of which apply to Saskatchewan. End-use diversity can be supported by identifying opportunities across multiple energy-intensive applications such as transport, power generation, space and water heating, manufacturing, resource extraction, and upgrading and refining.

The following hydrogen hub roadmaps have been released from either federal or provincial governments across Canada since 2020, highlighting opportunities for economic growth and reduced GHG emissions by way of an emerging hydrogen economy:

- The Government of Canada released the "Hydrogen Strategy for Canada: Seizing the Opportunities for Hydrogen" in December 2020, with plans to increase hydrogen production from fossil fuels, hydropower, renewable, and nuclear energy. [26]
- The Government of British Columbia published the "B.C. Hydrogen Strategy" in July 2021, in support of its climate change goals and the creation of clean-tech jobs. [27]
- The Government of Alberta published the "Alberta Hydrogen Roadmap" in November 2021. As the largest hydrogen producing province in Canada, their strategy highlights the potential for global market access while growing the hydrogen economy. [28]
- The Government of Ontario released "Ontario's Low-Carbon Hydrogen Strategy" in April 2022, for a self-sustaining hydrogen economy through the creation of local jobs, investment, and GHG emissions reductions. [29]
- The Government of Québec published the "2030 Québec Green Hydrogen and Bioenergy Strategy" in May 2022, with plans to increase the production and distribution of alternatives to fossil fuels in pursuit of a more diverse energy mix. [30]

Canada's first hydrogen hub was launched in the Edmonton Region in April 2021. Leaders from government, Indigenous groups, academia, and economic development brought forward a shared vision for the future of hydrogen fuel. Their plan, which focuses on heavy-duty trucks, rail, public transport, farm machinery, and home heating, received a boost from the Government of Canada in November 2022, with a $300 million investment through the Net-Zero Accelerator Initiative for the advancement of clean fuels in Canada. At an estimated cost of $1.6 billion, the project by Air Products Canada Ltd. will see the development of an autothermal reforming (ATR) hydrogen production facility complete with CO_2 capture technology. The federal government also announced their support for ten additional Alberta-based hydrogen-related projects in late 2022. [31,32]

The US Department of Energy (DOE) recently announced $6-7 billion of funding to support a nationwide hydrogen hub network for low-carbon hydrogen production. Various projects will engage local and regional stakeholders, including First Nations communities, and explore a range of efficient production options to further economic development of affordable hydrogen hubs across the country. Selection criteria for projects include the use of low-carbon production from fossil fuels, renewables and nuclear. End use criteria must include electrical power generation, industrial, residential and commercial heating, and transportation. [33]

1.3 Towards a New Hydrogen Value Chain

A hydrogen value chain consists of four main stages which include production, distribution, storage, and end use. Its development does not necessarily happen sequentially, however, as each component is mutually dependent on one another to create value. That is, hydrogen producers require end users, while end users need to have cost-competitive hydrogen readily available. These two components are also connected through the distribution and storage of hydrogen. Throughout the chain is the need for R&D and innovation, and the establishment of safety protocols, codes, and standards. As such, simultaneous development and collaboration of each component is required if this newly emerging economy is to come to fruition.

The chain concept may also convey the idea of simplicity, but hydrogen value chains are rather complex. The versatility that hydrogen offers as an energy carrier opens opportunities for value chains to be established within distinct markets. As shown in Figure 1.1, the value chain offers applications for feedstock, fuel for transport and space heating, and energy storage. It also supports opportunities for "blue" hydrogen production, which is the production of hydrogen from natural gas with CCS. Within each region, such as the RMJIC, one or more chains could evolve, and each market could grow separately or in tandem with one another.

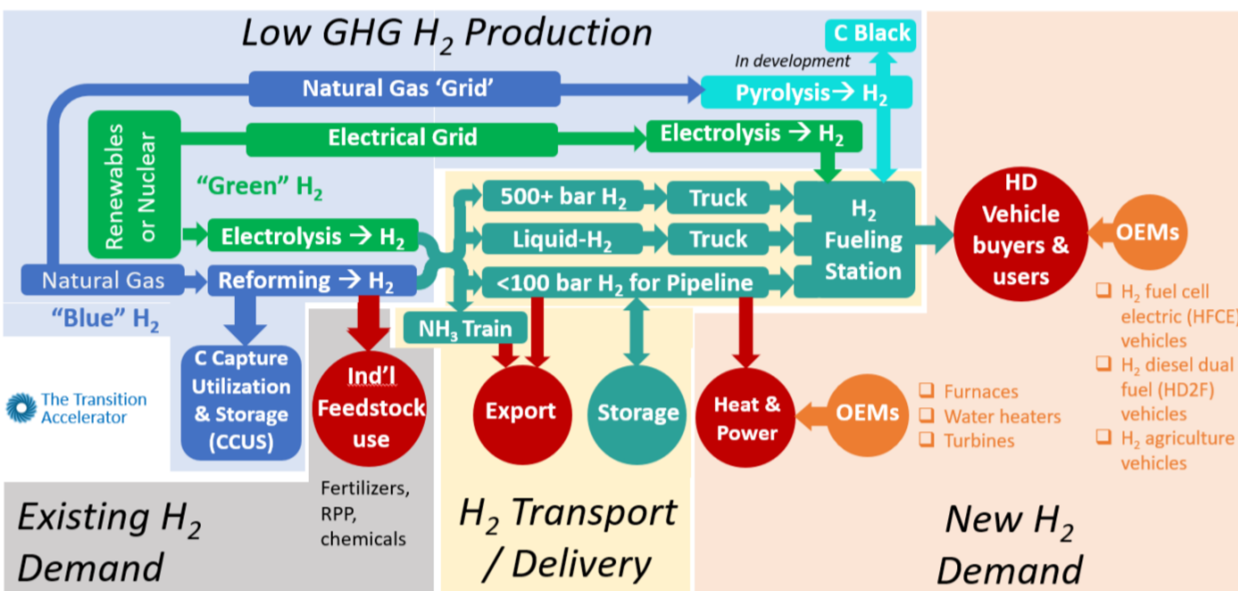

Figure 1.1 The new hydrogen value chain

Source: The Transition Accelerator [31]

Value chain complexity increases when there are multiple options for hydrogen production with hubs being built around more than one production pathway. A myriad of colors including "grey," "blue," and "green" imply various production methods with unique challenges. On the upside, the future hydrogen economy could be less constrained (geographically) than it is today. The production of hydrogen from renewable energy could mean the emergence of hub support from multiple locations throughout the province.

Because this is a new value chain, stakeholders naturally have questions about its development with cost being a key consideration. What is the most cost-effective method to produce hydrogen and how does this compare to conventional fuels? How much do current methods of distribution, including pipelines and transport tanks, add to the cost of a project? Where can hydrogen be produced most effectively and is this near the end user? Each question must be addressed early on so companies can begin to make near-, mid-, and long-term investment decisions. Both literally and conceptually, a hydrogen hub can shorten the distance between producers and end users allowing for quicker and more effective decision-making along the entire value chain. [31,34]

1.4 The RMJIC Feasibility Study/Foundation Report

This Foundation Report is the first step in the Transition Accelerator's four-stage process for launching hydrogen hubs. All hubs are expected to be active in all four areas. They do not necessarily need to occur in sequence, but a successful hub should include all four. The hydrogen hub stages are as follows:

A. **Foundation Report.** Documents the regional 'assets' that could be harnessed in a transition to a hydrogen economy and engages the key players in the concept. This would include the following:
   - Production Potential (by-product, "green" or "blue" hydrogen; could also include proximity to hydrogen pipeline)
   - Demand Potential (governments and private; wide range of sectors)
   - Transportation Opportunities (could include existing or unused pipeline infrastructure)
   - Funding Opportunities (various levels of government, private sector, philanthropy)

B. **Develop Shared Vision(s) for Possible Transition Pathways.** Builds on Stage A to engage a 'coalition of the willing' to articulate a strategy for building and connecting hydrogen supply to hydrogen demand. (It is possible that the foundation report will not lead to a 'coalition of the willing', and the regional efforts will not progress to creating a hub.)

C. **Techno-economic Analysis.** Critically assesses the ideas that are generated in Stage B. Stages B and C are highly iterative, feeding each other to improve the strategy and engage more stakeholders.

D. **Pilot, Demonstration and Commercialization Projects.** Using the insights gained in stages A, B and C, it should be possible to create compelling arguments for public and private investments in pilot, demonstration, and commercialization projects.

2 OVERVIEW OF THE RMJIC

2.1 Defining the RMJIC

The Regina-Moose Jaw Industrial Corridor (RMJIC) is located in southeast Saskatchewan. This hydrogen hub study considers a relatively narrow corridor that is bookended by the City of Regina and the town of White City in the east and the City of Moose Jaw to the west and includes the four rural municipalities (RMs) of Moose Jaw, Pense, Sherwood, and Edenwold.

The City of Regina is the provincial capital and the second largest city in Saskatchewan with a population of 226,404 in 2021. The City of Moose Jaw is 72 kilometers west of Regina with a population of 33,665 in 2021. The three RMs have a combined population of just over 2,700 people. Other communities in the region include the towns of White City, Grand Coulee and Pense, and the villages of Tuxford and Belle Plaine with a combined population of approximately 5,000 people.

The RMJIC Hydrogen Hub Study area of interest (AOI), as shown in Figure 2.1, falls within Treaty 4 territory. It includes the lands of the Cree, Saulteaux, Dakota, Nakota, Lakota, and the traditional territory of the Metis. The First Nations groups within the RMJIC are primarily located to the northwest and southeast of Regina with a combined population of approximately 2,900 as of 2021.

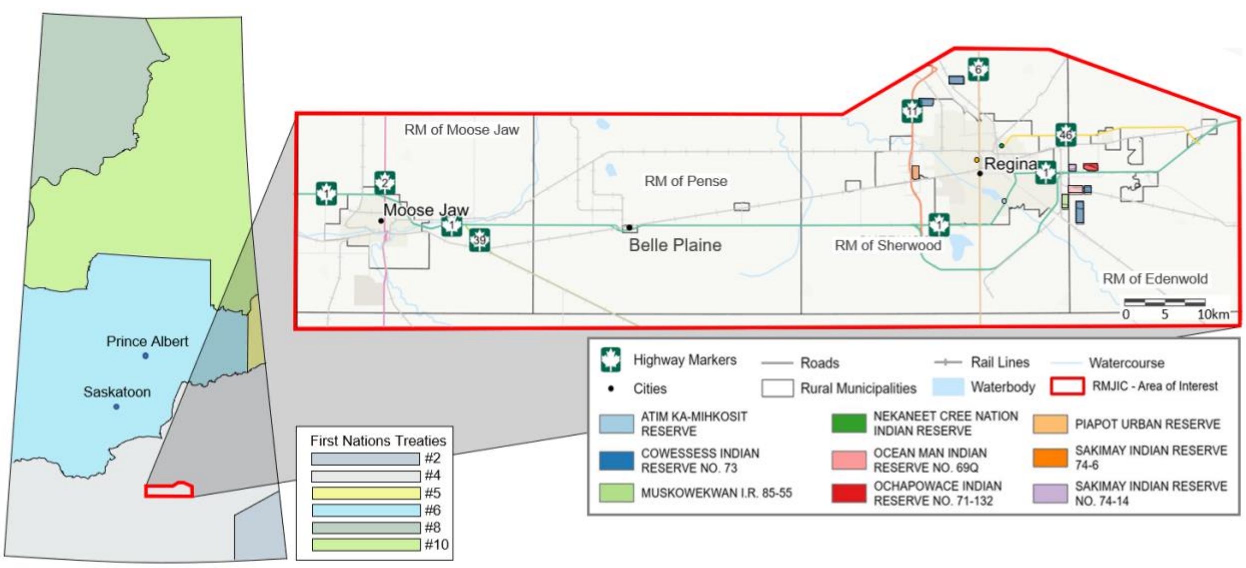

Figure 2.1 Area of interest (AOI) for the RMJIC Hydrogen Hub Study showing rural municipalities (RMs) and First Nations' communities.

Source: Esri Canada [3] (modified)

2.2 RMJIC Economy and Demographics

The RMJIC is situated on the Western Canadian prairie. Grain handling and food processing are major contributors to the economy given the large agriculture industry presence. Livestock production is also prominent in the area. Moose Jaw has one of the largest livestock distribution facilities in Saskatchewan [35]. Agricultural product manufacturing, including fertilizer and machinery, are important economic drivers for the RMJIC. One of the largest fertilizer operations in the province is located in Belle Plaine and several large agricultural equipment manufacturers are based in the cities of Regina and Moose Jaw.

Biofuel production is expanding within the corridor, partially driven by Canadian Clean Fuel Regulations, which were implemented in June 2022 [36]. The Federated Co-operatives Limited (FCL) Ethanol Complex in Belle Plaine produces 150 million litres of biofuel annually [37]. The processing of biomass from agricultural waste such as straw, is another growing sector in the area. Two large-scale projects have been announced that will look to add value to flax and wheat straw.

Among the key industries in the RMJIC are petroleum refining, steel manufacturing, and potash mining (Figure 2.2). Saskatchewan's largest oil refinery and only steel manufacturing plant are both located in Regina. There is one operating potash mine in the RMJIC, while several operating or proposed potash solution mines surround the region. A wide area of land in southern Saskatchewan is also emerging as a potential source of helium and lithium.

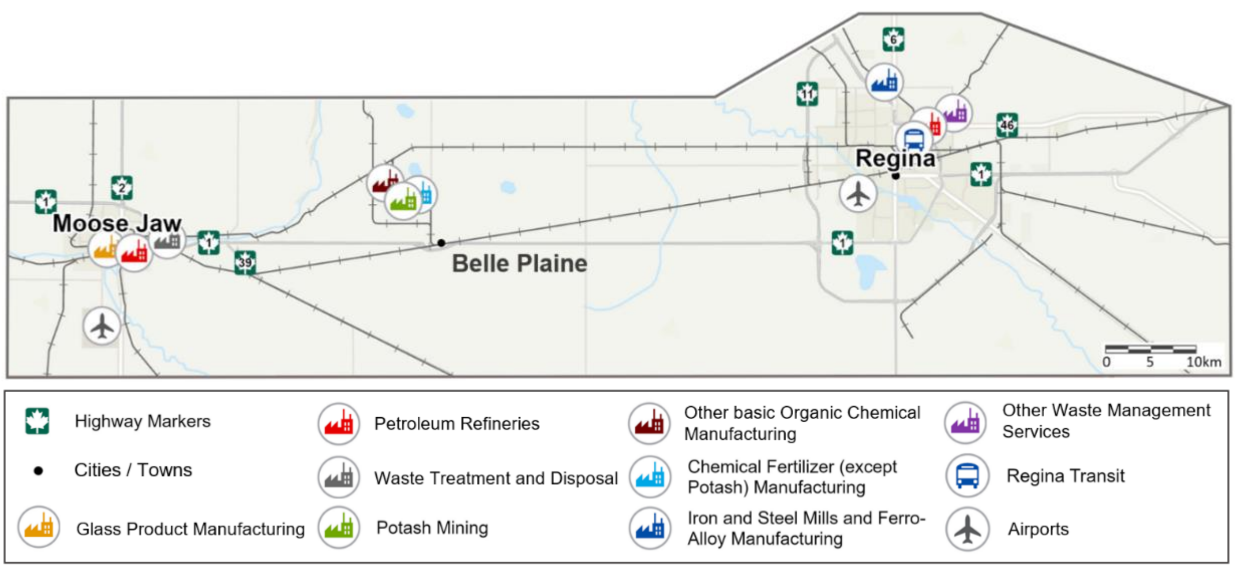

Figure 2.2 Key industries and services in the RMJIC.

Source: Esri Canada [3] (modified)

The RMJC was estimated to have just over 270,000 people in 2021. This represents 22.8% of the total population of Saskatchewan, which was approximately 1.183 million as of January 2022.

There were just over 100,000 private dwellings in Regina as of 2021. Of these, the single-detached house comprised the largest share with nearly 65,500 dwellings. The population density of the city was 57.6 people per square kilometer. In Moose Jaw, there were just over 15,000 dwellings, of which 10,750 were single-detached houses, and the combined RMs had a total of approximately 1,050 dwellings.

2.3 RMJIC Infrastructure

2.3.1 Current Infrastructure

Given the volume of agriculture industry exports from the RMJIC, both Moose Jaw and Regina have well-established facilities and infrastructure for the export of commodities globally. As shown in Figure 2.3, the region is well connected through highways and rail as the handling capacity of inland ports continues to grow. The Global Transportation Hub (GTH) in Regina is a transportation and logistics inland port which is serviced by Canadian Pacific Kansas City (CPKC) Limited. The road, rail, and port infrastructure are estimated to give the region access to over 60 million customers within a single day of travel. [38]

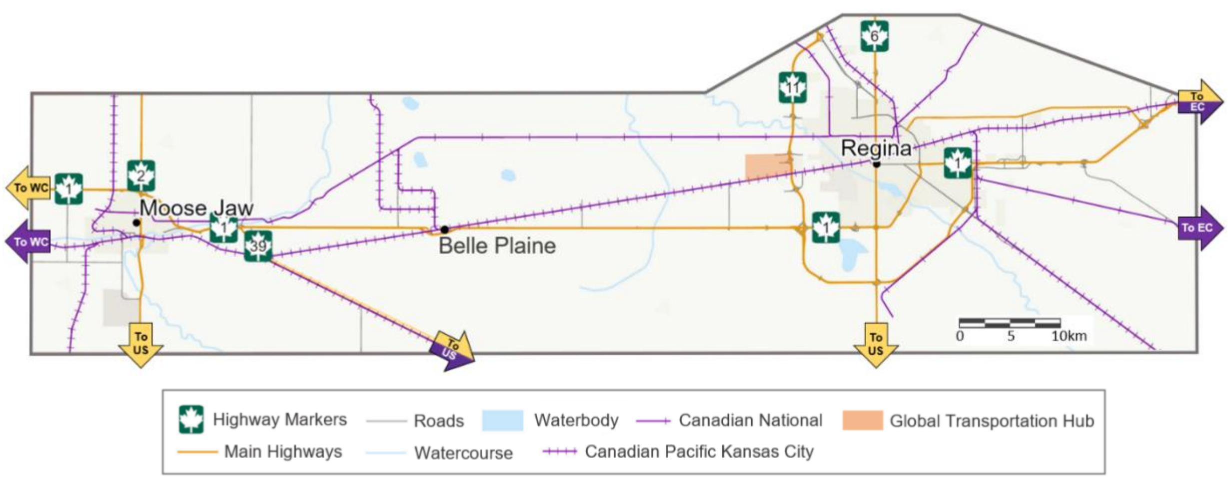

Figure 2.3 RMJIC major highways and rail networks.

Source: Esri Canada [3] (modified)

Highway network

TransCanada: The TransCanada (Highway 1) is the longest road corridor in Canada as it connects the east and west coasts (Figures 2.3 and 2.4). To the west of Moose Jaw, the TransCanada continues to Swift Current, Saskatchewan and then passes through Calgary, Alberta ending in Vancouver, British Columbia on the west coast. To the east of Regina, the highway connects to Winnipeg, Manitoba. Highway 1 also links Regina to Moose Jaw as it dissects the three RMs. A third key industrial center – the village of Belle Plaine – is also situated along this highway.

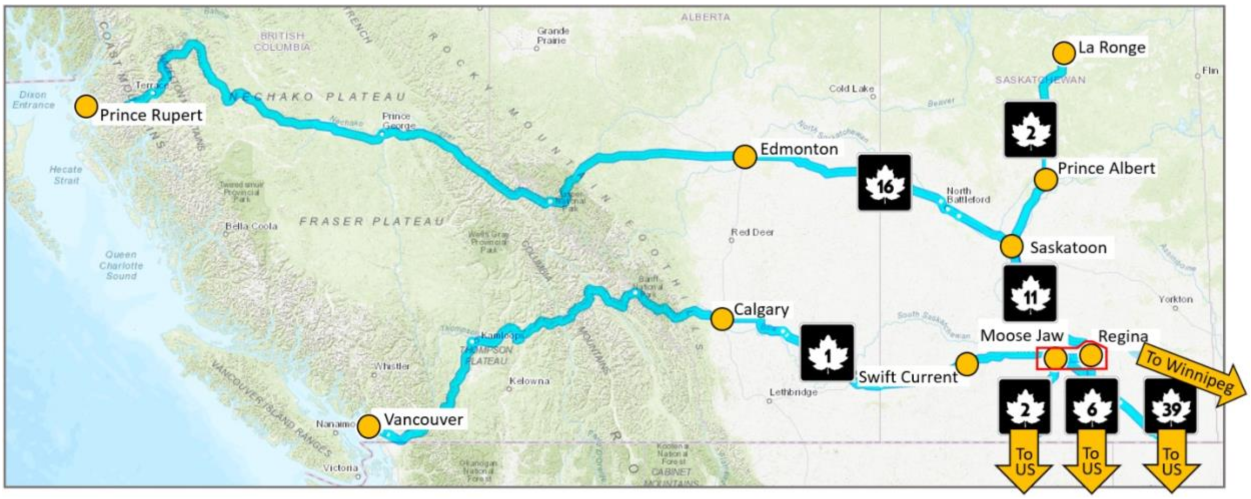

Figure 2.4 Major highway network from the RMJIC to British Columbia and the US.

Source: Esri Canada [3] (modified)

Highway 11: This four-lane divided highway marks a major north-south route that runs approximately 250 km from Regina to Saskatchewan's largest city of Saskatoon. From Saskatoon the road continues north and connects to the third largest city of Prince Albert, making this highway one of the more important transportation links in the province. From Saskatoon, Highway 11 links to Highway 16, another primary east-west interprovincial route. It passes through Edmonton, Alberta en route to a key marine port in Prince Rupert, British Columbia.

Highway 2: This major north-south route passes through Moose Jaw. It is estimated to be the longest highway in the province at just over 800 km. To the south, it extends to the Montana border crossing of West Poplar River, Saskatchewan. To the north, it runs from Moose Jaw and ends at La Ronge, Saskatchewan, a town 240 km north of Price Albert.

CanAm Highway: Both Regina and Moose Jaw have roadways that run south to the US border as part of the larger network known as the CanAm Highway. **Highway 6** from Regina links to the Montana border at the custom port of Regway. **Highway 39** is another north-south route connecting the TransCanada and Moose Jaw to the US.

Rail network

Canadian Pacific Kansas City (CPKC) Limited: The CPKC main line runs though the cities of Regina and Moose Jaw and the area of Belle Plaine as it connects to the port of Vancouver along the west coast (Figures 2.3 and 2.5). Moose Jaw currently holds the largest main line refueling facility on the CPKC North American Network. Other CPKC lines making connections in the region include the CPKC Weyburn, which is a second main line that passes through Moose Jaw. CPKC Outlook and CPKC Expanse Branch lines connect to Moose Jaw, running north and south. The Soo Line, operated by a subsidiary of CPKC, is a key rail network connecting Moose Jaw to locations in the US including Minneapolis and Chicago. [39]

Figure 2.5 Major railway network from the RMJIC to British Columbia and the US.

Source: Esri Canada [3] (modified)

Canadian National (CN) Railway: The CN Qu'Appelle main line runs to Regina and the CN Central Butte branch line extends from Regina to Moose Jaw. The CN Glenavon branch line connects Regina to the southeast region of the province. In the west, the CN main line connects to marine ports in Vancouver and Prince Rupert, British Columbia.

Short-line railways: Short-line railways also connect Regina to various regions of the province. The Stewart Southern Railway runs approximately 130 km northwest from Stoughton to Regina, and the Last Mountain Railway runs from Regina northwest to Davidson.

Oil and Natural Gas Pipeline Infrastructure

The federally regulated pipeline network for liquid and gas from Saskatchewan to British Columbia is shown in Figure 2.6 [40]. Major oil pipelines pass through the RMJIC and transport crude oil to the refineries in Moose Jaw and Regina with connections to the US. The Enbridge Canadian Mainline is one of the primary crude oil pipelines in the province. It runs from Alberta, through Saskatchewan, and to the United States Midwest and the U.S. Gulf Coast. Plains Midstream Canada operates the Wascana Pipeline that moves light crude oil from the Bakken in North Dakota to Regina where it connects to the Enbridge Mainline. [41]

Keystone Pipeline operated by TC Energy runs from Alberta to refineries in Illinois and Texas. The Cochin pipeline, operated by Pembina Pipeline Corporation, passes through the RMJIC starting from terminals in Illinois and delivers condensate to Fort Saskatchewan, Alberta. [42]

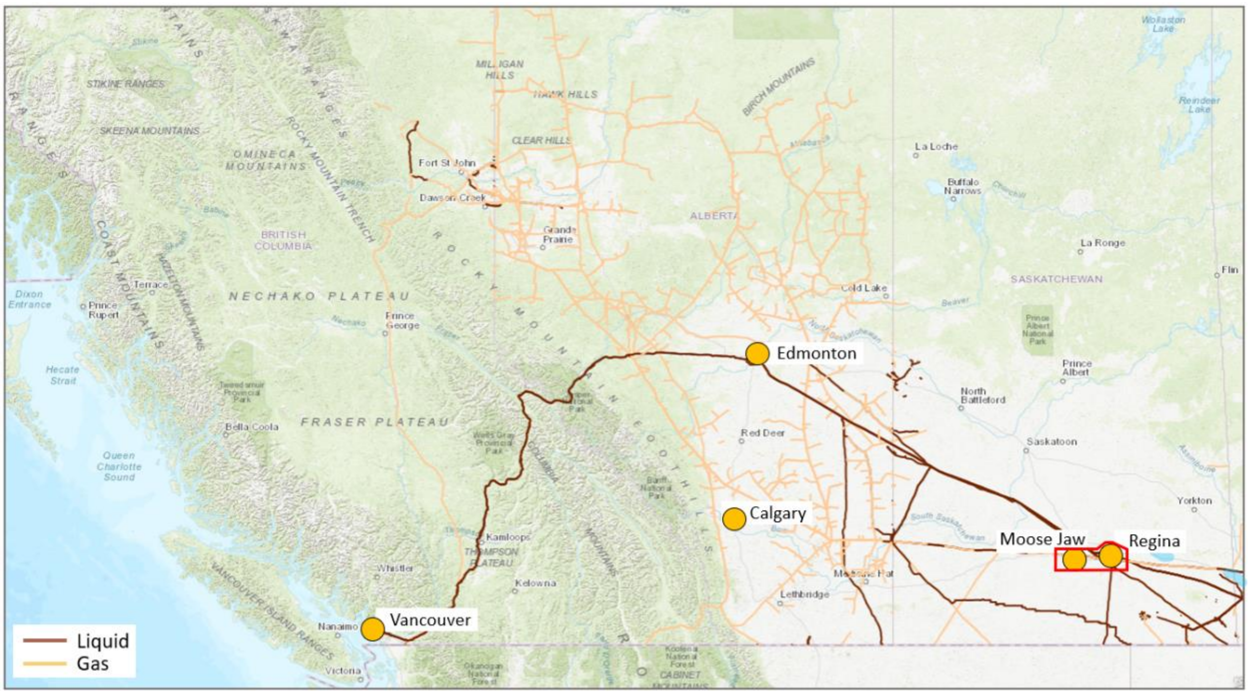

Figure 2.6 Federally regulated liquid and gas pipeline network throughout Saskatchewan, Alberta, and British Columbia.

Sources: CER [40] Esri Canada [3] (modified)

SaskEnergy is the provincial utility that supplies Saskatchewan with natural gas through an extensive pipeline network with connections to Regina, Belle Plaine, and Moose Jaw. The approximate locations of TransGas pipelines and natural gas gates, or town border stations, is shown in Figure 2.7. The figure also shows the general locations of natural gas storage in the RMJIC. Five underground caverns south of Regina have been used for natural gas storage with a total initial working gas capacity of approximately 3 billion cubic feet (Bcf).

SaskEnergy is building a major transmission line to supply the Great Plains Power Station, a 360 MW natural gas power plant being constructed near Moose Jaw by SaskPower for completion in 2024 [43]. SaskPower is also considering upgrades to the power system between Regina and Moose Jaw in preparation for future electricity demand [44]. The work includes new switching stations and transmission lines with plans for a new station at Belle Plaine.

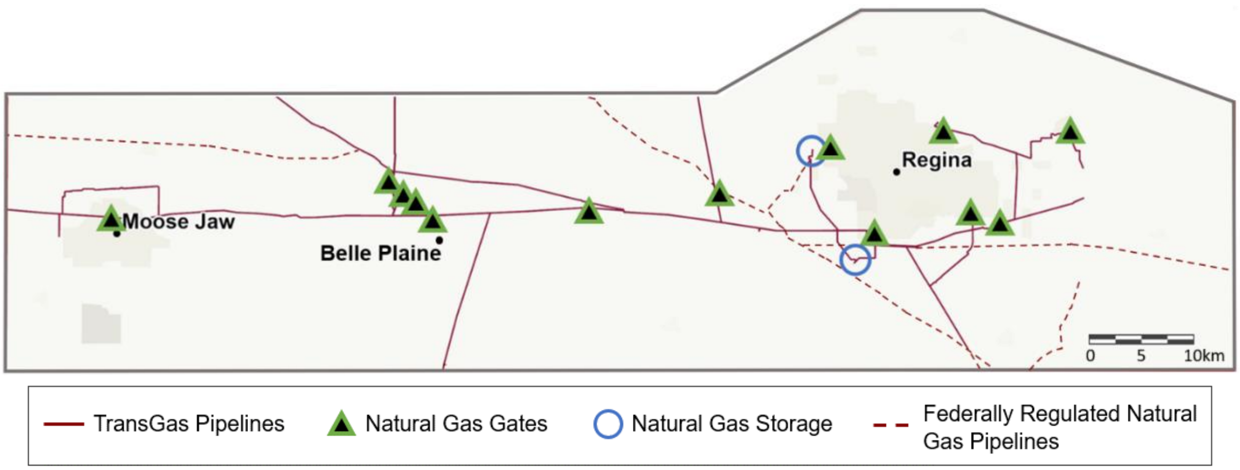

Figure 2.7 Locations of natural gas pipelines, gates, and storage.

Sources: SaskEnergy[3] and Esri Canada [3] (modified)

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2.3.2 Current and Potential Infrastructure

Renewable Power

While the region has some of the best solar profiles in Canada and moderate wind potential (Figures 2.8A and 2.8B – Province of Saskatchewan noted by red polygon), the only wind-solar operation in the RMJIC is the Cowessess Renewable Energy Storage Facility located on the outskirts of Regina to the southeast. As the first hybrid renewable energy system ever developed in Canada, it is rated for over 2,888 megawatt-hours (MWh) annually. A second renewable facility, The Foxtail Grove Solar Energy Project, is expected to begin production in 2023 to supply up to 10 MW of electricity to roughly 2,600 homes in the Regina area. [45,46]

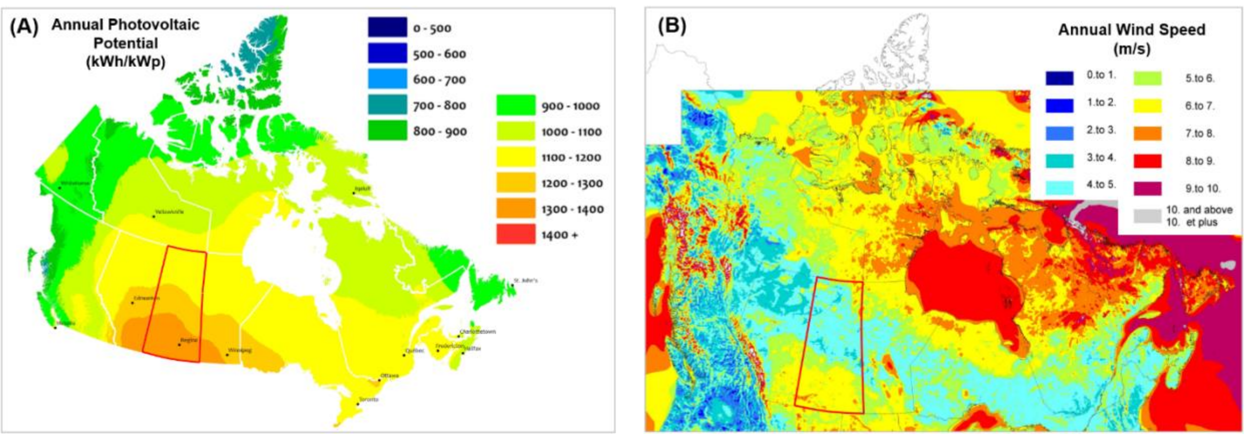


Figure 2.8 (A) Annual photovoltaic potential and (B) wind speed.

Sources: NRCan [47] and Environment and Climate Change Canada [48] (modified)

Underground storage for hydrogen and CO_2

Storage potential will be essential for the large-scale adoption of hydrogen. The halite deposits of the Middle Devonian Prairie Evaporite in Saskatchewan (Figures 2.9 and 2.10A) hold potential for future hydrogen storage. However, there are concerns for the competency of these units as gas storage reservoirs, and further work should be conducted regarding their safety and storage capacity in the region.

Saskatchewan has proven and prospective underground storage capacity for CO_2 within the Basal Cambrian Sandstone (Figures 2.9 and 2.10B) which extends west to Alberta, east to Manitoba, and to Montana and North and South Dakota in the US. While the extent of CO_2 storage capacity throughout the basin is largely prospective, the Weyburn-Estevan region south of the RMJIC has proven capacity which supports a CCUS hub and pipeline connections to the US. The RMJIC also has approved CO_2 storage and approved lease of space (LOS) for CO_2 storage south of Belle Plaine, as shown in Figure 2.11. Pipeline connections between current and future CCUS infrastructure throughout the RMJIC and surrounding areas will be key to satisfying future demand for low-carbon hydrogen production in the region. CCUS projects and related infrastructure in southern Saskatchewan are covered in Subsection 6.2.1.

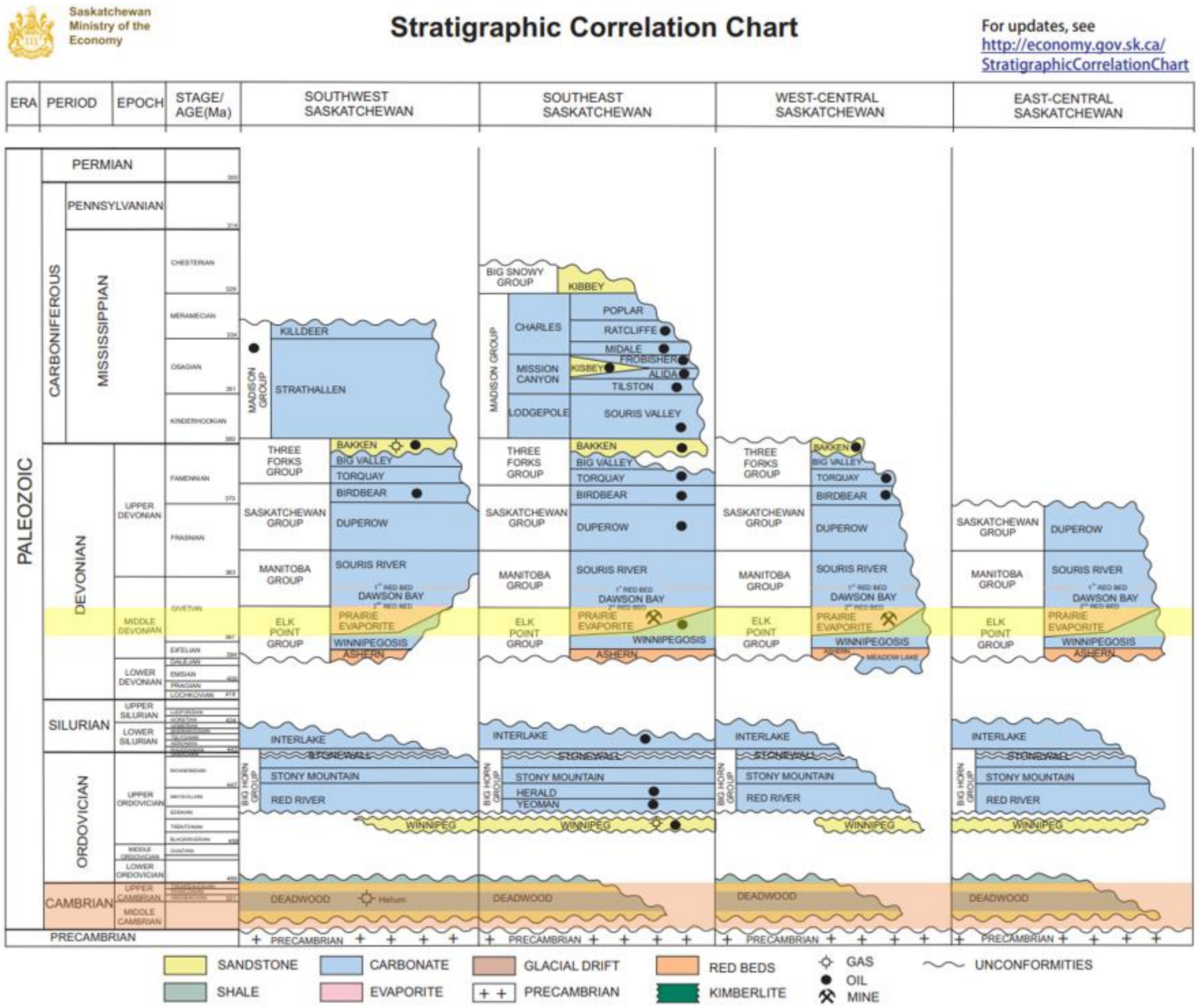


Figure 2.9 **Lower half of the Saskatchewan Geological Survey stratigraphic chart showing the location of the Middle Devonian Prairie Evaporite formation (highlighted yellow) for hydrogen storage potential and the units of the Basal Cambrian (highlighted orange) for current and future CO_2 storage potential throughout Saskatchewan.**

Source: Saskatchewan Geological Survey [49] (modified)

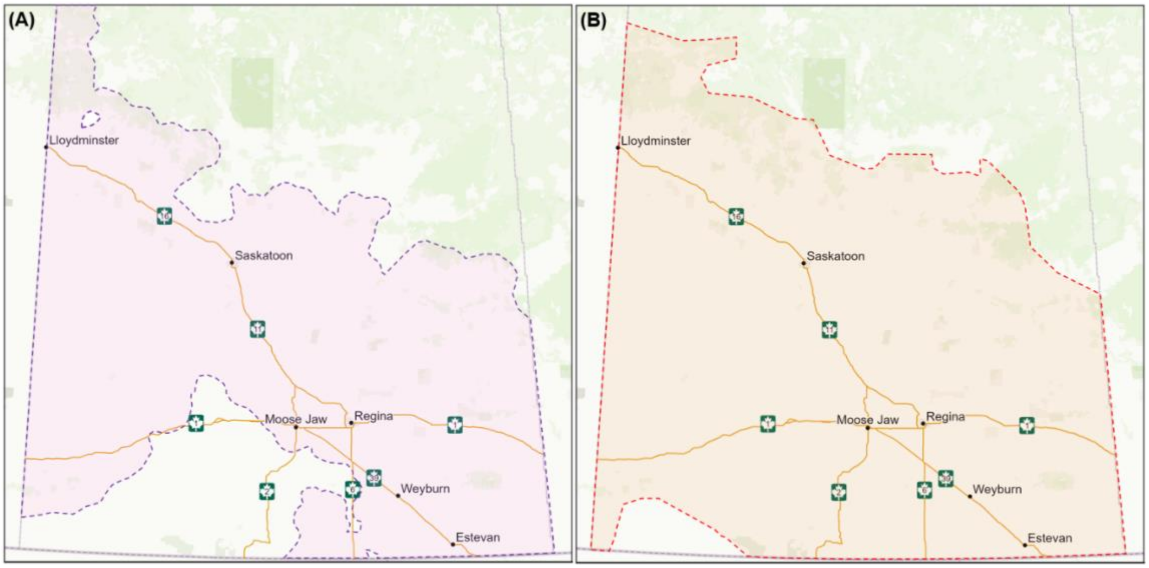


Figure 2.10 Approximate lateral extent of (A) the Prairie Evaporite and (B) the Basal Cambrian CO_2 storage potential throughout Saskatchewan.

Sources: Government of Saskatchewan [50] EERC [5] and Esri Canada [3] (modified)

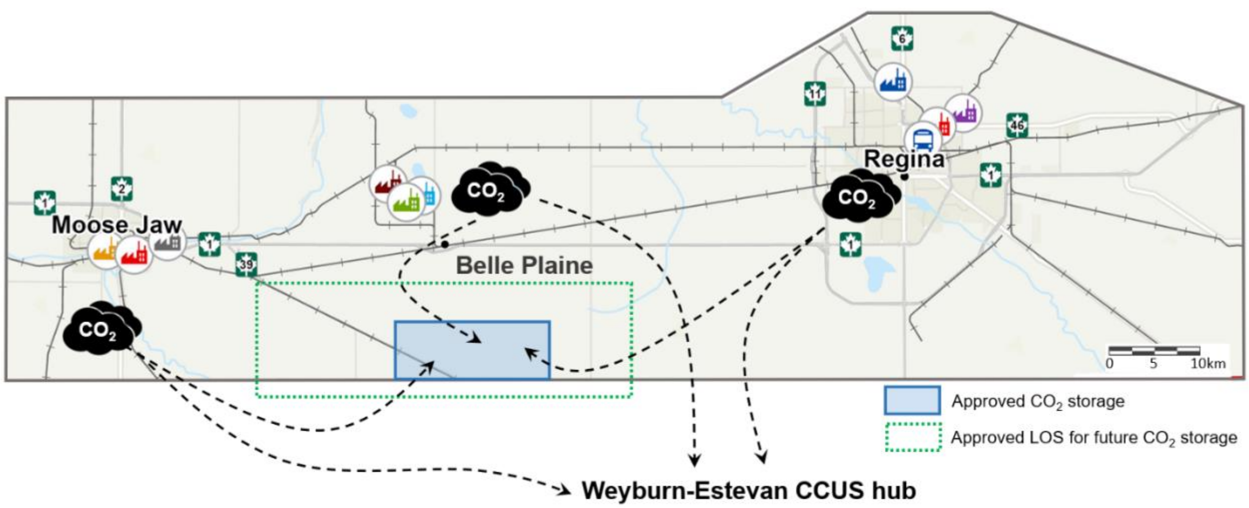


Figure 2.11 RMJIC industrial opportunities tied to current CCUS infrastructure in the Weyburn-Estevan region and approved CO_2 storage within the RMJIC.

Sources: Whitecap Resources Inc. and Esri Canada [3] (modified)

3 SASKATCHEWAN AND RMJIC EARLY ESTIMATES

3.1 Energy Use and Hydrogen Demand

3.1.1 Overview of Early Estimates

Early estimates of hydrogen demand throughout Saskatchewan and the RMJIC were produced using the most recent publicly available data from NRCan [52]. The top-down analysis considered current provincial energy use and the relative percentage of population for the RMJIC. The potential hydrogen demand in units of tonnes of hydrogen per day (t H_2/d) was calculated for each of five sectors using assumptions that included the percentage of energy that could possibly be transitioned to hydrogen. The total demand for hydrogen was estimated from:

- The energy content of fuel (PJ) to be transitioned to hydrogen,
- The high heating value (HHV) of hydrogen, and
- Process efficiencies.

The relative percentage of energy use for each of the five sectors throughout the province of Saskatchewan is shown in Figure 3.1. The energy use in petajoules per year (PJ/y) and subsequent potential hydrogen demand for Saskatchewan and the RMJIC is shown in Table 3.1. Transportation, which includes motive agriculture, uses the greatest amount of energy at 201 PJ/y province-wide followed by industrial at 157 PJ/y. At 22.8% of provincial energy use for the RMJIC, early estimates project a hydrogen demand of 325 t H_2/d between transportation and industry. A potential demand of 276 t H_2/d is largely split between the commercial and residential sectors with a minor portion for non-motive agriculture.

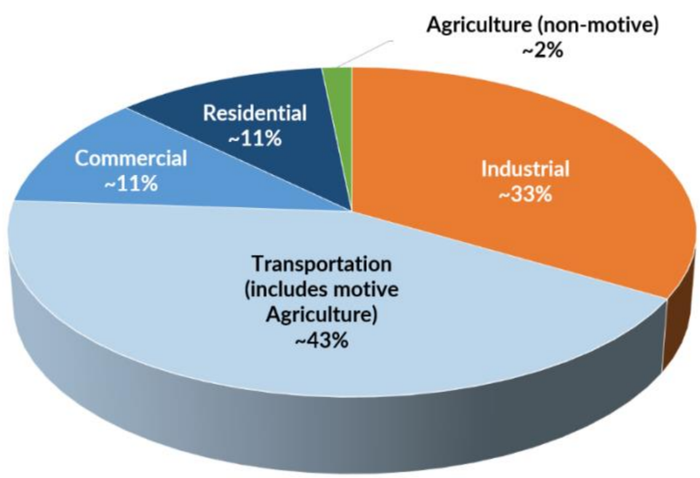


Figure 3.1 Relative percentages of provincial energy use for each of the five sectors.

Data: NRCan [52]

Table 3.1 Early estimates of hydrogen demand based on 2020 energy use data for Saskatchewan.

Sector	Saskatchewan				RMJIC @ 22.8%	
	Energy Use (PJ/y)		H_2 Demand		H_2 Demand	
	Total	Transition to H_2	kt H_2/y	t H_2/d	kt H_2/y	t H_2/d
Industrial	157	63	194	533	44	121
Transportation (includes motive Agriculture)	201	63	327	897	75	204
Commercial	53	21	216	591	49	135
Residential	53	21	216	591	49	135
Agriculture (non-motive)	8	3	9	25	2	6
Total	**471**	**171**	**963**	**2638**	**220**	**601**

The percentage of potential energy transition to hydrogen and assumed efficiencies specific to each sector are noted in the subsections below. The population counts used for Saskatchewan and the RMJIC were 1,183,000 and 270,000 respectively, which resulted in the 22.8% allocation of provincial energy use for the RMJIC.

3.1.2 Industrial

Early estimates of potential hydrogen demand were calculated for each of the seven industrial sectors in Table 3.2. More than 70% of potential industrial hydrogen demand is attributed to the businesses of petroleum refining and mining, quarrying, and oil and gas extraction. The latter comprises ~57% of total energy use for the province (Figure 3.2) which is largely attributed to potash mining in the RMJIC. Assumptions used to calculate early demand estimates, such as process and energy efficiencies and the HHV of hydrogen, are shown in Table 3.3.

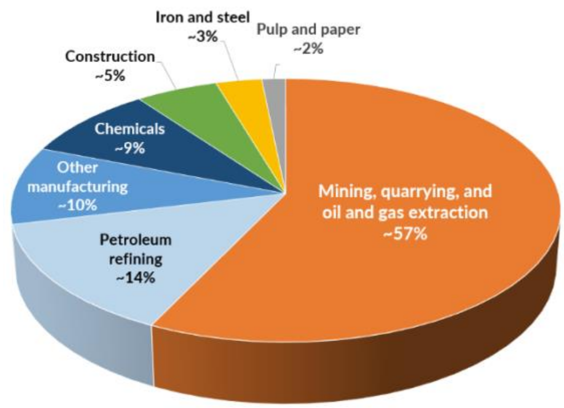


Figure 3.2 Relative percentages of provincial energy use across the industrial sector.

Data: NRCan [52]

Table 3.2 Early estimates of industrial hydrogen demand for Saskatchewan and the RMJIC.

Industry	Saskatchewan				RMJIC @ 22.8%	
	Energy Use (PJ/y)		H_2 Demand		H_2 Demand	
	Total	Transition to H_2	kt H_2/y	t H_2/d	kt H_2/y	t H_2/d
Mining, quarrying, and oil and gas extraction	90.0	36.0	111.2	304.7	25.4	69.5
Petroleum refining	22.2	8.9	27.4	75.2	6.3	17.1
Other manufacturing	15.1	6.0	18.7	51.1	4.3	11.7
Chemicals	14.2	5.7	17.5	48.1	4.0	11.0
Construction	8.6	3.4	10.6	29.1	2.4	6.6
Iron and steel	4.8	1.9	5.9	16.3	1.4	3.7
Pulp and paper	2.5	1.0	3.1	8.5	0.7	1.9
Total	**157**	**63**	**194**	**533**	**44**	**121**

Table 3.3 Assumptions for early estimates of industrial hydrogen demand.

Assumption	
Transition to H_2	40%
Fuel cell efficiency	60%
Gasoline efficiency	28%
Industrial heating efficiency	75%
Percentage of fuel cell applications	70%
Percentage of heating applications	30%
High-heating value of H_2	142 MJ/kg

3.1.3 Transportation

The transportation sector shows the greatest potential for hydrogen demand according to early estimates at 204 t H_2/d for the RMJIC (Table 3.4). While motive agriculture has the highest energy use of all province-wide transport (Figure 3.3), technology readiness is much further along in the conversion of medium- and heavy-duty trucks that run on hydrogen fuel. Western Canadian rail freight has also seen movement towards hydrogen technology since the first announcement of pilot projects in 2020 [53]. Cars and light-duty vehicles also comprise a sizeable share of total energy use, however, that market is assumed to be challenged by the growth of battery electric vehicles (BEVs) and advancements in battery technologies.

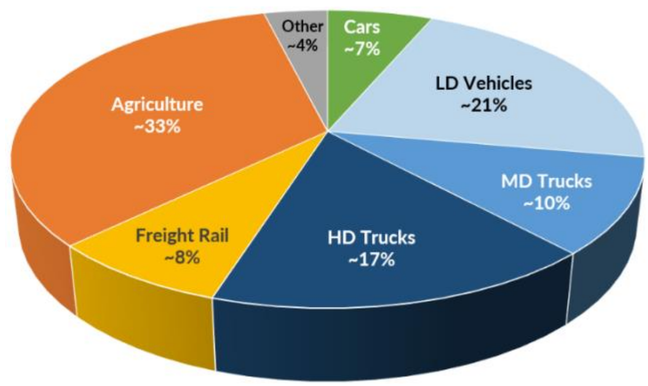


Figure 3.3 Relative percentages of energy use across the Saskatchewan transportation sector.

Data: NRCan [52]

Table 3.4 Early estimates of transportation hydrogen demand for Saskatchewan and the RMJIC.

Transportation	Saskatchewan				RMJIC @ 22.8%	
	Energy Use (PJ/y)		H_2 Demand		H_2 Demand	
	Total	Transition to H_2	kt H_2/y	t H_2/d	kt H_2/y	t H_2/d
Cars	12.9	1.3	3.6	10.0	0.8	2.3
LD Vehicles	42.9	4.3	12.1	33.1	2.8	7.5
MD Trucks	20.8	4.2	25.2	69.0	5.7	15.7
HD Trucks	33.8	27.0	163.8	448.7	37.3	102.3
Freight Rail	15.8	15.8	61.2	167.7	14.0	38.2
Agriculture	67.0	6.7	40.6	111.2	9.3	25.3
Other	7.8	4.0	20.9	57.3	4.8	13.1
Total	201	63	327	897	75	204

Additional assumptions used to generate early estimates of hydrogen potential in the transportation sector are shown in Table 3.5. They include the percentage of vehicles assumed for hydrogen transition and the relative efficiency for each. The assumptions for most means of transportation used throughout Saskatchewan and the RMJIC were based on previous work of the Transition Accelerator, with the exception of agriculture for which a 10% transition was assumed given the challenges associated with refuelling agriculture vehicles on-site.

Table 3.5 Additional assumptions for early estimates of transportation hydrogen demand.

Transportation	Transition to H_2 (%)	Relative Efficiency (J H_2/J petrol prod)
Cars	10	0.40
LD Vehicles	10	0.40
MD Trucks	20	0.86
HD Trucks	80	0.86
Freight Rail	100	0.55
Agriculture	10	0.86

3.1.4 Commercial, Residential, and Agriculture (Non-Motive) Sectors

Early estimates of the commercial and residential sectors show a 50/50 split on commercial and residential energy use throughout Saskatchewan (Table 3.6). Hydrogen demand estimates were based on a 15% transition for hydrogen blending with natural gas and a 25% transition for the adoption of hydrogen fuel cell technology to support growth in renewable power generation and back-up power. Assumptions used to calculate hydrogen demand include a natural gas heating efficiency of 91%, a hydrogen heating efficiency of 94%, and an HHV of hydrogen at 142 MJ/kg.

Assumptions for early estimates of non-motive agriculture were the same as those used for previous industry estimates (Table 3.3), to produce a hydrogen demand of 6 t H_2/d for the RMJIC.

Table 3.6 Early estimates of commercial, residential, and non-motive agriculture hydrogen demand.

Commercial & Residential	Saskatchewan				RMJIC @ 22.8%	
	Energy Use (PJ/y)		H_2 Demand		H_2 Demand	
	Total	Transition to H_2	kt H_2/y	t H_2/d	kt H_2/y	t H_2/d
Commercial	53	21	216	591	49	135
Residential	53	21	216	591	49	135
Total	**105**	**42**	**432**	**1183**	**98**	**270**

Agriculture (non-motive)	Saskatchewan				RMJIC @ 22.8%	
	Energy Use (PJ/y)		H_2 Demand		H_2 Demand	
	Total	Transition to H_2	kt H_2/y	t H_2/d	kt H_2/y	t H_2/d
Non-Motive	8	3	9	25	2	6
Total	**8**	**3**	**9**	**25**	**2**	**6**

3.1.5 Early Opportunities for the RMJIC

The **transportation** sector could see the early adoption of hydrogen and support for hydrogen hubs from medium- and heavy-duty trucking companies. While ~27% of transportation energy use in Saskatchewan is attributed to medium- and heavy-duty trucking, this sector has the potential to support hydrogen refuelling stations at the core of hub development. An RMJIC hydrogen hub could also present fuelling opportunities for freight rail and a share of light-duty vehicles and cars. Rail delivery could also be key for transporting hydrogen over the near- to mid-term to domestic markets and future export markets while pipeline infrastructure is being developed. As for agriculture-related challenges, there is an opportunity for accelerated R&D tied to the delivery of hydrogen fuel for farming given that nearly a third of all transportation energy use in Saskatchewan is from agricultural machinery.

Hydrogen fuel opportunities for **space heating or electricity generation** from hydrogen blending or fuel cells could support industry, commercial, residential, and non-motive agriculture. Hydrogen could be used to either displace natural gas or to stabilize the intermittency of renewable power. Efficiencies could be improved with co-generation power plants or combined heat and power (CHP) systems utilizing waste heat from engines or turbines [54]. Power-to-gas technology offers a solution to fluctuations in renewable power by blending hydrogen from renewables into a natural gas pipeline network. While using hydrogen for space heating is still in the pilot phase in Western Canada, the current blend of 5% hydrogen as being tested by ATCO in Edmonton, Alberta [55] could go as high as 10% to 15% with existing infrastructure. ATCO has also partnered with real estate developers near Edmonton to construct a community where household natural gas use is substituted by 100% hydrogen. However, it should be noted that current combustion technology and concerns for nitrogen oxide (NOx) emissions from the burning of hydrogen deserve further study to ensure that we are reducing the environmental burden associated with energy use as opposed to merely shifting it. While some critics estimate that the combustion of hydrogen produces 6 times more NOx emissions than the combustion of natural gas [56], recent studies have shown a near 6% reduction in NOx emissions from space heating with up to 20% hydrogen blending [57].

The potential for **hydrogen storage in salt caverns** within Canada is rather unique to Saskatchewan given the lateral extent of the opportunity. However, there are concerns for the competency of the local subsurface geology and cap rock integrity. Additional work, exploration, and comparison with analogous reservoirs in the US and parts of Europe is suggested as this could be a key economic driver for an RMJIC hydrogen hub. Sizeable and safe storage would be critical to enhancing the scalability of a local hydrogen economy and supporting the future development of “green” hydrogen in the region.

Given the lateral extent of the Basal Cambrian Sandstone, there is also great potential for **CO_2 storage**. Additional work to enhance this opportunity would not only support a future low-carbon hydrogen economy, but other CCUS initiatives throughout the RMJIC and the surrounding area.

4 PATHWAYS AND COSTS OF HYDROGEN PRODUCTION

4.1 Production Price Targets for Energy Sectors

Average energy costs in Western Canada are highlighted in Figure 4.1. Natural gas heating fuel costs are lower than what consumers pay for either transportation or electricity (per unit of energy). Retail target prices for hydrogen would therefore need to be from C$2 to C$3/kg to be competitive with the natural gas benchmark.

In Saskatchewan, natural gas is delivered to homes across the province through the crown corporation, SaskEnergy. The price includes the cost of transport, the cost of supply (primarily from Alberta), and federal and provincial taxes including the carbon tax. The commodity price for natural gas was C$4.20/GJ in August 2023. Customers were charged a basic monthly fee and a delivery charge of ~C$2.82/GJ or C$0.1113 per m^3.

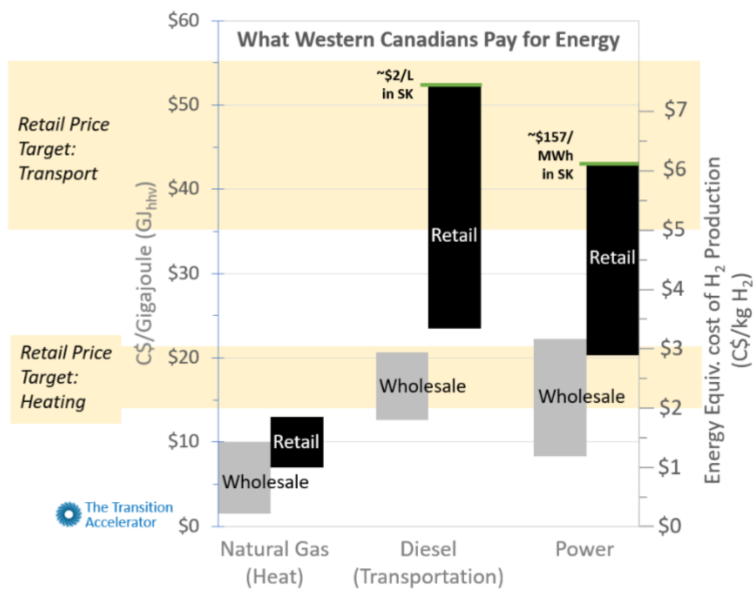


Figure 4.1 Comparison of fuel energy costs in Western Canada.

Source: The Transition Accelerator [31] (modified)

With the cost of diesel comparatively higher than natural gas at current prices, a transition from diesel to hydrogen is more likely over the near- to mid-term than hydrogen used as a replacement for heating fuels or peak power generation. At ~C$2/L for diesel, this corresponds to an equivalent hydrogen retail price of C$8 to C$10/kg based on an energy efficiency of 0.86 GJ H_2/GJ diesel [58]. If sold at prices equivalent to diesel, a hydrogen production cost of ~C$2/kg, which includes the cost of CCUS, would create a margin of C$6 to C$8/kg to cover transport and infrastructure costs.

Diesel prices in Saskatchewan hovered around the C$2/L mark (retail) from November 2022 to September 2023. Over this period, the minimum price was C$1.69/L, and the maximum price was C$2.17/L.

In addition to production costs, the economics of hydrogen transport, delivery, and fuelling stations are critical components of the hydrogen value chain, as discussed in Section 5.

4.2 Production Costs and Relative Carbon Intensity

Canada currently produces between 8,000 and 9,000 tonnes of hydrogen per day, with more than 70% coming from Western Canada, driven by the demand for oil refining and fertilizer feedstocks, and the low cost of natural gas in the region [59,60]. Most hydrogen will continue to be produced from the reforming of natural gas over the near- to mid-term, with greater adoption of CCS technology to 2030 and beyond. The share of hydrogen produced from electrolysis using low-emissions electricity, such as that from renewables and nuclear, could increase over the mid- to long-term as electrolyzer costs continue to decline. The area is also well positioned for the future of low-carbon hydrogen production with some of the best renewable energy potential in the country and plans for the development of new nuclear electricity production [47,48,61]. Other methods of hydrogen production suitable for Saskatchewan include biomass or coal gasification. Biomass could be an option for the RMJIC over the mid- to long-term with increased focus on R&D. There are issues with tar build-up which could adversely affect production and scale-up of hydrogen from biomass. Aside from the complexities of biomass gasification, its carbon intensity and production costs are relatively low and should be considered when diversifying future hydrogen production for the most competitive and accessible production methods. The cost of production from coal gasification cannot compete on cost with or without CCS. A comparison of hydrogen production costs for production methods most suitable for Saskatchewan is shown in Figure 4.2.

Figure 4.2 compares the cost of hydrogen production from multiple sources to the cost of diesel and natural gas production from 2022 to 2040. 4.2(A) shows the cost in Canadian dollars per kilogram (C$/kg) while 4.2(B) shows the cost in Canadian dollars per gigajoule (C$/GJ). While hydrogen production costs are often compared on mass, the use of energy units in 4.2(B) is more appropriate when comparing fuels of different energy densities (~120 to 140 MJ/kg for hydrogen, ~45 to 50 MJ/kg for natural gas, and ~42 to 45 MJ/kg for diesel). Comparisons in this section were made across fuel production only and included the cost of federal carbon taxes at the production source, estimated to 2040.

In terms of C$/kg, the cost of hydrogen production cannot compete with the cost of natural gas production through to 2040, nor with the cost of diesel production currently. However, by 2040, many of the hydrogen production options are projected to outperform diesel.

When using a more appropriate comparison of energy units (C$/GJ), the cost of natural gas production in 2022 is less than 60% the cost of hydrogen production from the ATR of methane with CCS. However, by 2030, more of the hydrogen production options will be nearing price parity with natural gas production. By 2040, most forms of hydrogen production are projected to be cheaper than the production of natural gas, in terms of energy units. When compared to the production of diesel, the cost per GJ of hydrogen production is higher in 2022 for hydrogen produced via electrolysis using renewables or nuclear power. By 2030, hydrogen production should be far cheaper than diesel production in each of the cases shown.

While hydrogen is expected to make significant gains in terms of production costs in the years to come, we must also consider the economics associated with the processing, transport, and delivery of hydrogen, as discussed in Section 5.

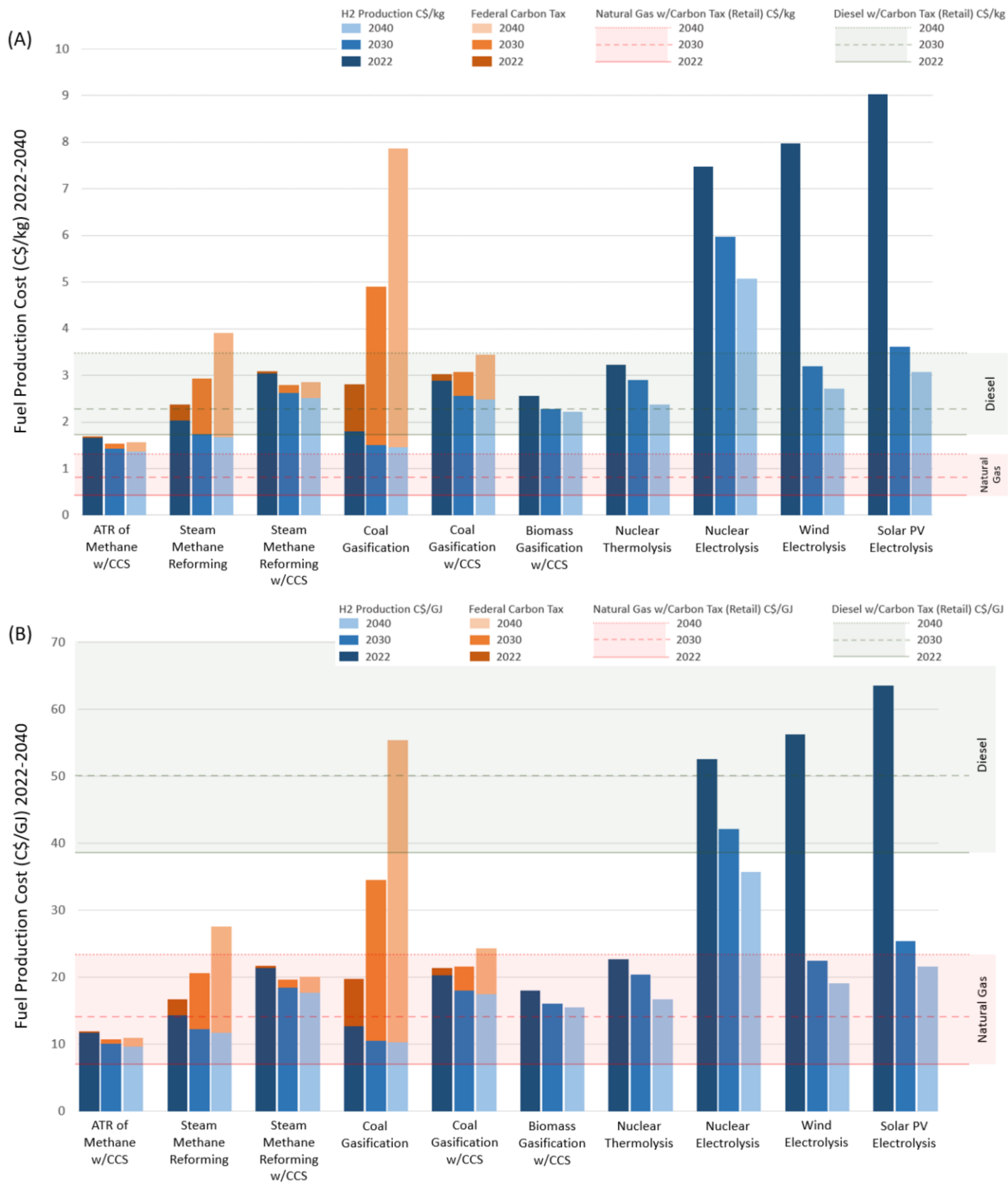


Figure 4.2 Cost of hydrogen production from various sources vs. cost of diesel and natural gas in (A) C$/kg and (B) C$/GJ (2022-2040).

Sources: IRENA [7], IEA [62,63], KPMG [64]

Relative carbon intensity

The relative carbon intensities for each of the hydrogen production methods noted in this study are shown in Figure 4.3. The figure depicts a trend similar to that of hydrogen production costs from Figure 4.2 due to the impact of federal carbon taxes. Upon comparison of the hydrogen production methods possible over the near- to long-term, the carbon intensity of the ATR of Methane with CCS is roughly half that of SMR with CCS. The carbon intensity increases by nearly ten times for SMR without CCS. Coal gasification without CCS is higher yet again in comparison to hydrogen produced from natural gas. The relative carbon intensities for each of nuclear and renewables-based hydrogen is slightly less than that for production from fossil fuels with CCS, whereas biomass gasification has the lowest carbon intensity of all the production methods noted as potential for Saskatchewan and the RMJIC.

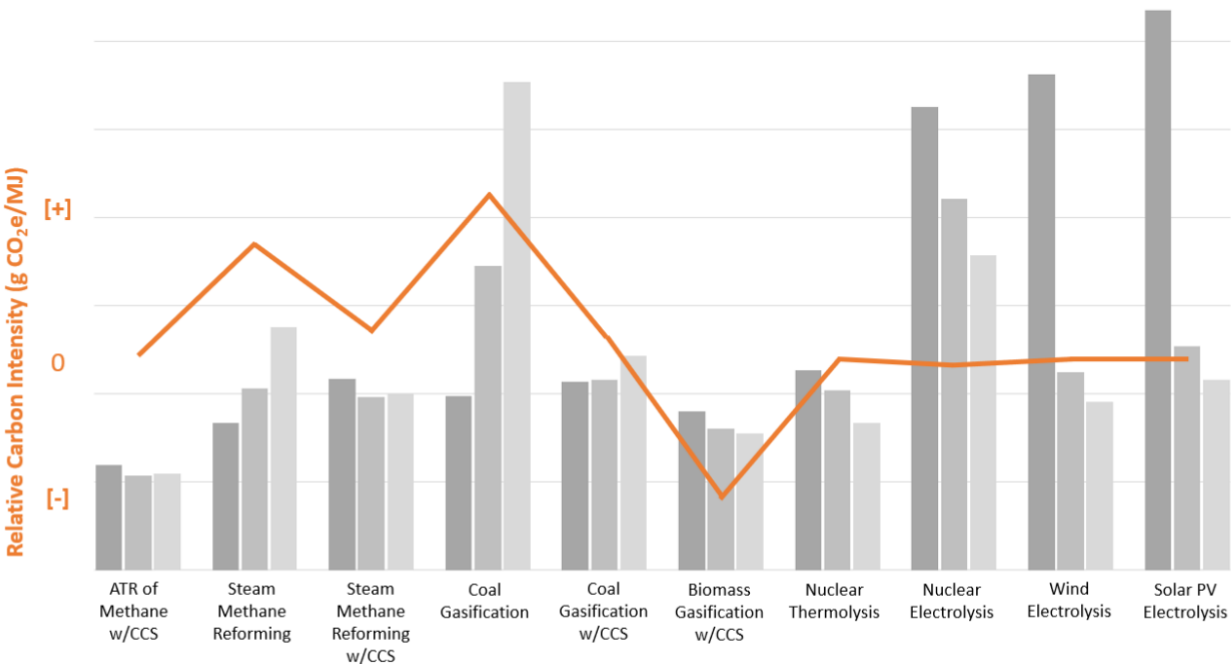


Figure 4.3 Relative carbon intensities for each of the hydrogen production methods noted in this study.
The relative carbon intensities of hydrogen production methods project a trend similar to that of hydrogen production costs (shown as a silhouette of Figure 4.2) due to the impact of federal carbon taxes on hydrogen production from fossil fuels.

Sources: Litun [58], UTAu [65], Rosa and Mazzotti [66]

4.3 Hydrogen from Natural Gas

4.3.1 Steam Methane Reforming (SMR)

A simplified process diagram for steam methane reforming (SMR) is shown in Figure 4.4. When compared to other production methods, SMR is competitive on cost and energy efficiency, with hydrogen purity improved up to 99.9% through the process of pressure-swing adsorption (PSA). A nickel catalyst is used to separate the hydrogen from natural gas and water at temperatures of ~850°C and pressures of ~2.5 megapascals (MPa). SMR produces carbon monoxide (CO) and hydrogen, and since CO can be a problem, a water-gas shift reaction (WGS) is used to turn the CO into carbon dioxide and produce more hydrogen. [67]

A typical SMR process would require 3.1 million m^3/d of natural gas to meet the annual early estimates of hydrogen demand for the RMJIC. In 2020, Saskatchewan produced ~10 million m^3/d of natural gas, or a mere 2% of all production throughout Western Canada. With significant declines in the province's natural gas production over the past decade [68], additional sources of low-carbon hydrogen production would have to be explored to ensure adequate supply for a future hydrogen hub in the region.

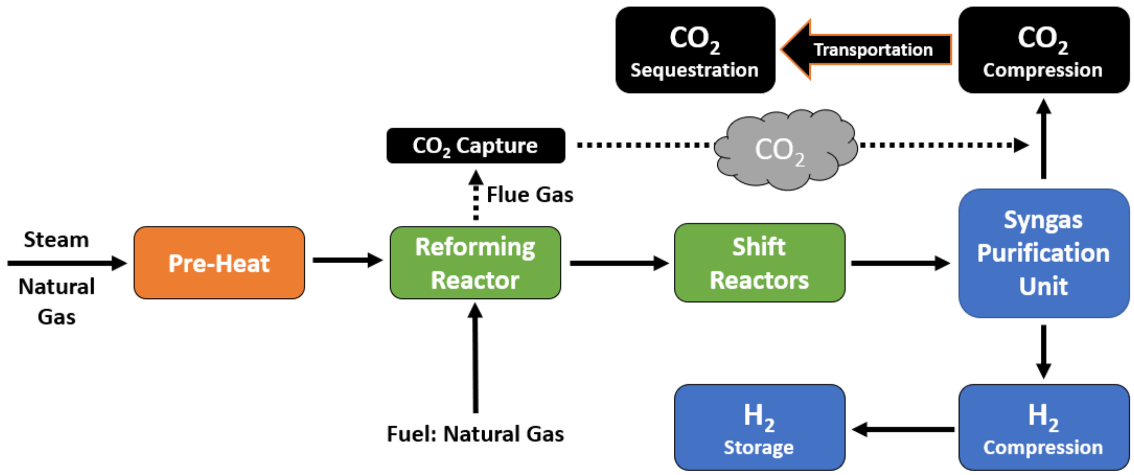


Figure 4.4 Simplified process flow diagram for steam methane reforming.

Source: Oni et al. [67] (reproduced)

4.3.2 Autothermal Reforming (ATR) of Methane

The autothermal reforming (ATR) of methane is not new, but interest in its use for the production of "blue" hydrogen is growing. The process is a combination of SMR and partial oxidation and is commonly used to produce methanol or ammonia from natural gas. In addition to the production of syngas it also produces hydrogen. Figure 4.5 is a simplified process flow diagram of an autothermal reformer with CCS. Syngas is created from the reaction of oxygen, steam, and methane with a nickel catalyst while the heat required for the reforming process is provided by partial oxidation. Once the syngas is cooled, both hydrogen and CO_2 are produced by WGS, and the hydrogen is separated and sent to a PSA unit where 90% is assumed to be recovered at nearly 100% purity. In addition to producing relatively low CO_2 emissions with higher capture rates than SMR, ATR with CCS can be the most economical option today at a hydrogen capacity above 200 t H_2/d. [67,69]

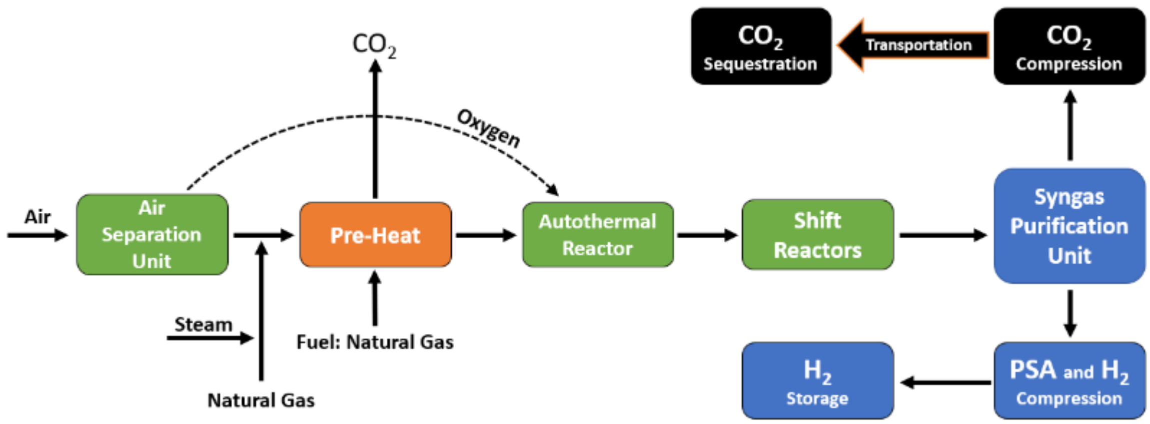


Figure 4.5 Simplified process flow diagram for autothermal reforming of methane.

Source: Oni et al. [67] (reproduced)

4.3.3 Natural Gas Decomposition (NGD)

Natural gas decomposition (NGD), or methane pyrolysis, is another alternative to SMR for "blue" hydrogen production when combined with CCS. This partial oxidation (or pyrolysis), which also produces carbon black, is lower on the technology readiness scale than either SMR or ATR. It also requires temperatures above 1000°C or near 800°C with the use of a catalyst such as iron ore. Once carbon is separated through NGD, unconverted natural gas is trapped in a PSA unit as 90% of the hydrogen is recovered at a purity near 100%. A fluidized bed reactor recycles the remaining gases. [67]

4.4 Hydrogen from Renewable Energy

Renewable energy and the process of electrolysis can produce hydrogen by splitting water molecules into hydrogen and oxygen. While wind and solar power are gaining popularity as low-emissions alternatives, they have relatively low capacity factors and are intermittent energy sources that cannot always provide firm power on demand. For example, at a capacity factor of roughly 34% throughout the RMJIC, a 3-megawatt (MW) wind turbine would produce just over 1 MW of power on average. Adding an electrolyzer to produce low-carbon hydrogen adds further inefficiencies to the system. However, the production of hydrogen from renewables, specifically excess renewables, is being actively pursued with efforts to decarbonize our energy use and help mitigate climate change. It is therefore important for Saskatchewan to demonstrate the production and utilization of hydrogen from renewable sources to help understand the technology for application and scale-up.

Figure 4.6 illustrates the effect of electricity cost and capacity factor on the levelized cost of hydrogen (LCOH) production, as adapted from the IEA's Future of Hydrogen Report in 2017 [70] and produced by the Transition Accelerator. Three case studies explored the LCOH at present, in 2030, and in a mature future market, as indicated by the following symbols on the corresponding surface plots and bar charts:

- ☆ **Dedicated intermittent renewables** (e.g., wind) having a capacity factor of 34% (3,000 hr/y) and a current LCOH of C$40/MWh declining to C$30/MWh by 2030.
- △ **Low-carbon grid power (grid high)** at an electrolyzer capacity factor of 68% (6,000 hr/y) and a delivery cost of C$80/MWh.
- ○ **Low-carbon grid power (grid low)** at an electrolyzer capacity factor of 68% (6,000 hr/y) and a delivery cost of C$20/MWh. Excess power from sources such as hydro or nuclear would have to be present for this scenario.

As the cost of renewable projects declines to 2030, and hydrogen production from intermittent sources (e.g., wind) approaches C$3/kg, the levelized cost of hydrogen from renewables closes in on that of (grid low) low-carbon grid power. Improved electrolyzer efficiency will also be required to bring the cost closer to hydrogen produced from natural gas. The RMJIC will have other alternatives for low-carbon hydrogen production over the mid- to long-term, including nuclear. When compared to more common methods of hydrogen production, the cost of electrolysis from small modular nuclear reactors is more difficult to estimate given the lack of data and projections of capital and operating costs.

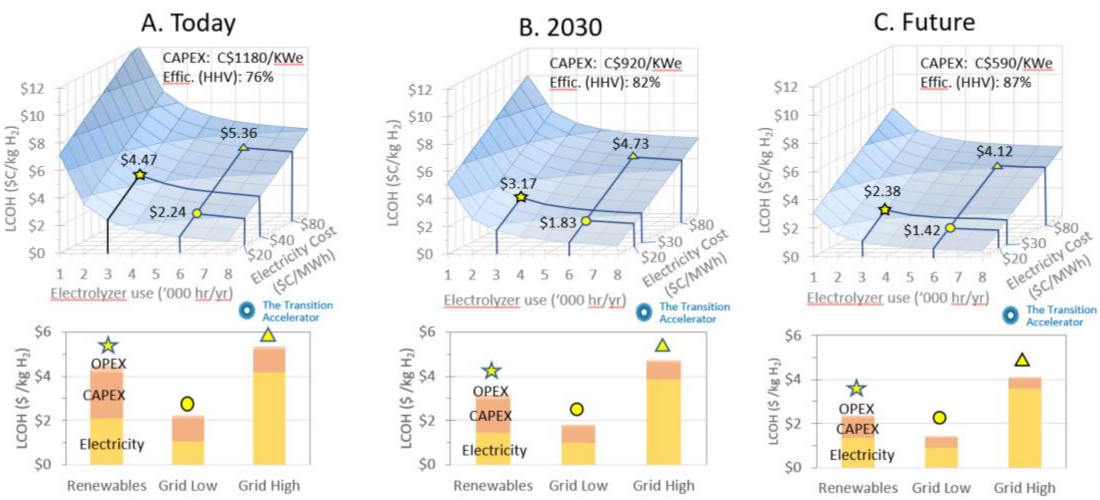


Figure 4.6 The effect of electricity cost and capacity factor on the levelized cost of hydrogen (LCOH).

LCOH from a 4.2 MW PEM electrolyzer today (A), in 2030 (B), and in a mature future market (C). Symbols refer to the three case studies described in the text. Model adapted from the IEA Future of Hydrogen (2017) report.

Source: The Transition Accelerator [31]

4.5 Other Possible Methods of Hydrogen Production in the RMJIC

4.5.1 Hydrogen from Small Modular Nuclear Reactors

There are over 70 conceptual designs globally to support the next generation of nuclear power. Termed small modular nuclear reactors (SMRs), or SMNRs to avoid confusion with the acronym for steam methane reforming, several units are being designed to produce up to 300 MW of electricity and excess thermal energy for process heat. Nuclear power offers a firm, uninterrupted source of flexible power to support the decarbonization of the electrical grid and the intermittency of wind and solar power. It can also provide low-carbon hydrogen production from electrolysis with potential for thermochemical options for greater overall efficiency and cost. [71,72]

Alkaline electrolyzers and PEM technologies are among the electrolytic methods for nuclear based-hydrogen production. However, high temperature steam electrolysis (HTSE) using solid oxide electrolytic cells (SOEC) could be employed more readily once HTSE production costs reach a competitive range. Temperatures of 700°C to 900°C are required to dissociate steam into hydrogen and oxygen and the current generation of nuclear reactors (Generation IV) includes designs with high outlet temperatures ideal for pairing with HTSE facilities. [73]

One advantage of thermochemical water splitting is that it uses a multi-step process and both heat and electricity to reduce the reaction temperatures required for hydrogen production [74]. While thermochemical cycles such as sulfur-iodine (S-I) and calcium-bromide (Ca-Br) are the more technologically mature options, copper-chlorine (Cu-Cl) cycles can accept a broader range of reactor designs due to lower operating temperatures. Lower temperatures are also associated with reduced materials failure and maintenance leading to reduced operational costs. Canadian R&D into Cu-Cl cycles and nuclear-based hydrogen production has been steady for more than a decade. [20-23]

The region could benefit from nuclear-based hydrogen production in the future as SaskPower is currently evaluating SMNRs for Saskatchewan's future power supply mix, with potential deployment in the mid-2030s [75].

4.5.2 Hydrogen from Coal, Crude Oil, Waste Plastics, or Biomass

Hydrogen can be produced from carbon-based raw materials through the process of gasification. The gas is purified from other contaminants including CO, CH_4, H_2S, NH_3, HCl, HCN, ash, and tar, which can decrease its calorific value in the process. [76,77]

All ranks of coal, from lignite to anthracite, can be utilized for hydrogen production by gasification using a variety of methods. Recent studies have shown plasma gasification to produce less slag waste and emissions compared to other methods of coal gasification. The system can also be designed to accommodate small coal capacities while producing useful thermal energy. The process of coal gasification injects oxygen and steam into a subsurface coal bed to produce CO, CH_4, H_2, and by-products such as CO_2 from fixed carbon within the coal [76,78]. Adding CCS technology can reduce the carbon footprint by up to 75% [79]. The production of hydrogen from coal with CCS may be the near- to mid-term solution to drive the hydrogen economy in countries largely dependent on coal resources, at least until lower-carbon sources catch up globally.

Hydrogen can be produced from crude oil via SMR akin to hydrogen production from natural gas. This involves the use of a steam reformer, high- and low-temperature shift converters, a CO_2 absorber, and a methanator. Studies have shown that the application of a CO_2 sorbent in the reformer, such as CaO, can significantly increase hydrogen purity. Shift reactions convert CO to H_2 over high- and low-temperature steps using an iron and chromium oxide catalyst and a copper and zinc oxide catalyst, respectfully. The CO_2 becomes chemically absorbed by alkanol amines in the absorption column, for which an increase in solvent flow rate and temperature can help to improve absorption efficiency. Both CO and CO_2 are hydrogenated to methane in the final steps. [80,81]

In-situ hydrogen production from oil is currently being piloted in Kerrobert, Saskatchewan by Proton Technologies. The process being tested oxidizes residual oil within mature reservoirs and separates the hydrogen for production at surface while sequestering CO_2 for permanent storage. [82]

Waste plastics have also been used to produce hydrogen via gasification. The Ebara Ube Process (EUP) was developed through the early 2000s to produce hydrogen for ammonia synthesis [83-85]. Unlike other forms of gasification, the EUP does not require a catalyst but is carried out under pressure and involves both pyrolysis and steam reforming. The process is therefore not easily sized for small-scale development due to the need for pure oxygen which requires a significant amount of energy and cost. However, there are low-temperature alternatives that involve the use of ruthenium catalysts. Recent studies of plastics pyrolysis have also focused on improved process efficiency through oxygen co-feeding to reduce the energy demand and rapid deactivation of catalysts [86]. Up to 20% of waste plastics by mass have also been added to lignite coal for co-gasification. The composition, volume, and properties of the produced gas were comparable to examples of coal gasification without the addition of waste. [87,88]

Based on the population of the RMJIC in 2021, and an average 0.5 kg of plastic disposed of daily per person in Canada, the total volume of waste plastics in the region could contribute approximately 12 t H_2/d to satisfy future potential RMJIC demand [89].

Biomass gasification can be achieved both biochemically and thermochemically. Biochemical gasification involves the processes of drying the biomass to remove moisture, followed by pyrolysis to break the biomass down into volatiles (bio-char) using heat from nearby biomass combustion. CO, CO_2, and water are produced during exothermic combustion and partial oxidation, which provides heat for endothermic processes. The final process is that of reduction where charcoal is converted to producer gas. However, there are issues preventing the scale-up of biochemical gasification, including the production of tar which can adversely affect hydrogen yield on the downstream side and the need for the development of new and more efficient catalysts. Also, the overall complexity of the biomass gasification process, from equipment to operating conditions, can drastically affect the ultimate concentration and yield of hydrogen. Advantages of the thermochemical process include greater efficiency, lower production costs, the ability to produce a wide range of feedstocks, and the use of lignocellulosic materials which cannot be used for biochemical gasification. Integrated gasification cycle systems that utilize both coal and biomass with CCS have been shown to decrease CO_2 emissions by ~7 times at a 20% biomass ratio and ~15 times once 100% biomass gasification is reached. [90-92]

5 HYDROGEN AS AN ENERGY CARRIER

5.1 From Industrial Feedstock to Energy Carrier

Hydrogen is well established as an industrial feedstock in commercial markets, primarily as a chemical intermediate in ammonia and methanol production. Apart from refining, these two chemicals are responsible for significant hydrogen consumption in Canada with 0.8 million tonnes of hydrogen used to produce 4.7 million tonnes of ammonia in 2020 [93]. As a key component in fertilizer production, demand for ammonia is expected to grow by 25% as nitrogen demand grows three-fold to 2050, according to Sustainable Development and Net-Zero Emissions Scenarios [94].

Ammonia and methanol also double as strong hydrogen carriers, with energy densities by mass and by volume closer to that of fossil fuels (Figure 5.1) [95-99]. This is not the case for hydrogen by itself, making it more difficult to transport and store. The challenges of transporting hydrogen have led to mounting research focused on the conversion of hydrogen gas into hydrogen-based liquid fuels, in addition to ammonia and synthetic methane. The energy efficiency of ammonia is slightly better than hydrogen, and the cost of converting hydrogen gas to ammonia has been shown to be less than 1/4 the cost of cooling hydrogen gas into a liquid hydrogen phase [100]. There are also efficiency losses to consider with the use of chemical intermediates.

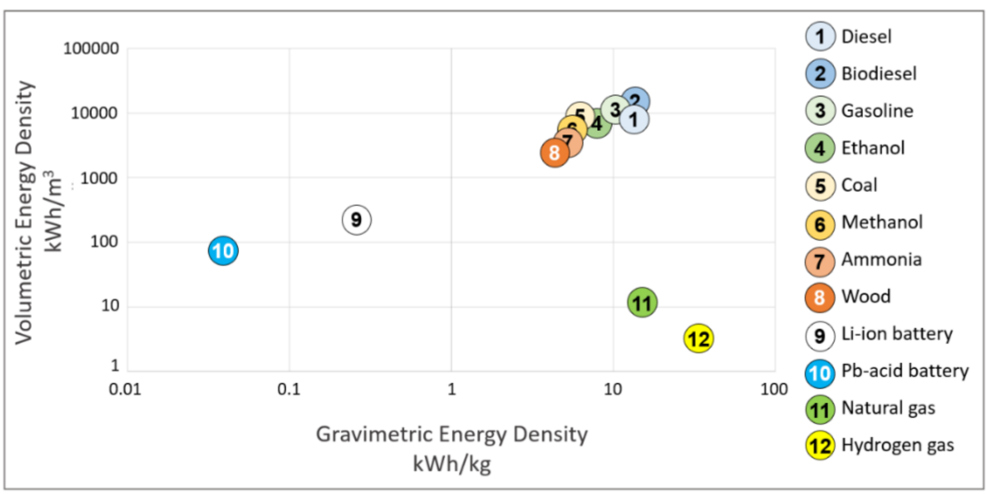


Figure 5.1 Volumetric and gravimetric energy densities of known carriers.

Data: [95-99]

In the production of methanol and olefins, hydrogen has been showing promise as a decarbonization feedstock with emerging carbon capture opportunities. Hydrogen produced from electrolysis and other forms can be combined with captured CO_2 to produce methanol in a synthesis reactor [101]. In recent years, there have been advances in the efficiency of catalysts and reaction mechanisms required for CO_2 hydrogenation [102]. As global demand for light olefins used in plastics manufacturing increases at an annual average rate of 3.5%, more sustainable forms of olefin production from hydrogenation are being developed via two reaction routes [103]. The more direct route converts CO_2 to CO under a reverse (WGS) reaction and then transforms the CO into olefins using Fischer-Tropsch synthesis. The other indirect route involves the reaction of CO_2 and hydrogen to generate methanol intermediates which diffuse into the pore channels of zeolites to produce olefins [104].

In the refining of heavy crude, hydrogen is used for the general upgrading to lighter oils with benefits that include an increase in oil and gas yield and the removal of undesirable elements such as sulfur. With a shift in the demand for greater diversity of chemical feedstock, innovations into traditional refining processes such as fluid catalytic cracking may be necessary to accommodate the growing demand for light alkenes, benzene, toluene, and xylenes (BTX) [104,105]. A boost in hydrogen demand for refinery use could lead to increased production from commercial suppliers, as was the case in the US in the mid-2010s [106].

Research into the use of hydrogen for steel manufacturing is also ongoing, largely throughout Europe. Examples include the HYBRIT project, the Carbon2Chem project, and the SALCOS project, with each focused on breakthrough technologies to reduce process emissions [107-109].

5.2 The Costs and Challenges of Hydrogen as an Energy Carrier

5.2.1 Hydrogen Transport and Fuelling Stations

As an energy carrier, the challenge with hydrogen is no different than that of other low-carbon energy options. It largely comes down to energy efficiency. From the production of electrolytic hydrogen through to transport, storage, and end use, the entire process can result in a 30% to 80% drop from its initial energy input [16,17]. Reducing the inefficiencies associated with hydrogen production, processing, and transport is one step to improving hydrogen supply costs.

As noted in Section 4, production costs are largely determined by the production method with hydrogen from natural gas currently much cheaper than hydrogen from renewable energy. However, when determining the total retail price targets for hydrogen, the costs of processing, transport, and fuelling also need to be considered. As shown in Figure 5.2, compressed hydrogen transported in tube trucks (TT) is estimated to be lower than hydrogen transported as a liquid (LH_2), while pipelines are the most cost-effective method of transport for longer distances. With project scale being the largest factor on cost, a 2 t H_2/day minimum threshold is required for economic viability of hydrogen fuelling stations (HFS), providing fuel for 40 large trucks or 100+ cars.

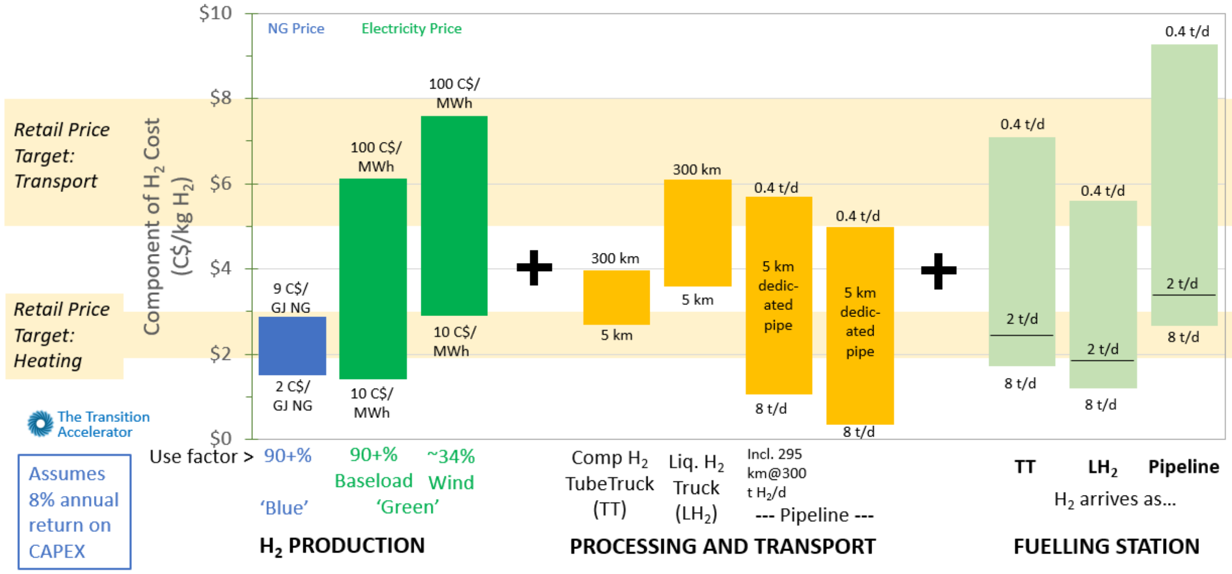


Figure 5.2 Economics of hydrogen production, transport, and fuelling stations.

Source: The Transition Accelerator [31]

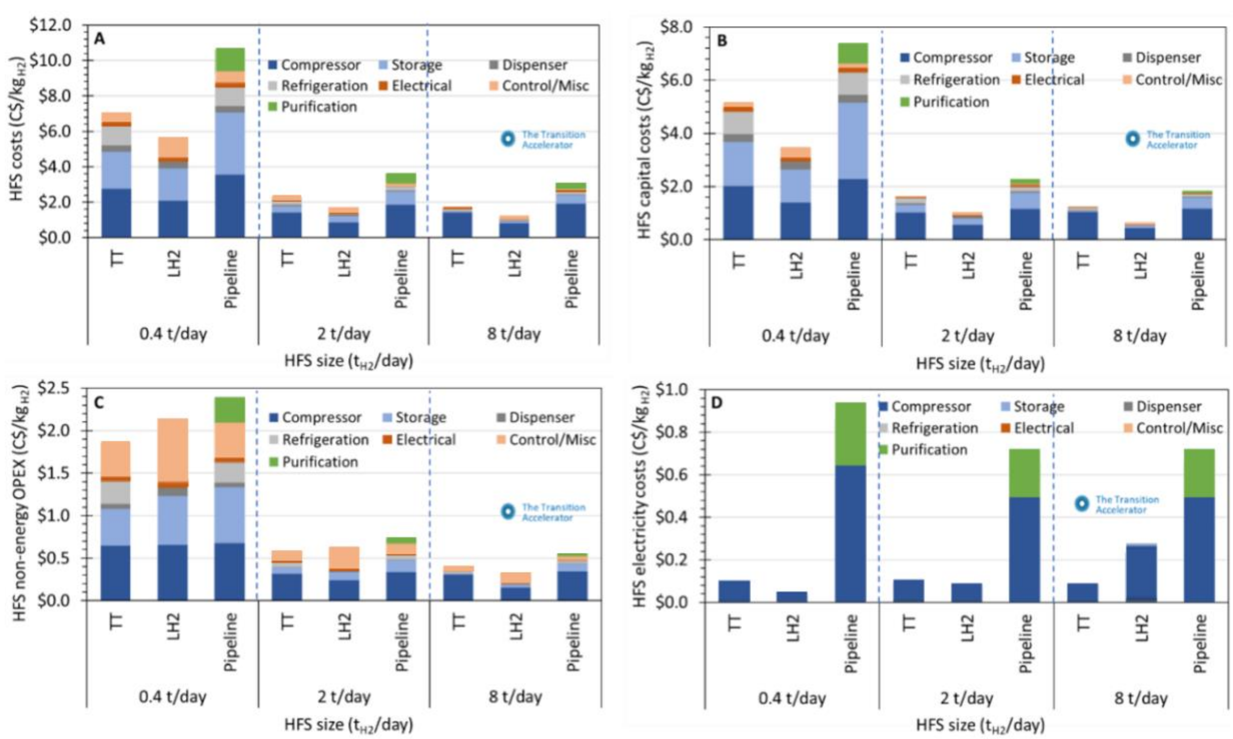


Figure 5.3 (A) HFS costs (C$/kg H_2), (B) HFS CAPEX, (C) HFS non-energy OPEX and (D) HFS electricity costs as a function of HFS size (t H_2/d).

Source: The Transition Accelerator [31] (modified)

Figure 5.3 presents the results of the cost analysis for an HFS as noted in Figure 5.2, which includes the costs of capital, operations, and electricity according to rates in Saskatchewan. The figure shows the results of three delivery methods: gaseous hydrogen in tube trailers (TT), liquid hydrogen (LH_2), and pipelines for hydrogen demands of 0.4, 2, and 8 t H_2/d.

The cost of a 2 t H_2/d HFS is only marginally higher than an 8 t H_2/d station, as the costs of compression and storage drop significantly from a station serving 0.4 t H_2/d. The maximum threshold of 8 t H_2/d avoids continuous back-to-back fuelling which requires considerable compression and storage capacity leading to a dramatic rise in cost. In the case of pipeline transmission, the cost of purification is much higher for smaller stations. Per kilogram of hydrogen, liquid hydrogen stations cost less to operate with lower costs for liquid storage compared to gas storage and pumps compared to compressors. However, the total cost of an HFS is counteracted by the cost of liquefaction. [31]

5.2.2 Compression

While hydrogen has the highest energy density per mass of any fuel, it has remarkably low energy density per volume and requires significant storage space when compared to other fuels. At 200-bar pressure, as shown in Figure 5.4, hydrogen gas has nearly a third of the energy density of methane (which represents natural gas). Similarly, liquid hydrogen has lower energy density than methanol, propane, and octane (which represent gasoline). The adiabatic work required to compress hydrogen is over 22 MJ/kg at 800 bar compared to roughly 2.5 MJ/kg for methane at the same pressure. [110]

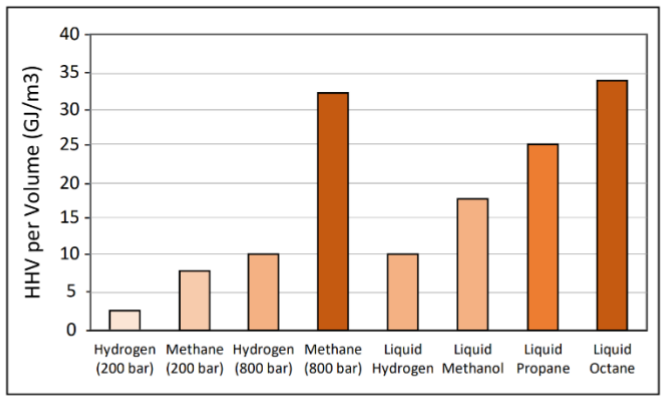


Figure 5.4 Volume HHV energy density of different fuels.

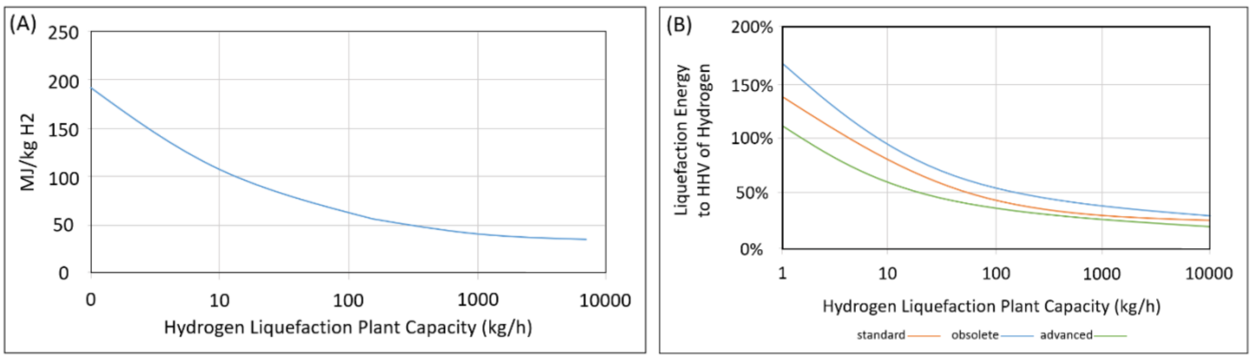
Source: Bossel and Eliasson [110] (reproduced)

5.2.3 Liquefaction

The liquefaction of gases relates to changing a gas to a liquid state for improved transport and storage capacity [111]. For heavy gases like carbon dioxide or oxygen, liquefaction can be accomplished by increasing the pressure at ambient temperature, but for light gases like hydrogen, significant cooling must be applied for liquefaction to occur. The capital cost of a 100 t/d liquefaction unit was approximately C$370M in 2022, with an additional C$10M for a 3,500 m^3 storage unit and C$36M/y in operating costs [112]. However, given the amount of energy required for the liquefaction process, it is likely to be more carbon-intensive and less efficient than hydrogen gas compression. The energy efficiency of liquification is currently 30% to 35% according to the US DOE [113]. While it is more economical to transport liquid hydrogen over long distances than gaseous hydrogen because of its higher mass, boil-off during delivery is problematic due to this ambient heating. At liquefaction plants and in transport, some of stored hydrogen will be lost through "boil off" as the tanks warm up naturally to ambient conditions. The cost of power to liquefaction compressors could be lowered to compensate for energy losses. Research into converters, inter-cooling, insulation, and automation could also help to improve efficiency and lower costs.

Theoretically, only 4 MJ/kg of work is required to cool and condense hydrogen gas to -253°C under atmospheric pressure. At a temperature slightly warmer than absolute zero (-273.15°C), the process consumes a mere 2.8% of its energy content. However, the Carnot cycle and physical effects such as the Joule-Thompson Effect (gas expansion) occur during the cryogenic refrigeration of the gas to consume at least 40%, or 57 MJ/kg, of the HHV energy content of hydrogen which is 142 MJ/kg. [110]

As shown in Figure 5.5 (A), the specific energy input decreases to approximately 40 MJ/kg H_2 as liquefaction plant capacity increases to 10,000 kg/h. In (B), nearly 30% of the HHV energy is consumed during liquefaction at the maximum plant capacity shown. It is therefore possible that upwards of 30% of the HHV energy would be consumed during liquefaction to meet RMJIC hydrogen demand according to the early estimates in Section 3. This would ultimately lead to higher costs associated with liquefaction for processing and transport when compared to compressed hydrogen gas, as shown in Figure 5.2.



Source: Bossel and Eliasson [110] (reproduced)

Figure 5.5 A) Typical energy requirement for the liquefaction of 1kg of hydrogen as a function of plant size and (B) actual energy requirement for the liquefaction of 1kg of hydrogen at its HHV.

5.2.4 Decompression

Most real gases cool when decompressed freely at constant enthalpy. In the case of hydrogen, the initial temperature must be low for the gas to remain cool upon expansion. This is again due to the Joule-Thomson Effect and the relatively weak van der Waals forces between hydrogen molecules which cause the gas to heat up as the molecules move farther apart [114]. As illustrated in Figure 5.6, the ambient temperature rises upon expansion as hydrogen gas approaches its maximum inversion temperature of ~200K. While concerns for ignition resulting from this negative Joule-Thomson effect are largely unfounded to date, this effect adds costs associated with refrigeration as shown in Figure 5.3 [114,115].

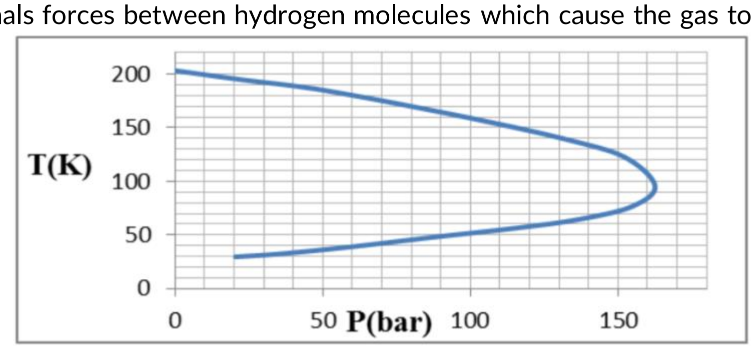


Figure 5.6 Hydrogen gas inversion curve.

Source: Peschka [115]

5.2.5 Pipeline Transport

Most of the pure hydrogen pipelines that currently exist are not used for hydrogen as an energy carrier, but as a chemical commodity. Energy is consumed during the transport of gas via pipeline with compressors installed at regular intervals. In the case of moving natural gas, approximately 0.3% of the gas is spent every 150 km to power compressor stations [110]. Hydrogen requires nearly 3.6 times the energy required for pipeline transport than natural gas, as the process consumes at least 1.4% of pure hydrogen volume every 150 km. Therefore, roughly 15% of the total volume of pure hydrogen gas would be required for pipeline transport from the RMJIC to the coast of British Columbia.

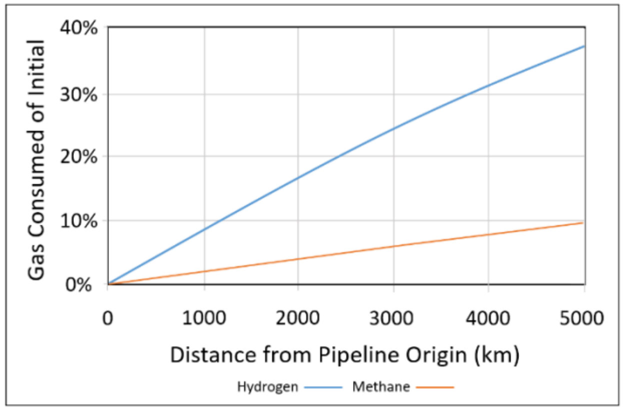


Figure 5.7 Percentage of gas consumed for hydrogen and natural gas (represented by methane) to travel via pipeline.

Source: Bossel and Eliasson [110] (reproduced)

5.2.6 Costs of Using Liquid Organic Hydrogen Carriers (LOHCs)

Research into the use of liquid organic hydrogen carriers (LOHCs) is ongoing [116-119]. Hydrogen can combine with other substances to produce liquid suitable for transport and storage. Once transport is completed via pipeline, road, or rail, hydrogen molecules are removed from the liquid carrier through a reversal of the conversion process and the LOHC is ready for reuse. [120]

Options for LOHCs include methanol and MCH (methylcyclohexane) from the hydrogenation of toluene. As an industrial feedstock, methanol is used in the chemical production of solvents, adhesives, plastics, and fuel applications, of which a third supports the production of formaldehyde [121-124]. In addition to being a product of coke oven gases, MCH can be produced by catalytic reformation of fossil fuels or separation of aliphatic hydrocarbons [125]. It should be noted that the use of LOHCs is not an emissions-free process and that a life-cycle comparison of all options is suggested when considering a low-emissions future.

Distribution of LOHCs

The levelized cost of hydrogen distributed to fuelling stations by rail transmission through various hydrogen carriers is shown in Figure 5.8. Each scenario consists of transmission to city gates by a unit train with a carrying capacity of 50 t H_2/d. Total costs include the production of hydrogen and the respective carrier, decomposition, storage, and distribution. Costs were normalized to the distribution of hydrogen gas to a refuelling station. Distribution using methanol carriers was estimated to be near the cost of gaseous hydrogen distribution since both methanol and hydrogen are produced during the ATR of methane and an additional step would not be required for hydrogen production. [124]

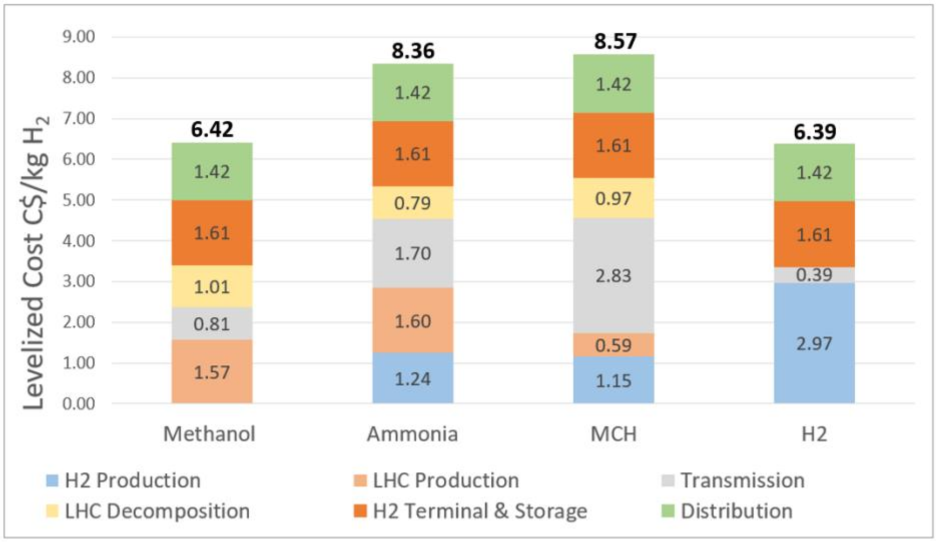


Figure 5.8 The levelized cost of hydrogen distributed to fuelling stations using rail transmission.

Source: Papadias et al. [124] (reproduced)

Long-distance pipeline for LOHCs

The costs of long-distance transmission of hydrogen carriers via pipeline, as shown in Figure 5.9, were optimized according to pipe diameter. The cost of transmitting methanol or ammonia via pipeline from Regina to the coast of BC, for example, would be roughly C$0.25 to C$0.30/kg H_2, or about half the cost of transmitting hydrogen gas the same distance. Transmitting MCH is shown as the most expensive option via pipeline at distances beyond 600 km to 700 km. [124]

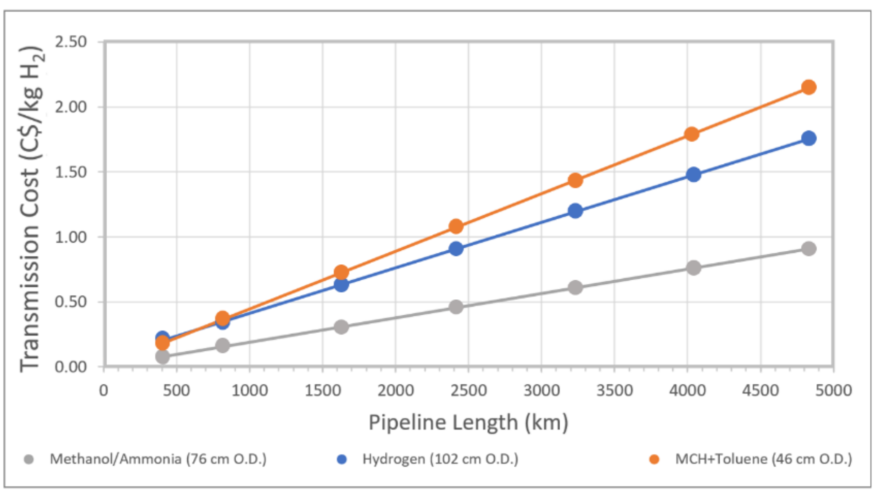


Figure 5.9 Pipeline transmission costs according to pipeline length for each of methanol/ammonia, hydrogen, and MCH.

Source : Papadias et al. [124] (reproduced)

5.2.7 Geological Storage of Hydrogen

There are three possible types of geological storage of hydrogen: depleted reservoirs, aquifers, or salt caverns. Salt cavern storage (SCS) is among the more successful and mature methods for gaseous hydrogen storage in large volumes, with capital costs ranging from C$127/kg for 100 t H2 (C$12.7 million) to C$26/kg for 3,000 t H2 (C$78 million). Annual storage costs range from approximately C$23/kg to C$4/kg over the same scale (C$2.3 million to C$12 million) [126]. At working gas capacities of 100,000 tonnes, the total levelized cost of SCS for hydrogen, which includes capital and storage, can be as low as C$3.40/kg H2 [127]. Mitsubishi Power (Magnum Development) and H2Teesside (BP and Protium) are planning two large hydrogen storage facilities in salt caverns in Utah, along with hydrogen infrastructure [128,129]. As gas storage could play a critical role in our energy future, in-depth studies should be considered for hydrogen stored in regional salt caverns as there are several factors that can have significant effects on the feasibility of this opportunity. Cavern storage represents a small share of all underground gas storage in Canada, with nearly 86% of salt cavern capacity found in Saskatchewan. In the United Kingdom, over 30 caverns are used for storing natural gas [130-133]. Knowledge of SCS for natural gas should be leveraged when assessing hydrogen storage potential since similar caverns may not be suitable for hydrogen due to physiochemical differences such as lower viscosity, overriding, and higher mobility of hydrogen leading to gravity segregation. [134,135]. The geologic suitability of SCS is affected by 1) local geological properties, and 2) total capacity and deliverability, as well as other variables.

1) Geologic Suitability

Suitability of SCS is affected by local geological properties that impact cavern size, stability, containment, and other critical factors. Of the salt deposits found in Saskatchewan, the Prairie Evaporite Formation is the thickest and most laterally extensive. The Lower Salt of the Middle Devonian Prairie Evaporite stretches across the center of the province to the US border and ranges up to 180 m thick (Figure 5.10) and from 700 m to 2,700 m deep [136]. Studies on the geologic suitability for SCS of hydrogen suggest a minimum thickness of 70 m to 200 m for cavern development. Salt thickness less than 70 meters may result in caverns that are too small to store economic gas volumes. The suggested depth range for cavern storage is approximately 1,000 m to 2,000 m [4,130-132,134,137,138]. Salt deformation has been reported to occur at depths greater than 1,800 m below the surface [139,140].

Mineralogical changes within the salt are variable across the extent of the Prairie Evaporite resulting in some areas of Saskatchewan being more or less suitable for cavern storage. The Prairie Evaporite consists of an upper salt that contains the potash beds and other accessory minerals such as interbedded clays. SCS built on thin bedded salt formations is less stable due to a lack of purity with increased mineralogical heterogeneity [139,140]. Interbeds could lead to containment issues, cavern development complications, and other problems associated with the presence of halotolerant or halophilic (salt-tolerant or salt-loving) microorganisms and possible reactions with injected hydrogen [141]. Therefore, it is suggested that SCS for hydrogen be relatively pure and free of shale and carbonate interbeds, potash, anhydrite, or gypsum [136]. Below the potash beds of the Prairie Evaporite lies a unit of massive salt, or halite, which could be an ideal location for the development of cavern storage.

The Prairie Evaporite Formation is directly overlain by the Dawson Bay Formation. The geology of the Dawson Bay varies across Saskatchewan from being tight with no fluid flow to being porous and water filled.

Locally it may be a suitable caprock for hydrogen storage, however, no known studies have been completed to verify if it is a suitable caprock for hydrogen.

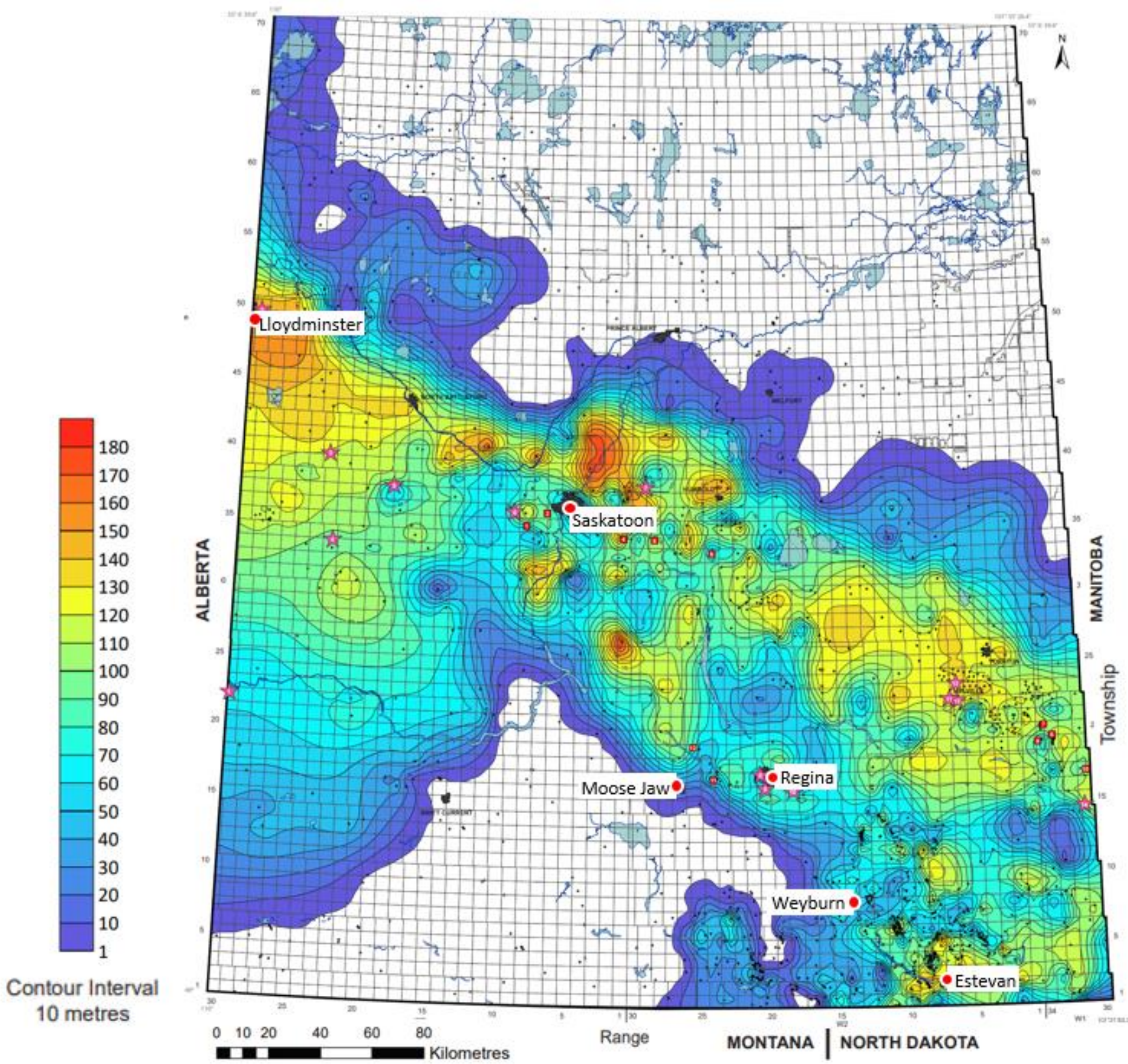


Figure 5.10 Thickness of the Lower Salt of the Middle Devonian Prairie Evaporite throughout Saskatchewan.

Sources: Saskatchewan Geological Survey [142] and Esri Canada [3] (modified)

2) Total Capacity and Deliverability

Capacity refers to the total volume of gas that a cavern can hold in units of thousand cubic feet (Mcf) or billion cubic feet (Bcf). Deliverability is often expressed in terms of the rate of gas withdrawal, such as thousand cubic feet per day (Mcf/d) or billion cubic feet per day (Bcf/d), and varies based on properties such as cavern size, pressure, and depth. Deliverability will ultimately affect cycling times and whether the salt cavern can satisfy demand fluctuations. Pressures among operating US salt caverns located at depths up to 1,340 m below surface are as low as 55 bar, while studies suggest that favorable working gas pressures are more in the 1,500 to 1,600 m depth range, similar to the depths in the RMJIC. Based on Figure 5.11, pressures in the RMJIC could fall between ~100 bar and ~270 bar.

Some of the unknowns regarding salt storage potential in the RMJIC could be confirmed with in-depth geological and engineering studies. Local geological information such as salt thickness, suitability of salt for containment, interactions between salt impurities and hydrogen, and caprock suitability should be investigated. Geological exploration techniques should be conducted to determine the local properties as discussed above. Exploration may include seismic, drilling wells, rock mechanics and other in-depth studies to understand the local caprock and the salt. Studies should also be conducted regarding the minimum operating pressures required to maintain cavern stability, minimum cavern size for economic feasibility, and studies for subsidence and cavern shrinkage over time. Once an area is selected for cavern development, source water for cavern mining, and zones for disposal must be considered prior to starting the mining process. Additional unknowns that need to be determined prior to proceeding with SCS include: the minimum distance from existing potash mines to prevent interaction between storage and mining operations, wellhead and wellbore materials appropriate for the unique properties of hydrogen, and a maintenance plan for these assets as required by safety codes and standards.

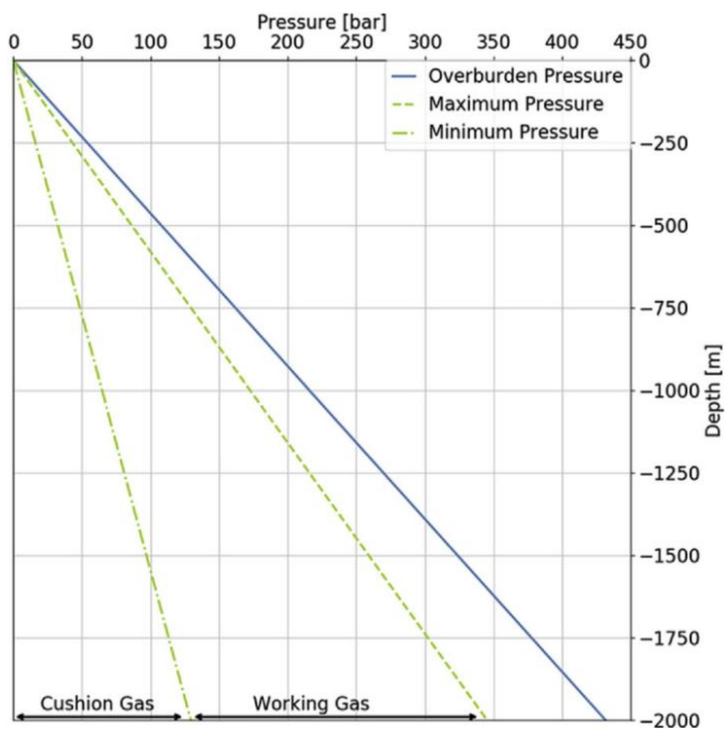


Figure 5.11 Suggested working gas pressures for salt cavern storage.

Source: Caglayan et al. [137]

6 HYDROGEN DEMAND AND INDUSTRIAL PARTNERS IN THE ENERGY TRANSITION

6.1 Hydrogen Demand Estimates

Overview of detailed estimates

Estimates of hydrogen demand in this section were prepared according to area activity and assumptions specific to the RMJIC, and in some cases specific to the province of Saskatchewan. An annual escalation rate of 1.5% was used to estimate energy use in 2028 and 2035 from public provincial data [52]. The relative percentages of energy sources in each sector and subsector were also acquired from this data set. The results of the analysis and assumptions used are included in the respective subsections that follow.

RMJIC hydrogen demand in 2028 and 2035 is largely attributed to industry, however, the majority is intended for feedstock, as shown in Figures 6.1 and 6.2 and Tables 6.1 and 6.2. Feedstock use comprises ~98% of total demand in 2028 and ~84% of total demand in 2035 due to the application of hydrogen in oil refining and fertilizer production in the region.

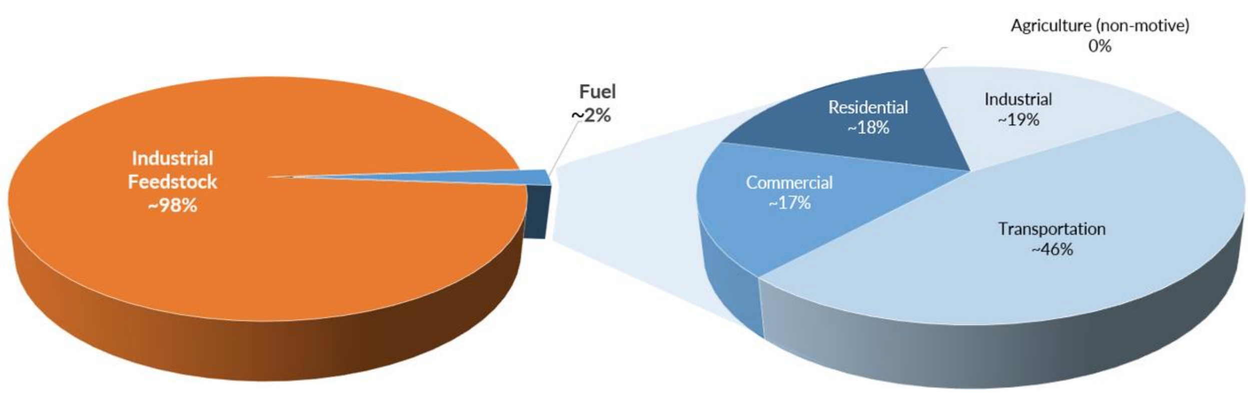


Figure 6.1 RMJIC hydrogen demand in 2028 based on area activity.

Estimates of hydrogen demand for fuel include the use of hydrogen fuel cell technology for backup power and the combustion of hydrogen for the direct replacement of diesel and natural gas. While this foundation report does not cover the emissions associated with hydrogen combustion, further analysis should be conducted to ensure that direct substitution for fossil fuels will reduce the environmental burden in the transition to a low-emissions future.

Estimates for RMJIC hydrogen fuel demand total 16 t H_2/d by 2028, with early movement in fuel cell technology for power generation and pilots in the transportation sector. While there are few renewable energy projects within the RMJIC currently, growth in a local hydrogen economy could support the intermittency and subsequent development of wind and solar power. In addition to backup power, hydrogen fuel cells are capable of providing low-carbon grid power to replace fossil fuels, especially in areas where scale does not justify the adoption of CCUS infrastructure.

Table 6.1 RMJIC and provincial hydrogen demand in 2028.

Hydrogen Demand 2028		
Sector	Saskatchewan ($t\ H_2/d$)	RMJIC ($t\ H_2/d$)
Industrial Feedstock	731	675
Industrial Fuel	20	3
Transportation Fuel	14	7
Commercial Fuel	11	3
Residential Fuel	12	3
Agriculture Fuel (non-motive)	0	0
Total	787	691

~ 16 t H_2/d

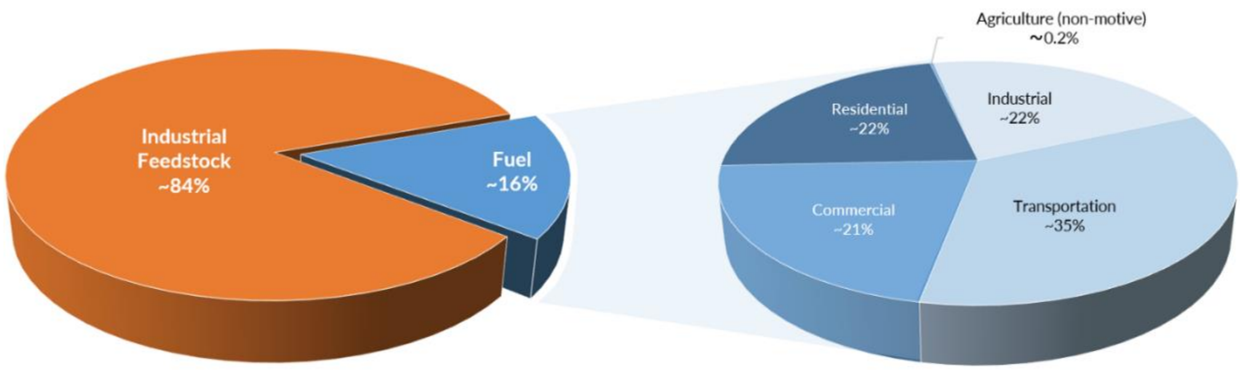


Figure 6.2 RMJIC hydrogen demand in 2035 based on area activity.

By 2035, RMJIC hydrogen fuel demand is estimated to experience exponential growth to nearly 146 t H_2/d, of which more than one third is comprised of transportation fuel. This portion is largely attributed to the movement of long-haul freight by medium- and heavy-duty trucks and rail. Assumptions for 2035 include a 20% hydrogen transition for the trucking industry between H2DF retrofits and HFCE trucks, a 10% transition for freight rail, and a 10% blending rate with natural gas given the pilot activity in western Canada to date.

Table 6.2 RMJIC and provincial hydrogen demand in 2035.

Hydrogen Demand 2035		
Sector	Saskatchewan ($t\ H_2/d$)	RMJIC ($t\ H_2/d$)
Industrial Feedstock	811	749
Industrial Fuel	220	32
Transportation Fuel	126	51
Commercial Fuel	137	31
Residential Fuel	142	32
Agriculture Fuel (non-motive)	1	0.3
Total	1438	895

~ 146 t H_2/d

6.2 Industrial

The RMJIC is home to some of the key industries that provide energy and food security for Saskatchewan in addition to Canadian and global markets. Oil refineries in Regina and Moose Jaw support the transportation of people and critical goods and services, and the fuelling of farm machinery. Local potash and fertilizer producers support agriculture and food production. Others provide services such as the transmission and distribution of natural gas, steelmaking, or the manufacturing of glass products. While each of these industries have a key role to play in providing critical goods and services, the transition to cleaner fuels and grid decarbonization comes with opportunities tailored to industries in the RMJIC.

With the exception of the demand associated with industrial feedstocks, demand for hydrogen as a replacement fuel for natural gas will be low over the near- to mid-term (Table 6.3). Hydrogen blending pilots similar to those with ATCO Gas in Alberta [143] could be possible through to 2035 with exponential growth for hydrogen fuel continuing from the mid-2030s to the point of a low-emissions future (see Section 6.4). Estimates in Table 6.3 were made using assumptions and considerations noted in Table 6.4.

Table 6.3 RMJIC industrial hydrogen demand in 2028 and 2035 according to sector activity.

Industrial Sector	Saskatchewan 2028	RMJIC 2028		
	Energy Use (PJ/y)	Energy Use (PJ/y)	Energy for Transition (PJ/y)	H_2 Demand (t H_2/d)
Total	138	56	35	678
Feedstock Total	38	35	35	675
Fuel Total	100	21	0.2	3
Industrial Sector	**Saskatchewan 2035**	**RMJIC 2035**		
	Energy Use (PJ/y)	**Energy Use (PJ/y)**	**Energy for Transition (PJ/y)**	**H_2 Demand (t H_2/d)**
Total	153	63	41	781
Feedstock Total	42	39	39	749
Fuel Total	111	24	2	32

Table 6.4 Assumptions and considerations for RMJIC industrial hydrogen demand estimates.

Industry	% of Total Energy Use from Fossil Fuels	% for Feedstock vs. Fuels	% Blending for Fuel in 2028 and 2035	% of SK activity in the RMJIC	Considerations for RMJIC Activity
Mining, quarrying, and oil and gas extraction	75.7	All Fuel	1 and 10	15	There is only one active mine within the RMJIC. Minor oil and gas extraction in the RMJIC.
Petroleum refining	75.7	90 vs. 10	1 and 10	95	Two of the three oil refineries in SK are in the RMJIC.
Other manufacturing	49.4	All Fuel	1 and 10	20	Number of industries in the RMJIC vs. SK total.
Chemicals	80.6	90 vs. 10	1 and 10	90	Large chemical manufacturing facility in the RMJIC. Minor chemical production in Saskatoon.
Construction	93.5	All Fuel	1 and 10	30	Construction is highest in urban centres. Some large-scale mining construction outside RMJIC.
Iron and steel	30.0	All Fuel	1 and 10	100	The only steel manufacturer in SK is in Regina.
Pulp and paper	10.0	All Fuel	1 and 10	0	No paper processing in the RMJIC.

6.2.1 Carbon Capture, Utilization, and Storage

Within the RMJIC there are several industries and services with CO_2 emissions greater than 10,000 tonnes per year. The 9 facilities listed in Table 6.5 produce a total of ~3.5 million tonnes of CO_2 annually [144], which suggests there's plenty of room for the adoption of carbon capture technology and future opportunities for hydrogen. The development of CCUS infrastructure for "blue" hydrogen production from natural gas could also support local industries on future carbon reduction initiatives. In southern Saskatchewan, CO_2 has been utilized in EOR to reduce the emissions associated with syngas and power production. As for the underground storage component, the Basal Cambrian Sandstone of the Williston Basin was estimated as having 57 Gt of prospective saline storage potential for CO_2 throughout the province in 2011 [51] and ~250 Gt of potential (P50) in 2014. It is possible that the Black Island Member of the Late Ordovician Winnipeg Formation made a secondary contribution to the latter estimate [5].

Table 6.5 RMJIC industries emitting 10,000+ t CO_2/y.

Type of Business	Location	Approximate Total Emissions ($t\ CO_2/y$)
Petroleum refining and upgrading	Regina	1,790,000
Potash solution mining	Belle Plaine	698,000
Nitrogen fertilizer production	Belle Plaine	546,000
Steel manufacturing	Regina	232,000
Natural gas transmission	Regina	104,000
Ethanol production	Belle Plaine	71,000
Petroleum refining and upgrading	Moose Jaw	63,000
Natural gas distribution	Regina	17,000
Glass bead manufacturing	Moose Jaw	10,000

Source: Government of Canada [144]

Figure 6.3 shows the approximate locations and relative emissions of seven of the CO_2 contributors in Table 6.5. The emissions attributed to natural gas transmission and distribution are likely not confined to one specific area and are therefore not represented on the map. Figure 6.3 also shows the location of the CCUS hub in southern Saskatchewan comprised of two major projects, the locations of approved CO_2 storage and approved lease of space (LOS) for future CO_2 storage, and the approximate extent of the Basal Cambrian in the province which holds the geologic units being targeted for EOR and CO_2 storage.

The Weyburn-Estevan CCUS hub includes the Whitecap Resources Inc. operated CO_2 EOR project which has stored over 40 megatonnes (Mt) of CO_2 to date with the potential to store an additional 75 Mt in the Weyburn Unit and surrounding lands [145]. The target formation for the Weyburn Unit EOR process is the Midale formation. Figure 6.3 shows the CO_2 pipelines which connect the Weyburn Unit to operations in Estevan and the location of a CO_2 pipeline connection to the US. The Weyburn Unit, and the neighbouring Midale Unit, receive CO_2 from the Dakota Gasification Company synfuels plant in Beulah, North Dakota. Over the past 27 years, EOR projects throughout Saskatchewan have added over 100 million barrels of incremental oil production and reduced CO_2 emissions by 37% per barrel compared to conventional oil production [146].

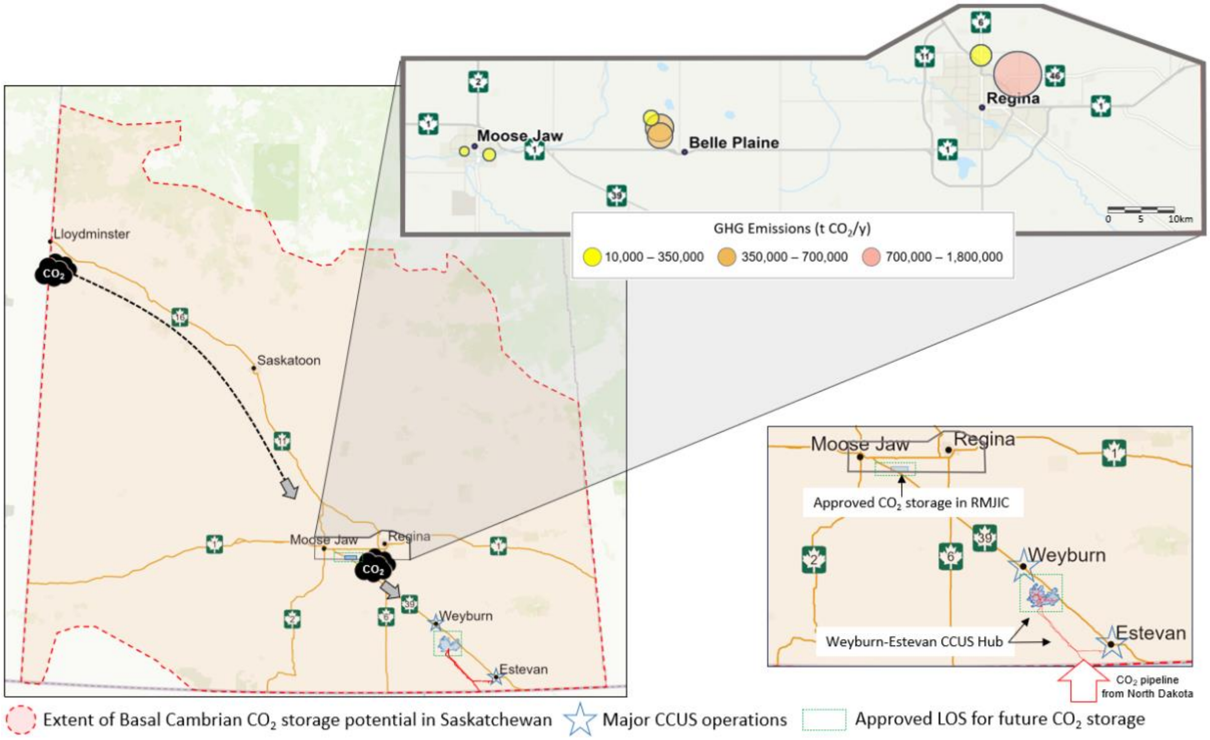


Figure 6.3 RMJIC emissions, CCUS operations, and the approximate lateral extent of Basal Cambrian CO_2 storage potential in Saskatchewan.

Sources: EERC [51] and Esri Canada [3] (modified)

Estevan has the world's first successful deployment of CO_2 capture technology on a coal-fired power generation unit. The Boundary Dam Carbon Capture Project (SaskPower) has captured over 5.3 million tonnes of CO_2 since commencing operations in 2014, for storage in both the Weyburn Unit and The Aquistore project in Estevan [147]. The Aquistore project was designed to use CO_2 from the Boundary Dam Power Station to demonstrate the potential for subsurface storage in the region's deep saline reservoirs. Situated below most of the regional hydrocarbon and potash production at over 3150 m below the surface, the Basal Cambrian Sandstone provides a secure location for CO_2 storage. The Aquistore regional-scale storage potential (P50) for the key geological units of the Deadwood and Black Island Formations was 3.1 Gt in 2014, based on model simulations [148]. At that time, the site was expected to sequester approximately 34 million tonnes after 50 years with room for optimization.

In addition to the future storage of CO_2 from facilities in the RMJIC and the surrounding region, there could be opportunities for even greater adoption of CCUS with the development of a CO_2 transmission line from Lloydminster through Saskatoon. Lloydminster could also serve as a second location for a hydrogen hub in Saskatchewan, given the flow of traffic along Highway 11 and Highway 16, and the refining, upgrading, and EOR operations in the local area.

Additional work would be beneficial to further characterize the CCUS potential of the Basal Cambrian Sandstone throughout Saskatchewan. The aquifer has a collection of data in the National and Plains CO_2

Reduction (PCOR) Partnership Atlas. Local-scale modelling of this data could help to refine areas with the highest storage potential for future management of CO_2 storage opportunities and risk [149].

6.2.2 Regional Interest in a Hydrogen Economy

The SRC conducted a survey of the industrial and commercial sectors in the RMJIC to gauge interest in a future hydrogen economy for the region. 70% of respondents said they were planning to diversify their energy use, with solutions ranging from on-site renewables and hydrogen to increased electrification and reduced reliance on fossil fuels. 55% of respondents foresee a role for hydrogen in the energy transition with 30% likely to produce a portion of their total demand. Nearly 55% foresee a role for hydrogen in the transportation sector followed by the industrial sector at nearly 40%. At C$65/t CO_2, the current rate of federal carbon tax is making an impact on the business of nearly half of the respondents who share an interest in the early adoption of hydrogen. While there is plenty of interest in a hydrogen economy from stakeholders within the RMJIC, there were no commitments for the future adoption of hydrogen aside from those industries currently producing for their own use as industrial feedstocks. There are a number of steps that would have to be taken prior to securing commitments from regional stakeholders, as outlined in the Checklist for Hub Development in Subsection 7.2 and Developing a Shared Vision for Hydrogen in Section 9.

6.2.3 Joint CCUS Opportunities in the RMJIC

The RMJIC holds a major opportunity for CCUS in the production of "blue" hydrogen for petroleum feedstock and other uses. The petroleum refinery in Regina, owned and operated by FCL, is currently pursuing the production of low-carbon hydrogen from natural gas with CCUS. While the company plans to capture 500,000 tonnes of CO_2 between their refinery and ethanol plant, the RMJIC will require significant investment in CCUS infrastructure to meet future hydrogen demand for all sectors as shown in 2035 estimates (Table 6.2) and those projected for a possible low-emissions future (Section 6.5). The general location of the FCL refinery would be ideal for the supply of hydrogen to refuelling stations near the TransCanada Highway in Regina's east end, as will be discussed in Section 6.3.

Hydrogen feedstocks are also produced at the nitrogen fertilizer plant in Belle Plaine (Yara). The facility currently consumes all the hydrogen it produces via SMR without CCS; however, the plant uses roughly 90% of its industrial process CO_2 as an additional feedstock for urea production. As for the diluted CO_2 stream from natural gas use for boilers and space heating, the company indicated there is no immediate opportunity for the adoption of CCUS infrastructure at the Belle Plaine facility. Yara has also given some thought to the future of "green" hydrogen from renewables for a low-carbon ammonia product, noting that reduced steam production from SMR would lead to increased emissions on the front end from increased boiler run-time for steam required on-site. It is also believed that there could be more opportunities to decarbonize ammonia production through electrification over the near- to mid- term than through the burning of hydrogen. [150]

Steel manufacturer Evraz is embracing the future of alternative energy and energy carriers including hydrogen and CCUS. They are currently exploring the integrity and energy density of hydrogen for application in their reheat furnaces. Once their casted metal slabs are cooled, they are reheated prior to the rolling process. The company's goal is to eventually use 100% hydrogen for this process, for which fuel cells could be an option. They also have a great deal of interest in the manufacturing of hydrogen pipeline and the development of related safety specification codes and standards. Evraz also has several projects ongoing related to CCS in terms of capture, pipeline transportation, and storage. [151]

Potash producer Mosaic would have concerns for the application of CCUS at their Belle Plaine facility. The Deadwood Formation, which is the company's zone of interest for brine injection, is a primary target for CO_2 capture in southern Saskatchewan. Therefore, any storage of CO_2 from their facility would have to be transported a safe distance from their Belle Plaine operations, for which a dedicated CCUS pipeline network or hub would be beneficial. [152]

The remainder of the GHG emitters in Table 6.5 would likely not be in the business of CCUS-supported hydrogen production. Additional opportunities from the remaining industry players would fall under the use of hydrogen as a heating fuel, ramping up from the mid-2030s to the point of a low-emissions future. For industries that would use machinery transitioned from diesel and gasoline, such as the construction sector, the technology readiness is expected to be relatively low over the near- to mid-term with hydrogen demand up to 3 t H_2/d by 2035.

6.3 Transportation

The relative percentage of RMJIC hydrogen demand in 2035 by vehicle type is shown in Figure 6.4. Medium- and heavy-duty trucks were estimated to consume ~56% of the total followed by ~23% for freight rail, both of which have pilots ongoing in Canada. Agriculture represents ~9% of the total by 2035 from a mere 2% estimated for hydrogen pilot demonstrations (Table 6.6). Cars and light duty vehicles also make up a smaller share given the anticipated growth in the BEV market for these vehicles.

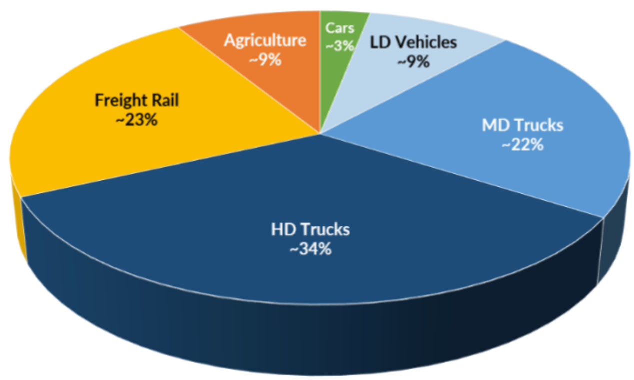


Figure 6.4 Relative percentage of RMJIC hydrogen demand for the transportation sector in 2035 by vehicle type.

Data: NRCan [52]

Table 6.6 Transportation hydrogen demand in (A) 2028 and (B) 2035.

(A) Transportation	Hydrogen Demand 2028: Transition to H_2 (%)	Saskatchewan ($t\ H_2/d$)	RMJIC ($t\ H_2/d$)
Cars	0	0	0
LD Vehicles	0	0	0
MD Trucks	5	4	2
HD Trucks	5	6	3
Freight Rail	1	3	2
Agriculture	0	0	0
Total		14	7

(B) Transportation	Hydrogen Demand 2035: Transition to H_2 (%)	Saskatchewan ($t\ H_2/d$)	RMJIC ($t\ H_2/d$)
Cars	2	7	2
LD Vehicles	2	20	4
MD Trucks	20	22	11
HD Trucks	20	35	17
Freight Rail	10	23	12
Agriculture	2	20	4
Total		126	51

6.3.1 Medium- and Heavy-Duty Trucking

Medium- and heavy-duty trucking is seen as a possible application for the early adoption of hydrogen when compared to the retail cost of diesel fuel (Figure 4.1). Trucks can be equipped with either HFCE technology or retrofitted H2DF engines that can burn both diesel and hydrogen. HFCE vehicles have been designed to reduce vehicle weight and extend driving range when compared to BEVs.

H2DF engines could be an important stepping-stone in the transition to hydrogen while building supply and infrastructure for fuelling stations. Their port-injection systems can utilize about 40% hydrogen [153] and CO_2 emissions can be reduced by 86%. Engine efficiencies are 26% higher than conventional diesel engines, with the latest R&D demonstrations showing diesel substitution rates up to 90% when using direct injection [154]. However, H2DF engines also contribute to nitrogen oxide (NOx) emissions. While this technology will be key during the early- to mid-term, a transition to HFCE trucks over the mid- to long-term is expected as costs of hydrogen production through to distribution become more competitive with legacy fuels, especially when considering the rise in federal carbon taxes and other incentives.

The AZETEC project in Alberta is investigating the benefits of hydrogen use in heavy-duty trucking. The 64-tonne trucks are designed to travel up to 700 kilometres between refuelling stops at -40˚C to 40˚C. By the end of the project, they will have travelled more than 500,000 km along a commercial corridor. They've noted the importance of showing the robust nature of the hydrogen technology in terms of distance travelled, payload, and emissions reduction. [155]

RMJIC truck traffic

To estimate hydrogen demand for medium- and heavy-duty trucking in the RMJIC, trucking data was acquired from the Saskatchewan Ministry of Transportation and the Saskatchewan Trucking Association. It included the annual daily traffic from 2017 to 2021 as well as the distance travelled on each section of highway in the province. Figure 6.5 shows the data as mapped near cardlock diesel fuelling stations as over 1,000 trucks per day in each of Regina and Moose Jaw. The trucks included in the data set are from classes 5 through 13, which represent the total of most medium- and heavy-duty trucks that travel on Saskatchewan highways. Suggested locations of future HFS would serve the high volume of truck traffic in the region. In Regina, an HFS could fall within 5 km of the refinery as a potential source of "blue" hydrogen production, should FCL decide to capture CO_2 from their hydrogen production unit.

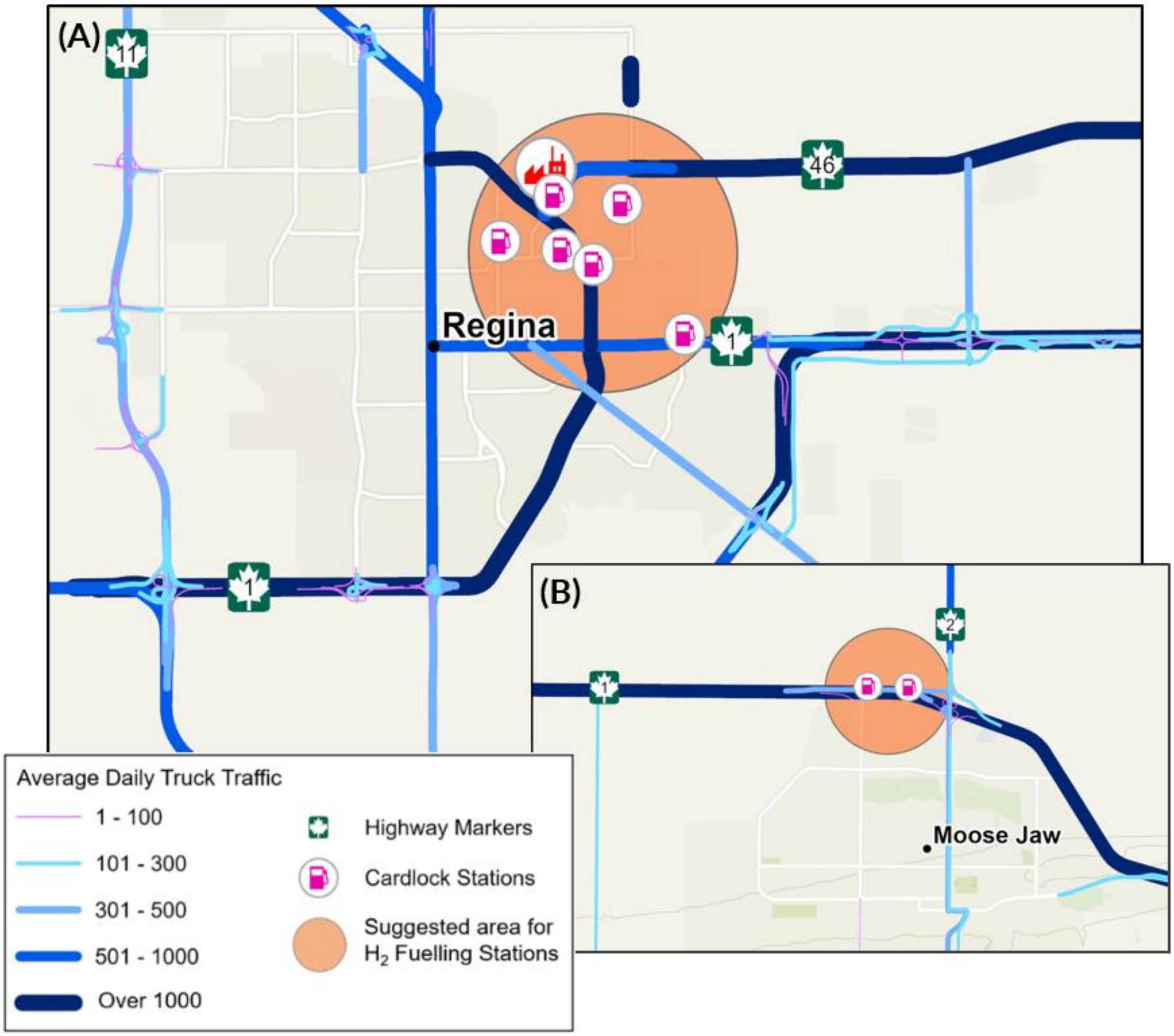


Figure 6.5 Daily medium- and heavy-duty truck traffic volumes passing through Regina (A) and Moose Jaw (B).

Source: SK Ministry of Transportation and SK Trucking Association (data); ESRI [3] (modified)

The trucking analysis was performed for the entire province of Saskatchewan given the data provided, and assumptions were made (Table 6.7) to scale the results to the RMJIC in 2028 and 2035 (Table 6.6), and in a low-emissions scenario (Section 6.5). At a retail price target of C\$5 to C\$8/kg for hydrogen transport fuel (Figure 5.2), the fuel cost per kilometer for medium- and heavy-duty trucking would fall between C\$0.39/km and C\$0.63/km assuming a range of 7.86 kg H_2/100 km and 45.9 kg/refill [156,157]. The total calculated range of 573 km/refill is conservative when compared to targets of 700 km to 1000 km on a full tank [158,159]. A total of 3 to 4 hydrogen fuelling stations, each providing 8 t H_2/d, would be required to satisfy the trucking demand in the RMJIC by 2035, based on 2017-2021 medium- and heavy-duty truck traffic. The Transition Accelerator estimated that a 2 t H_2/d fuelling station would meet the minimum economic threshold with a relatively minor cost adjustment in C\$/kg H_2 compared to an 8 t H_2/d station (Figures 5.2 and 5.3). A total of 6 to 7 fuelling stations would be required to accommodate the total transportation hydrogen demand in the RMJIC by 2035, which is near the current number of cardlock diesel fuelling stations in the region.

Table 6.7 Assumptions for the medium- and heavy-duty trucking analysis for 2028 and 2035.

Assumptions	Assumed %
Medium-duty trucks on SK highways	39
Heavy-duty trucks on SK highways	61
Transition to H_2 in 2028 and 2035	5 and 20
H2DF trucks in 2028 and 2035	90 and 70
Hydrogen used in H2DF trucks	40
HFCE trucks in 2028 and 2035	10 and 30
Hydrogen used in HFCE trucks	100

6.3.2 Cars and Light-Duty Vehicles

An estimate of hydrogen demand for cars and light-duty vehicles was conducted similar to that for medium- and heavy-duty trucking, with data provided by the Saskatchewan Ministry of Transportation. No demand was added to 2028 estimates as that segment of the industry is expected to remain relatively quiet over the next few years with more interest in BEV alternatives to ICEs. By 2035, it is assumed that fuel for test pilots and the use of hydrogen cars and light-duty vehicles will account for 2% of the Saskatchewan transportation sector, resulting in a hydrogen demand of nearly 6 t H_2/d. It was also assumed that fuel cell technology would be used primarily for hydrogen cars and light-duty vehicles, with no contribution from H2DF technology.

6.3.3 Freight Rail

According to NRCan data, freight rail in Saskatchewan consumed nearly 16 PJ of energy in 2020, 100% of which was attributed to diesel fuel. With HFCE locomotive pilots emerging in Western Canada, RMJIC estimates of hydrogen demand remain within the demonstration stage through 2028 and climb to 10% of freight rail by 2035.

Since announcing plans for hydrogen-powered rail in 2020, CPKC Limited expanded their Hydrogen Zero-Emission Locomotive (H20EL) pilot project to three units in 2022. The project allows the retrofit of diesel engines to hydrogen fuel cells and avoids the cost of manufacturing a new chassis for each unit. The latest project announcement is the addition of (8) 200-kW fuel cell modules to their initial order, all to be manufactured by Ballard Power Systems [160]. ATCO and CPKC recently announced a joint project to develop hydrogen production and fuelling facilities at the Calgary and Edmonton railyards, with facilities supported by solar power and electrolysis from the provincial electricity grid. [161]

Like heavy-duty transport, the use of hydrogen fuel for rail is attractive in that it is suited for long-haul applications. While hydrogen-powered trains are somewhat in their infancy globally, countries like Germany are leading the charge. In August 2022, the country debuted the first ever rail line powered exclusively on locomotives using HFCE technology [162]. The engines consume 1 kg of hydrogen for every 4.5 kg of fuel demanded by diesel-fuelled trains, with a range of 1,000 km on a single tank of hydrogen. In addition to the 14 trains deployed in Bremervörde, Germany, manufacturer Alstom has 27 units destined for Frankfurt before moving on to Italy and France. Other prototype fuel cell trains are being investigated in China, Japan, Taiwan, the UK, and the US.

Rail can also be used to transport hydrogen in cryogenic tanks to locations not served by pipeline. In September 2022, Bahn AG announced its plans to transport liquid hydrogen by rail in Germany, from marine ports into the inner regions of the country [163]. LOHCs offer an advantage here in that existing tanks already used for the transport of oil product could be used. The estimated capacity of these tanks is 70 cubic meters per unit at a price of approximately US$135,000 [164]. This would require the approval of hydrogen transport by rail, which has not yet been granted within Canada [165]. Nonetheless, CN Railway has stated that it sees the potential of shipping hydrogen in tank cars reaching the same level as crude transport today [166].

Switcher locomotives

Mid-term adopters of hydrogen applications could include switcher locomotives, which can consume up to 10% of the demand for rail fuel [157]. Although they do not move long distances, they operate steadily throughout the day and are therefore a significant source of GHG emissions [167]. Infrastructure could include one hydrogen fuelling station per yard [168].

Change Energy Services developed seven scenarios for the use of hydrogen for switcher locomotives. They estimated that one locomotive would require 75 kg of hydrogen per day. The study also compared the costs of either delivering hydrogen to the yard or producing hydrogen on-site through electrolysis. The cost of converting one switcher locomotive to hydrogen was estimated at C$7M. Pilot projects assessing the potential of hydrogen-applications for short line rail operators is already underway in BC. Southern Railway of British Columbia, in partnership with Loop Energy and Hydrogen In Motion, also announced in 2021 that it was converting a diesel locomotive to run on HFCE technology [169].

6.3.4 Agriculture

Motive agriculture used 67 PJ of energy throughout Saskatchewan in 2020, or ~33% of the province's total energy demand for transportation. The fuelling of agricultural machinery will be challenging given that current refuelling of diesel is often done on-site. This would add significant cost to hydrogen delivery. However, given the sizeable portion of energy use and subsequent emissions from the (motive) agriculture sector, there is an opportunity here for R&D into low-carbon solutions.

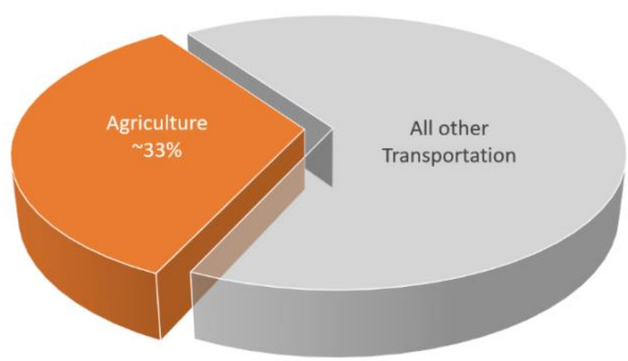


Figure 6.6 Relative percentage of motive agriculture energy use in the provincial transportation sector.

Data: NRCan [52]

RMJIC hydrogen demand for motive agriculture will be relatively low in the near- to mid-term with an assumed 2% transition to 2035 for pilot testing with minor infrastructure growth. Less than 2% of all farms in Saskatchewan are within the boundaries of the RMJIC, so estimates of hydrogen demand in 2028 were based on only 2% of provincial activity, while estimates for 2035 were based on 10% of the provincial agriculture demand with greater access in the future to hydrogen infrastructure and pilots for agricultural vehicles.

Companies in the UK are now starting to develop hydrogen-powered farm equipment, including dual-fuel tractors that run on a combination of hydrogen and diesel. Like dual-fuel medium- and heavy-duty trucks, these units can run on 100% diesel when hydrogen is not available [170]. In terms of infrastructure, on-site refuelling will require either dedicated hydrogen pipelines to transport fuel from hydrogen hubs or the cost of delivery via road and/or rail and LOHCs to drop significantly. Alternatively, hydrogen could be produced on-site from grid power or renewable energy in remote areas. Companies such as BayoTech are converting biomethane derived from biogas into hydrogen, with applications from livestock producers to feedlots [171].

Another option is using ammonia as a fuel, which has the advantage of leveraging existing supply chains linked to fertilizer production. Tractors are being developed that can crack the ammonia to produce hydrogen, which is then used in hydrogen fuel cells [172]. Dual-fuel tractors that run on anhydrous ammonia with diesel have started trials at the University of Minnesota [173]. Demonstrations are also ongoing for ammonia use in grain dryers [174].

6.4 Commercial, Residential, and (Non-Motive) Agriculture

6.4.1 Space and Water Heating

The primary source for home heating in Saskatchewan is natural gas. Hydrogen could be considered as a low-emissions alternative for replacing at least some of the natural gas by blending it into existing natural gas pipelines. Parts of Europe are leading the research to determine a maximum safe and efficient blending rate. The Energy Networks Association (ENA) in the UK is preparing to add 20% hydrogen by volume to the gas grid in 2023 [175]. In Alberta, ATCO is developing a project to demonstrate 5% blending by volume into a portion of Fort Saskatchewan's natural gas distribution system [55]. It is worth noting that there are limited regions of the UK where town gas, typically comprised of 25% to 60% hydrogen, was once used for heating [176]. Legacy pipelines in these areas could be capable of higher hydrogen blending rates than natural gas pipelines in Canada.

Hydrogen demand estimates for commercial and residential space and water heating were adjusted from early estimates with the addition of hydrogen blending rates assumed at 10% by 2035 (Table 6.8). Only 1% was added in 2028 to account for possible pilot demonstrations. This resulted in a hydrogen demand of 2.5 t H_2/d and 2.6 t H_2/d for each of the commercial and residential sectors in 2028, and a demand of 31 t H_2/d and 32 t

Table 6.8 Commercial and residential hydrogen demand in (A) 2028 and (B) 2035.

(A) Sector	Saskatchewan 2028			RMJIC 2028	
	PJ/y	1% H_2 Blending		1% H_2 Blending	
		PJ/y	t H_2/d	PJ/y	t H_2/d
Commercial	35	0.4	11	0.1	2.5
Residential	43	0.4	12	0.1	2.6

(B) Sector	Saskatchewan 2035			RMJIC 2035	
	PJ/y	10% H_2 Blending		10% H_2 Blending	
		PJ/y	t H_2/d	PJ/y	t H_2/d
Commercial	39	5	137	1.2	31
Residential	48	5	142	1.2	32

H_2/d for each of these sectors, respectively, by 2035.

It should be noted that the replacement of natural gas for hydrogen in space and water heating comes with unique challenges. These include direct emissions that deserve further research into the volume and type of pollutants and their respective carbon intensities. Recent studies have shown an emissions reduction of less than 6% by blending hydrogen with natural gas up to 20% by volume [57]. Existing infrastructure would also require significant upgrades to enable hydrogen blending in the Saskatchewan natural gas network.

6.4.2 Microgrids

A microgrid is a self-sufficient energy system which serves a specific geographic area such as a community, business, or campus. With the use of renewable energy and storage components, a microgrid can operate independently from a primary electrical grid. Reliable microgrids often employ fossil fuel generation for backup power production when renewables and electrical storage are not available. There may be an opportunity to use a HFCE or H2DF to provide reliable backup power to offset diesel, natural gas, or propane generators. Electrolyzers could be used on-site to generate hydrogen for storage, thereby displacing the need for electrical energy storage. For the RMJIC, microgrids could be integrated into hospitals, campuses, housing complexes, or as backup power for mines or businesses linked to the existing grid. Microgrids could also be used for backup power in off-grid communities throughout the province.

6.4.3 Agriculture (Non-Motive)

Non-motive agriculture represents a minor portion of total energy use for the province of Saskatchewan at roughly 8 PJ/y in 2020. With hydrogen delivery to remote areas challenged over the near- to mid-term, it is expected that opportunities for non-motive agriculture will be low. Therefore, there was no activity assumed by 2028 and only a minor transition (2%) by 2035 to account for technology development in non-motive agricultural applications.

6.5 Future Hydrogen Demand in a Low-Emissions Scenario

6.5.1 A Hydrogen Economy for Saskatchewan

Natural Resources Canada's (NRCan) *Hydrogen Strategy for Canada* highlights the potential for our country to be a leader in the production, end-use, and export of hydrogen. The RMJIC has many qualities in favor of successful hydrogen hubs, giving Saskatchewan a competitive advantage in the development of a robust hydrogen economy. However, there are challenges that will need to be addressed for hydrogen to contribute to a low-emissions future. The following points summarize the key strengths and weaknesses specific to the RMJIC and the future of hydrogen as an alternative fuel and energy carrier for the region.

Key aspects that are working now

- ☐ The RMJIC and surrounding area has expertise in **hydrogen production and CCUS** for the early development of low-carbon "blue" hydrogen from natural gas. Southern Saskatchewan also has proven and promising capacity for future **CO_2 storage**.
- ☐ The RMJIC has strong **road and rail infrastructure** to support hydrogen hubs. The TransCanada and Canada's rail network connect Saskatchewan to the Port of Vancouver in the west and to Ontario

and the Maritimes in the east. More than 1,000 medium- and heavy-duty trucks pass through the corridor daily which could give rise to the early development of hydrogen fuelling stations and support the future of trucking and freight rail with pilot demonstrations ongoing in each of these subsectors in Western Canada.

- ☐ Saskatchewan has some of the best **renewable energy** potential in the country and is also supporting the development of **new nuclear** in Canada. Both could be used to produce low-carbon hydrogen in the future.

Key aspects that require greater effort

- ☐ The development of **dedicated CO_2 pipelines** would be key to transporting CO_2 to underground storage in southern Saskatchewan. In addition to supporting low-carbon hydrogen production, a CO_2 pipeline network could encourage the adoption of CCUS technology from larger industries in the RMJIC and further the development of regional EOR for added emissions reduction.
- ☐ The development of **dedicated hydrogen pipelines** will be critical to moving high volumes of hydrogen fuel for the future of power generation and space heating. Until then, aside from its use as a transportation fuel, Canada's hydrogen economy will be restricted to pilots and early commercialization projects. While the repurposing of natural gas transmission lines is being explored, it comes with risks of embrittlement and failure under high concentrations of hydrogen.
- ☐ Innovation into **hydrogen fuel cell technology** should be accelerated with diverse applications testing. Hydrogen fuel cell R&D should focus on cost, performance, and reliability over long periods in extreme cold temperatures.

6.5.2 Future Hydrogen Demand Estimates

Estimates of hydrogen demand in a low-emissions future were prepared using the same methods as the estimates for 2028 and 2035 in Section 6.1 (Figure 6.7 and Table 6.9). The year 2050 was chosen for the future state for the purpose of energy data escalation where required. Assumptions for the future state are aggressive to highlight the infrastructure and advances in technology that would be required for hydrogen to make a significant contribution to emissions reduction in the RMJIC.

The key assumptions for the future state are as follows:

- ☐ The development of a CCUS hub in the RMJIC to support the production of low-carbon hydrogen. The primary source would be the refinery in Regina with other opportunities throughout the region.
- ☐ The development of dedicated pipelines for hydrogen allowing transport to fuelling stations, major industry (50%), commercial

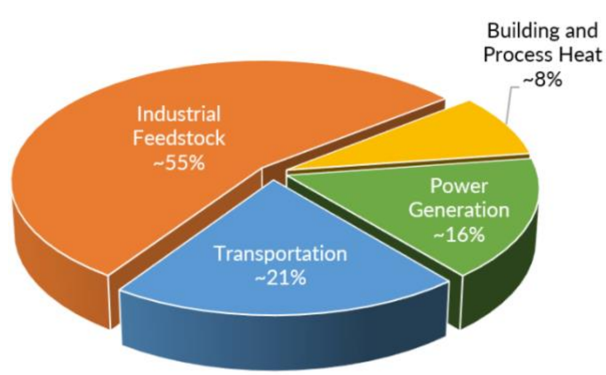


Figure 6.7 Relative percentage of hydrogen demand by market in the RMJIC in a low-emissions future.

and residential areas (50%), and agriculture (10%, or 1% of SK agriculture demand) from the RMJIC.

- ☐ A shift from the early adoption of H2DF technology for medium- and heavy-duty trucking to primarily HFCE vehicles.
- ☐ An increase in the use of fuel cells for backup power and to support the growth of renewable energy.

Table 6.9 RMJIC and provincial hydrogen demand by market in a low-emissions future.

Hydrogen Demand Low-Emissions Future		
Market	Saskatchewan ($t\ H_2/d$)	RMJIC ($t\ H_2/d$)
Industrial Feedstock	1021	943
Transportation	794	352
Power Generation	1449	279
Building and Process Heat	801	145
Total	4065	1719

~ 776 $t\ H_2/d$

Industrial feedstocks were estimated to consume ~55% of total demand by 2050, as shown in Figure 6.7. Increases in transportation are largely due to a 60% share of medium- and heavy-duty trucks and a 30% share of freight rail transitioning to HFCE technology. A 10% transition for agricultural vehicles accounts for 25% of the RMJIC hydrogen demand in the transportation sector. Inputs for power generation and building and process heat come from all sectors, except for transportation and feedstock use. Assumptions were otherwise the same as those used for estimates in Section 6.1.

6.5.3 Emissions Reduction from the Adoption of Hydrogen

Total emissions for the province of Saskatchewan in 2020, excluding those from electricity generation, were nearly 25 Mt CO_2e [52]. This total would climb to 39 Mt CO_2e by 2050 at an escalation of 1.5%. The adoption of hydrogen in a low-emissions future could see up to a 33% reduction in emissions between all fuel markets, as shown in Table 6.10. Reductions from the use of hydrogen for backup power generation and the replacement of natural gas for building and process heat assume that emissions from the burning of hydrogen result in a net 15% improvement over natural gas with dedicated pipelines at 50% capacity [57].

Table 6.10 RMJIC and provincial CO_2e reductions by market in a low-emissions future.

CO_2 Reduction Low-Emissions Future				
Market	Saskatchewan		RMJIC	
	Energy Use Reduction (PJ/y)	Emissions Reduction (Mt CO_2/y)	Energy Use Reduction (PJ/y)	Emissions Reduction (Mt CO_2/y)
Transportation	117	8.1	52	3.6
Power Generation	94	4.7	21	1.0
Building and Process Heat	52	0.4	11	0.1
Total	~263	~13	~84	~5

6.6 Future Opportunities for Hydrogen Fuel

6.6.1 City-Owned Vehicles

The City of Regina is planning to replace their existing diesel bus fleet with BEV buses starting in 2025. They expressed interest in the future of HFCE vehicles for the remainder of their fleet and provided city-owned vehicle data. An analysis was performed on two of the city's 'other' fleet vehicles for which there was adequate data. In addition, an analysis of their current bus fleet was completed should the city choose to add hydrogen bus units to their planned BEV fleet in the future.

Freightliner M2-106 fleets

The M2-106 is a vehicle used by municipalities and industry for construction and the collection of garbage and recycling. The City of Regina had 25 unique units of this diesel model in 2019, with anywhere from 12 to 24 units in operation every month. These vehicles could be replaced by HFCE trucks. Total estimated hydrogen demand for full replacement of the M2-106 fleet, as shown in Table 6.11, was based on an assumed diesel fuel mileage of 25.6 to 30.1 L/100 km for that size of unit and a range of 7.86 kg/100 km [155] for a similar HFCE truck. Total hydrogen demand for this fleet was estimated at 1.3 to 1.6 t H_2/d. At an average retail cost of C$2.10 for diesel fuel, the retail cost of hydrogen fuel would have to be between C$7/kg and C$8/kg for HFCE trucks to be competitive on fuel with the current diesel fleet. These replacements were estimated to require an additional 29 to 34 fills per day at a fuelling station assuming a 46.5 kg tank for an HFCE unit.

Table 6.11 Summary of the analysis for HFCE trucks as a possible replacement for diesel units.

HFCE Truck	RMJIC 2023	
Typical mileage range (kg/km)	0.0786	
Hydrogen demand by all units per day (kg)	1333	1567
Hydrogen demand by all units per month (kg)	39,982	47,010
Hydrogen cost per month (retail C$4/kg)	159,929	188,041
Hydrogen cost per month (retail C$6/kg)	239,893	282,062
Hydrogen cost per month (retail C$8/kg)	319,857	376,082
Number of fills per day	29	34

Goshen G4500

The Goshen G4500 is a vehicle which can be used as a public transit van for elderly or physically handicapped persons. The City of Regina had 33 of these gasoline units in 2019, ranging from 26 to 33 units in operation every month. These vehicles could be replaced by HFCE utility vans which are currently being produced in Canada [177]. Information was limited in terms of fuel economy and tank size, so fuel economy was assumed to fall between rates for cars on the market and published rates for heavy-duty vehicles. In terms of fuel, HFCE utility vans were estimated to be competitive at a hydrogen fuel cost between C$7/kg and C$8/kg when compared to gasoline at an average retail cost of C$1.60/L and gas mileage for the Goshen 4500 (Table 6.12). A total replacement of this fleet with HFCE vans was estimated to demand an additional 5 to 8 fills per day at a fuelling station assuming a 20 kg tank.

Table 6.12 Summary of the analysis for HFCE utility vans as a possible replacement for gasoline units.

HFCE Utility Van	RMJIC 2023	
	Low	High
Typical mileage range (kg/km)	0.03	0.05
Hydrogen demand by all units per day (kg)	99	165
Hydrogen demand by all units per month (kg)	2,971	4,952
Hydrogen cost per month (retail C$4/kg)	11,885	19,808
Hydrogen cost per month (retail C$6/kg)	17,827	29,711
Hydrogen cost per month (retail C$8/kg)	23,769	39,615
Number of fills per day	5	8

Transit bus analysis

The City of Regina transit bus fleet is comprised primarily of Nova (brand) buses with a small number of Vicinity (brand) buses for a total fleet of just over 100 units. As shown in Table 6.13, fuel economy for their diesel bus fleet was assumed to be between 55 L/100 km and 78 L/100 km based on the published rates of similar units. Fuel economy for a similar HFCE bus was estimated to be between 7 kg/100 km and 8 kg/100 km [178,179]. Retail fuel costs for hydrogen buses were estimated to be competitive at current rates between C$12 and C$14/kg. The city could revisit the potential of an HFCE fleet to support their BEV fleet in a low-emissions future scenario for the RMJIC. In addition to a comparison of future capital and operating costs between both units, there should be some consideration of charging time of BEV's versus fuelling time of HFCE's and the practicality of each in colder climates.

Table 6.13 Summary of the analysis for HFCE transit buses to support the Regina Transit fleet in a low-emissions future.

Hydrogen Buses (both Nova and Vicinity units)	Low-Emissions Future	
	Low	High
Typical mileage range (kg/km)	0.070	0.080
Hydrogen demand by all buses per day (kg)	1243	2015
Hydrogen demand by all buses per month (kg)	37,299	60,454
Hydrogen cost per month (retail C$4/kg)	149,197	241,816
Hydrogen cost per month (retail C$6/kg)	223,796	362,724
Hydrogen cost per month (retail C$8/kg)	298,395	483,632
Number of fills per day	33	53

6.6.2 Airport Ground Vehicles

Despite hydrogen powered flights being years away, some airport authorities could develop into small hubs with on-site hydrogen production to supply fuel for a range of airport ground vehicles and equipment. Potential applications include cargo trucks, baggage tuggers, and equipment such as forklifts and de-icing trucks.

These "on-airport" applications are considered nearer-term opportunities for hydrogen use in the aviation industry compared to aircraft. The transition primarily involves replacing equipment that uses diesel fuel with hydrogen fuel or fuel cells. In addition, there are opportunities for hydrogen in supplying backup power for the airport and possibly heat generation. [180]

Using data from the Airport Cooperative Research Program that estimated the fuel use and emissions of different ground support equipment (GSE), the Commonwealth Scientific and Industrial Research Organization (CSIRO) estimated the levelized cost of transport (LCOT) for diesel and hydrogen for GSE [181]. The LCOT for all but the de-icing trucks is lower for hydrogen than it is for diesel (Table 6.14). Assessments for some of these applications have already been conducted. As early as 2006, through the Canadian Transportation Fuel Cell Alliance, the Government of Canada provided over $860,000 for a pilot project to test hydrogen fuel cell use in baggage tuggers at the Vancouver International Airport [182]. The Hamburg Airport in

Table 6.14 Comparisons of diesel- and hydrogen- fuelled ground equipment for airports.

Equipment	Fuel Type	Fuel consumption (gallons of diesel or kg of hydrogen	LCOT $/hour
Cargo tractors	Diesel	3,958	17.17
	Hydrogen	1248	9.42
Belt loaders	Diesel	2,859	26.89
	Hydrogen	1,870	26.00
Aircraft tugs	Diesel	19,599	229.55
	Hydrogen	10,256	190.41
De-icing trucks	Diesel	8,146	190.77
	Hydrogen	5,329	205.52
Forklifts	Diesel	998	8.92
	Hydrogen	641	8.69

Germany has also demonstrated the use of fuel cells for tuggers [180] and in 2022, the Edmonton International Airport (EIA) announced that it would be developing hydrogen infrastructure [183]. It is suggested that further studies and comparison with similar BEV units be conducted for the two airports in the RMJIC. The Regina Airport Authority (RAA) has already committed to reducing GHG emissions in partnership with SaskEnergy on a small-scale CO_2 capture project [184].

7 CALL TO ACTION

7.1 Opportunities for Hub Development

The RMJIC has opportunity, interest, and unique qualities in favor of a hydrogen hub and related CCUS infrastructure development for Saskatchewan. The region has reasonable potential for the production, transport, and use of low-carbon hydrogen in support of future hydrogen hub development. Each point is preceded by either a green or yellow traffic light indicating the readiness to act, which is independent of stakeholder commitment, and currently between the phases of pre-R&D to pre-pilot and demonstration.

Production of low-carbon hydrogen from natural gas. The refinery in Regina and the urea plant in Belle Plaine both produce hydrogen from natural gas. However, their primary focus is on production to support their operations. The refinery has announced their intent to capture 500,000 tonnes per annum of CO_2 which can utilize existing storage and possibly support new investments in CCUS infrastructure. An investment in CCUS infrastructure could enable the production of low-carbon hydrogen and support other carbon reduction initiatives throughout the RMJIC and the surrounding region.

Medium- and heavy-duty road freight. Trucks in provincial classes 5 through 13 account for nearly 40% of all transportation in Saskatchewan with over 1,000 units passing through the RMJIC daily. Provincial traffic data was used to estimate the fuelling station demand in the corridor with a 20% transition to H2DF retrofits and HFCE trucks by 2035 and a 60% transition to HFCE trucks in a low-emissions future. Assuming 8 t H_2/d per fuelling station, the RMJIC could support 3-4 fuelling stations by 2035 on trucking demand alone.

Freight rail. 97% of the diesel demand for rail transport in Saskatchewan is used to haul freight. With HFCE trains currently being demonstrated in Western Canada, estimates of 10% hydrogen transition and 50% of provincial freight rail energy demand would require 12 t H_2/d from the RMJIC by 2035.

Dedicated pipelines. Local steel manufacturers are interested in the development of safety codes for pure hydrogen pipeline in advance of the greater transition. They are also working on projects tied to CO_2 pipeline and related projects in CCS.

Gas storage. Saskatchewan has at least 3 Gt (P50) of regional storage potential south of the RMJIC suitable for CO_2 and ~250 Gt of prospective CO_2 storage (P50) throughout the province. Hydrogen storage potential and the competency of salt caverns in the RMJIC deserves further study. The cost of cavern storage for hydrogen can range from C$127/kg for 100 t H2 to C$26/kg for 3000 t H2. Annual storage costs range from approximately C$23/kg H2 to C$4/kg H2 over the same scale and would improve with increased cycling of hydrogen gas. The total levelized cost of SCS for hydrogen, which includes capital and storage, can be as low as C$3.40/kg H2 for working gas capacities of 100,000 tonnes.

Future low-carbon hydrogen production from renewable electricity. Saskatchewan has some of the best renewable energy potential in the country and plans for the development of new nuclear. Both are capable of producing low-carbon hydrogen to help satisfy our future energy demands.

7.2 Checklist for Hub Development

The following is a checklist for the development of an RMJIC hydrogen hub based on the regional and provincial hydrogen demand from 2028 to a low-emissions future. Over the near-term, there are opportunities for laying the groundwork in advance of hydrogen infrastructure development through the 2030s. These opportunities include the development of a hydrogen hub consortium (see Section 9), identifying stakeholders for commercial implementation, fostering connections with First Nations communities and other hydrogen hub groups, and the engagement with academia for R&D opportunities along the entire value chain. While the initial focus is largely on the small-scale development of the hydrogen fuel market, an expansion to other markets is expected as the demand for low-carbon hydrogen increases over the mid- to long-term, as shown by the estimates in Section 6.

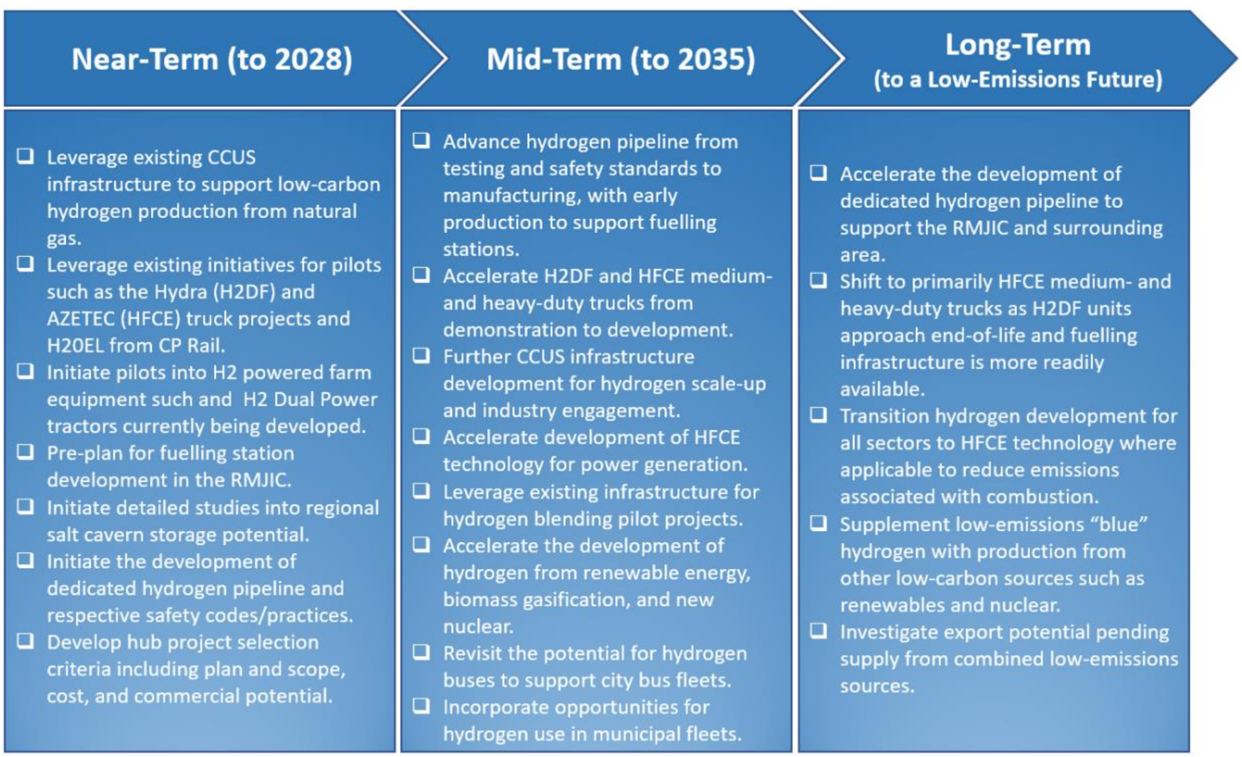


Figure 7.1 Checklist for RMJIC Hydrogen Hub Development.

8 HYDROGEN FUNDING IN CANADA

8.1 Federal Government

Department of Finance Canada

Carbon Capture, Utilization, and Storage Investment Tax Credit

Supports both geological storage and storage in concrete for CCUS projects designed to operate for a minimum 20 years. The ITC amount would be determined by the equipment type and the ratio of stored CO_2 according to eligible uses, which excludes EOR projects. [1]

Clean Hydrogen Investment Tax Credit

The Clean Hydrogen Investment Tax Credit was first introduced in 2022. It supports 15% to 40% of the cost of eligible projects focused on the production of clean hydrogen. Credit % is based on the carbon intensity of the production process, with less intensive projects earning the highest rate and no credit offered for projects with carbon intensities equal to or greater than 4 kg CO_2e/kg H_2. Projects that utilize captured CO_2 for EOR are also ineligible for this tax credit and excluded from the carbon intensity calculation. [2]

Funding may also emerge from commitments between Canada, the US, and Mexico. From meetings held in early 2023, the three countries committed to developing a North American clean hydrogen market, including potential cooperation on research and development, safety codes and standards, cross-border hydrogen clusters, green freight corridors, and integrated maritime operations. [185]

Natural Resources Canada (NRCan)

Zero Emission Vehicle Infrastructure Fund

Approximately $680 million was allocated to the Zero Emission Vehicle Infrastructure Program (ZEVIP) which is expected to be completed in 2027. The focus is to increase the number of charging and refuelling stations in Canada, which includes hydrogen. [186]

Clean Fuels Fund

The Clean Fuels Fund offers repayable funding for new facilities or existing facilities producing clean fuel in Canada. Potential projects include feasibility or engineering studies. The first batch of intakes closed in 2021 but Indigenous-led project applications are still being accepted at the time of writing. [187]

Energy Innovation Program - Carbon Capture, Utilization and Storage

An example of funding programs that indirectly support hydrogen development is Canada's Energy Innovation CCUS Program, for which 'blue' hydrogen projects would be eligible. It has allocated approximately $320 million over seven years for research into CCUS technologies. In 2021-22, $50 million was provided for FEED studies for large-scale CCUS facilities.

The "capture" portion of this program closed in October 2022 and intake for "storage and transportation" projects closed in April 2023. Expression of interest for "utilization" projects opens in the fall of 2023. [188]

Transport Canada

Incentives for Medium- and Heavy-Duty Zero-Emission Vehicles (iMHZEV) Program

The IMHZEV program offers nearly $550 million in funding over four years. Launched in July 2022, the iMHZEV Program provides incentives to purchase or lease eligible MHZEVs, which includes class 8 heavy-duty FCEV trucks. [189]

National Research Council (NRC)

Advanced Clean Energy Program: Hydrogen

NRC will work with collaborators on research projects covering the entire value chain – production, distribution and storage, system integration and utilization. It offers partners hydrogen expertise and facility space to run research projects. [190]

NRC Industrial Research Assistance Program (NRC IRAP)

NRC manages the IRAP program which offers small and medium-sized business (SMEs) financial or technical support for projects relating to technical innovation. [191]

Innovation Science and Economic Development Canada (ISEDC)

Strategic Innovation Fund (SIF)

SIF is targeted for "large-scale, transformative and collaborative projects." Priority areas currently include net-zero, biomanufacturing, intellectual property, aerospace, and semiconductors. [192]

Net Zero Accelerator Fund

The Net Zero Accelerator Fund falls under SIF. It provides $8 billion to support large-scale investments in key industries with the goal of achieving a net-zero economy and reducing greenhouse gas (GHG) emissions. Recent hydrogen investments from the fund include the Blue Hydrogen Energy Complex in Alberta. The federal government has committed $300 million in addition to provincial investments of just over $160 million [193,194].

Prairies Economic Development Canada (PrairiesCan)

Regional Innovation Ecosystems (RIE) in the Prairie provinces

The RIE is available for companies in Alberta, Saskatchewan, and Manitoba. Prairies Canada announced in January 2023 an investment of over $9 million to support the development of the hydrogen sector in

Alberta. Funding will flow to Edmonton Global, the Alberta Motor Transport Association and C-FER Technologies for various hydrogen initiatives. [195,196]

8.2 Funding Agencies

Natural Sciences and Engineering Research Council of Canada (NSERC)

NSERC supports hydrogen research and most of its funding has gone to researchers at universities. It reports on funding dollars for hydrogen storage, fuel cells, hydrogen blending and hydrogen production.

Canadian Foundation for Innovation

CFI invests in research at universities, hospitals, and non-profit research institutions. Previous hydrogen-related projects/groups that have received research support from CFI include Advanced Materials Ontario, Clean Marine Propulsion Lab, High-Pressure Facility for Biomass Conversion, and Sustainable Low Carbon Fuels Research Lab. [197]

Sustainable Development Technology Canada (SDTC)

SDTC provides direct investment to small and medium-sized enterprises in Canada for the development of technology at the pre-commercialization stage. It lists several projects that support companies developing hydrogen technologies including Hydra Energy, Loop Energy, and Hydrogenics (now Cummins). [198]

Natural Gas Innovation Fund (NGIF)

NGIF Cleantech Ventures invests in cleantech start-ups within the energy sector. The fund has expanded to included renewable natural gas and hydrogen. NGIF also offers Industry Grants which is an accelerator offering grants to start-ups working on challenges in the natural gas sector. A number of hydrogen projects have received this grant over the past few years, including Proton Technologies operating in Saskatchewan. [199,200]

Federation of Canadian Municipalities (FCM)

FCM offers a wide variety of funding programs that directly or indirectly relate to hydrogen initiatives. It offers loans and grants to municipalities looking to adopt zero-emission vehicles. There are also specific past examples of funding provided for hydrogen under other FCM programs. [201]

Canadian Urban Transit Research and Innovation Consortium (CUTRIC)

CUTRIC is a non-profit national organization that supports RD&D for zero-carbon transportation solutions. The Smart Rail Innovation Program (2022-2025) includes the Hydrogen Rail Feasibility Modelling and Pilot Deployment Initiative. The Zero Emission Transit Fund, started in 2021, provides $2.75 billion over five years for transit agencies looking to adopt battery electric buses or hydrogen fuel cell electric buses. [202,203]

9 DEVELOPING A SHARED VISION FOR HYDROGEN

A successful hydrogen hub starts with a consortium of those who share a vision for a hydrogen economy in a diverse energy future. The consortia should include representatives from all levels of government, First Nations representatives, companies along the entire value chain, industry associations, universities, and research institutes. The goal is to develop a strategy to attract public and private sector funding and then see the vision through to development. With initial funding, hub growth and awareness should be supported by full-time staff to attract resources, connect with like-minded groups, and act on new funding opportunities. Dedicated staff should have some technical knowledge of hydrogen, from its production and processing to delivery, storage, and end uses.

Early demonstrations in the production and use of low-carbon hydrogen are key to garnering public support for a shared vision. A focus on smaller-scale hydrogen distribution to serve the transportation market would be ideal in terms of cost and technology readiness. An RMJIC consortia should bring together the parties that have the expertise and interest in the early development of hydrogen including local producers, steel manufacturers, and potential end users. The consortia should also connect with existing transportation demonstrations such as the Hydra and AZETEC Projects and the H20EL Rail Project with Canadian Pacific Kansas City. A deep dive into the regional geological storage potential for hydrogen also deserves early attention, which could garner support from universities and research groups.

Beyond the transportation sector, current infrastructure could be leveraged over the near- to mid-term to expand our shared vision. Hydrogen blending demonstrations, such as those of ATCO in Alberta, would be the first step to hydrogen adoption for space and process heating across multiple sectors, and a precursor to dedicated hydrogen pipelines in a low-emissions scenario. We should also seek opportunities for collaboration with solar and wind projects through the near- to mid-term to showcase hydrogen's potential as a contributor to the shortcomings of renewable energy.

The consortia should also connect with other regional hydrogen hubs developing in Canada, as the entire network could benefit from the sharing of knowledge. An RMJIC consortia would have plenty to gain from the Edmonton Region Hydrogen Hub which has been operating since 2021. There is also talk of a "green" hydrogen hub to be developed in Atlantic Canada.

APPENDIX A Equations

A.1 Industrial

$$E_{ih2} = E_i \, \%_{ih2} \tag{1}$$

where

E_{ih2} =potential industrial hydrogen energy usage

E_i = current overall industrial energy usage

$\%_{ih2}$ = assumed industrial percentage that could potentially be converted to hydrogen

$$m_{ih2} = E_{ih2} \frac{\eta_i}{\eta_{ifc}} \frac{1}{E_{h2hhv}} \%_{fc} + E_{ih2} \frac{\eta_i}{\eta_{ih}} \frac{1}{E_{h2hhv}} \%_{ih} \tag{2}$$

where

m_{ih2} = potential mass of industrial hydrogen usage

η_i = assumed overall industrial efficiency

η_{ifc} = fuel cell efficiency

η_{ih} = overall industrial heating efficiency

E_{h2hhv} = higher heating value of hydrogen (142 MJ/kg)

$\%_{ifc}$ = assumed percent that could potentially be converted to hydrogen fuel cell

$\%_{ih}$ = assumed percent that could potentially be converted to hydrogen heating

A.2 Commercial

$$E_{ch2} = E_c \ \%_{ch2} \tag{1}$$

where

E_{ch2} = potential commercial hydrogen energy usage

E_c = current overall commercial energy usage

$\%_{ch2}$ = assumed percent that could potentially be converted to hydrogen

$$m_{ch2} = E_{ch2} \frac{\eta_c}{\eta_{ng}} \frac{1}{E_{h2hhv}} \%_{ch2} \tag{2}$$

where

m_{ch2} = mass of hydrogen

E_{h2hhv} = higher heating value of hydrogen (142 MJ/kg)

η_c = commercial natural gas heating efficiency

η_{ng} = commercial hydrogen heating efficiency

$\%_{ch2}$ = assumed percent that could potentially be converted to hydrogen

A.3 Residential

$$E_{rh2} = E_r \ \%_{rh2} \tag{1}$$

where

E_{rh2} = potential commercial hydrogen energy usage

E_r = current overall commercial energy usage

$\%_{h2c}$ = assumed percent that could potentially be converted to hydrogen

$$m_{rh2} = E_{rh2} \frac{\eta_r}{\eta_{ng}} \frac{1}{E_{h2hhv}} \%_{rh2} \tag{2}$$

where

m_{rh2} = mass of hydrogen

E_{h2hhv} = higher heating value of hydrogen (142 MJ/kg)

η_r = commercial natural gas heating efficiency

η_{ng} = commercial hydrogen heating efficiency

$\%_{rh2}$ = assumed percent that could potentially be converted to hydrogen

A.4 Transportation

$$E_{th2} = E_t \, \%_{th2} \, (1 + i)^y \tag{3}$$

where

Et_{h2} =potential transportation hydrogen energy usage

E_t = current overall transportation energy usage

$\%_{th2}$ = assumed transportation percentage that could potentially be converted to hydrogen

i = annual rate of escalation (%)

$$m_{th2} = E_{th2} \frac{\eta_g}{\eta_{fc}} \frac{1}{E_{h2hhv}} \%_{fc} + E_{th2} \frac{\eta_g}{\eta_g} \frac{1}{E_{h2hhv}} \%_g \tag{4}$$

where

m_{th2} = potential mass of transportation hydrogen usage

η_g = assumed overall gasoline efficiency

η_{fc} = fuel cell efficiency

E_{h2hhv} = higher heating value of hydrogen (142 MJ/kg)

$\%_{fc}$ = percent to be deployed to hydrogen fuel cell operation

$\%_g$ = percent to be deployed to hydrogen IC engine operation

Example

For transportation energy of 100 PJ:

2028: $E_{th2} = E_t \ \%_{th2}\ (1+i)^y = 100\ PJ\ x\ 10\%\ x\ \ (1+1.5\%)^5 = 10.7\ PJ$

$$m_{th2} = E_{th2}\ \frac{\eta_g}{\eta_{fc}}\ \frac{1}{E_{h2hhv}}\ \%_{fc} +\ E_{th2}\ \frac{\eta_g}{\eta_g}\ \frac{1}{E_{h2hhv}}\ \%_g = 10.7\ x\ \frac{0.28}{0.6}\ x\ \frac{1}{142}\ x\ 1000\ x\ 0.3 + 10.7\ x\ \frac{0.28}{0.28}\ x\ \frac{1}{120}\ x\ 1000\ x\ 0.7 = 10.6 + 62.4 = 73\ \text{kt H2/y}$$

2035: $E_{th2} = E_t \ \%_{th2}\ (1+i)^y = 100\ PJ\ x\ 10\%\ x\ \ (1+1.5\%)^{15} = 12.0\ PJ$

$$m_{th2} = E_{th2}\ \frac{\eta_g}{\eta_{fc}}\ \frac{1}{E_{h2hhv}}\ \%_{fc} +\ E_{th2}\ \frac{\eta_g}{\eta_g}\ \frac{1}{E_{h2hhv}}\ \%_g = 12.0\ x\ \frac{0.28}{0.8}\ x\ \frac{1}{142}\ x\ 1000\ x\ 0.6 + 12.0\ x\ \frac{0.28}{0.28}\ x\ \frac{1}{120}\ x\ 1000\ x\ 0.4 = 17.7 + 40 = 57.7\ kt\ H2/y$$

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