

Towards a Fuel Hydrogen Economy in the Calgary Region:

A FEASIBILITY STUDY



David B. Layzell

Dinara Millington

Robert Lee

The Transition
Accelerator



L'Accélérateur
de transition

Towards a Fuel Hydrogen Economy in the Calgary Region:

A FEASIBILITY STUDY

David B. Layzell, Ph.D., FRSC

Energy Systems Architect and Research Director
THE TRANSITION ACCELERATOR

Dinara Millington, MA

Western Network Lead
THE TRANSITION ACCELERATOR

Robert Lee

Principal Consultant
AUBERON ENERGY SERVICES CORP.

TO CITE THIS DOCUMENT:

Layzell D.B., Millington D. and Lee R. (2023) Towards a Fuel Hydrogen Economy in the Calgary Region: A Feasibility Study. Transition Accelerator Reports: Volume 5, Issue 1. Pp 1-64. ISSN 2562-6264 (English Report).

English version of this document available at <https://transitionaccelerator.ca/towards-a-fuel-hydrogen-economy-in-the-calgary-region/>

Version: 1

TABLE OF CONTENTS

TABLE OF CONTENTS	ii
ABOUT THE TRANSITION ACCELERATOR	iv
ABOUT THE AUTHORS	v
FIGURES, TABLES	vi
List of Figures	vi
List of Tables	vii
LIST OF ABBREVIATIONS	viii
ACKNOWLEDGMENTS	x
EXECUTIVE SUMMARY	xi
1 INTRODUCTION	1
1.1 TOWARDS A NEW VALUE CHAIN FOR A FUEL-HYDROGEN ECONOMY	2
1.2 THE NEED FOR HYDROGEN HUBS AND CORRIDORS	3
1.3 THE CALGARY REGION FEASIBILITY STUDY	4
2 THE CALGARY REGION	6
2.1 HISTORY & ECONOMY	6
2.2 DEMOGRAPHICS & ECONOMY	7
3 HYDROGEN 101	9
3.1 INTRODUCTION	9
3.2 PROPERTIES OF HYDROGEN AND ITS DERIVATIVES	11
3.3 THE ECONOMICS OF HYDROGEN PRODUCTION IN CANADA	13
3.4 THE ECONOMICS OF MOVING HYDROGEN AND BUILDING FUELING STATIONS	16
4 TOP-DOWN ESTIMATES OF FUEL HYDROGEN MARKET IN A NET-ZERO FUTURE	19
4.1 INTRODUCTION	19
4.2 TRANSPORTATION	19
4.3 BUILDINGS	22
4.4 ELECTRICAL GENERATION	24
4.5 TOP-DOWN SUMMARY	26
5 CITY OF CALGARY-OWNED INFRASTRUCTURE	28

5.1	INTRODUCTION	28
5.2	MUNICIPAL TRANSIT	28
5.3	OTHER MUNICIPAL VEHICLES	30
5.4	NATURAL GAS & ELECTRICITY DEMAND FOR BUILT SPACES	31
6	THE CALGARY INTERNATIONAL AIRPORT	36
6.1	INTRODUCTION	36
6.2	AIRPORT TRANSPORTATION	36
6.3	SPACE & WATER HEATING	38
6.4	POWER GENERATION (AND COGENERATION)	40
7	FREIGHT RAIL DEMAND	42
7.1	INTRODUCTION	42
7.2	FUEL USE AND EMISSION REDUCTION POTENTIAL	43
7.3	CP'S HYDROGEN LOCOMOTIVES	43
8	HEAVY-DUTY ROAD FREIGHT	45
8.1	INTRODUCTION	45
8.2	TRUCK TRAFFIC ON MAJOR HIGHWAYS	46
8.3	TRUCKING COMPANIES AND FUELING STATIONS	48
9	POTENTIAL PARTNERS IN THE FUEL HYDROGEN SUPPLY CHAIN	50
9.1	INTRODUCTION	50
9.2	POINT SOURCE CO ₂ EMISSIONS	51
10	PLANNING FOR PIPELINES	54
10.1	INTRODUCTION	54
10.2	TRANSMISSION PIPELINE NETWORK	54
11	CALL TO ACTION	57
12	REFERENCES	60



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.

ABOUT THE AUTHORS

Dr. David B. Layzell, Ph.D., FRSC

THE TRANSITION ACCELERATOR

David B. Layzell is an Energy Systems Architect with the Transition Accelerator, a Faculty Professor at the University of Calgary and a Director of the Canadian Energy Systems Analysis Research (CESAR) initiative. Between 2008 and 2012, he was Executive Director of the Institute for Sustainable Energy, Environment and Economy (ISEEE), a cross-faculty, graduate research and training institute at the University of Calgary. Before moving to Calgary, Dr. Layzell was a Professor of Biology at Queen's University, Kingston (cross appointments in Environmental Studies and the School of Public Policy), and Executive Director of BIOCAP Canada, a research foundation focused on biological solutions to climate change. While at Queen's, he founded a scientific instrumentation company called Qubit Systems Inc. and was elected 'Fellow of the Royal Society of Canada' (FRSC) for his research contributions.

Dinara Millington MA

THE TRANSITION ACCELERATOR

Dinara Millington is a Western Network Lead at The Transition Accelerator. Dinara is responsible for catalyzing the development and linkage of a network of strategically located hydrogen hubs across Western Canada. This work includes building and managing strategic relationships, identifying promising locations for new hubs in Western Canada and developing systems of communication and knowledge sharing to link new hubs. Her advanced knowledge of the energy industry and regulatory landscape and her technical and leadership skills have contributed to Dinara's almost 20-year energy career. In her previous role, Dinara was responsible for leading research programs, liaising with a Board and senior management, assisting in fundraising, and managing various committees. Her effective communication skills and ability to work with a wide range of internal and external stakeholders are evidenced through the publication of numerous research reports and appearances in articles and televised interviews with local, national, and international media. Dinara holds a Bachelor's and Master's Degree in Economics from the University of Calgary.

Robert Lee

PRINCIPAL CONSULTANT, AUBERON ENERGY SERVICES CORP

Robert Lee is the principal consultant and owner of Auberon Energy Services Corp., providing upstream marketing, risk management, business development and midstream consulting services. Bob has over 35 years of experience in the energy industry and has held senior positions at production and pipeline/gas processing companies. His broad experience includes working with Canadian First Nations and International industry partners to develop natural gas infrastructure projects in the Western Canadian Sedimentary Basin. He is a graduate of SAIT Polytechnic's Mechanical Engineering Technology program. Bob was engaged by The Transition Accelerator as an independent HUB Facilitator consultant to work in conjunction with the Calgary Region Hydrogen HUB to assist in generating this Hydrogen HUB Foundation Report.

FIGURES, TABLES

List of Figures

Figure ES.1 The Location of Key Hydrogen-Related Infrastructure in the Calgary Region.....	xiv
Figure 1.1 Canada's Existing Energy System (A) and the Needed Transition to Net-Zero Emissions (B).....	1
Figure 1.2 New Hydrogen Value Chain.....	2
Figure 1.3 The Transition Accelerator's Hub Creation Process.....	4
Figure 2.1 The Calgary Region.....	6
Figure 2.2 Proportion of Alberta's Population in Calgary Region (left) and Distribution within the Region(right).....	8
Figure 3.1 Costs (\$/GJhhv) for Fuel Energy Demand in Western Canada.....	10
Figure 3.2 A Comparison of the Cost of Blue or Green H ₂ Production from Countries in the Asia-Pacific Region.....	13
Figure 3.3 The effect of electricity cost & capacity factor on the levelized cost of H ₂ (LCOH) production for a 4.2 MW PEM electrolyzer today (A), in 2030 (B) and in the future (C) when the market is mature.....	14
Figure 3.4 The effect of natural gas cost & scale of production (tH ₂ /d) on the levelized cost of H ₂ (LCOH) from a steam methane reformer coupled to carbon capture and storage today (A), in 2030 (B) and in the future (C) when the market is mature.....	15
Figure 3.5 An Overview of the Economics for Producing, Processing and Transporting Hydrogen and for Providing Fueling Stations for HD Vehicles.....	17
Figure 4.1 The energy use for transportation by various vehicle types in Alberta in 2019 (pie chart) and the projected zero-emission fuel alternatives that the authors suggest are most appropriate in a net zero future (doughnut chart).....	21
Figure 4.2 Calgary Region NG Demand (Space & Water Heating and Industrial Consumption).....	23
Figure 4.3 Energy use for space and water heating and other (mostly electricity) by Residential (blue shaded sections in the pie chart) and Commercial buildings in Alberta in 2019 (pie chart), and the projected zero-emission fuel alternatives that the authors suggest are most appropriate in a net zero future (doughnut chart).....	24
Figure 4.4 Electricity Generation in Alberta in 2021, Attributed to the Conversion Technology.....	25
Figure 4.5 Estimate of Potential Domestic Market for Fuel H ₂ in Alberta in a Net-Zero Emission Energy Future.....	27
Figure 5.1 Location of Calgary Transit Garage, Fueling and Maintenance Facilities.....	29
Figure 5.2 Summary of Fuel Use by City of Calgary Vehicles in 2019.....	31
Figure 5.3 Natural Gas (A) and Electricity (B) Use by City of Calgary Owned Infrastructure in 2019.....	31
Figure 5.4 Potential Sites for H ₂ Cogeneration Facilities in Calgary Wastewater Treatment Facilities.....	35
Figure 6.1 Monthly NG Demand for Space & Water Heating at the Calgary International Airport in 2019 (bars) and the Estimate of Fuel H ₂ Demand in a Zero-Emission Energy System (dashed line).....	39
Figure 7.1 Location of CP (red lines) and CN (blue lines) Infrastructure in Calgary Region.....	42
Figure 8.1 Comparison of Medium Duty (MDV) and Heavy Duty (HDV) Vehicles Supporting Freight Transportation in Alberta.....	45
Figure 8.2 Heat Map Depicting Traffic Flows Along Provincial Highways in Calgary Region (red colour), with Specific Highways Identified for More Detailed Analysis.....	46
Figure 8.3 Location of Truck Stop/Cardlocks & Trucking Companies in the Calgary Region.....	48
Figure 9.1 Map Showing the Major GHG Emitters in the Calgary Region.....	51

Figure 9.2 Possible Placement of CO ₂ Pipeline Infrastructure (yellow and orange) and Rail Corridors (purple) That Could Be Used for CO ₂ Gathering.....	52
Figure 9.3 Map of CCS Reservoir Potential in Saline Aquifers.	53
Figure 10.1 ATCO South Integrated Transmission System with High to Low-Pressure Gates.....	55
Figure 10.2 Location of Abandoned (A) and Discontinued (B) Natural Gas Pipelines and Discontinued Jet Fuel Pipeline (C).....	56
Figure 10.3 Possible Locations for Initial H ₂ Fueling Stations That Could Later Benefit from Pipeline Access to the Gas.	56
Figure 11.1 Overview of what a Calgary Region Hydrogen Hub would work to deploy in Phase 1 of an effort to establish a fuel hydrogen economy in the region.....	57

List of Tables

Table 2.1 Regional Demographics.....	8
Table 3.1 Physical Properties of Hydrogen.....	12
Table 4.1 Calculation of the Possible Fuel Hydrogen Demand for Transportation in a Future Net-Zero Emission Energy System with the Energy Demand of Alberta in 2019.	20
Table 4.2 Calculation of Possible Fuel H ₂ Demand for Building Space & Water Heating in a Future Net-Zero Emission Energy System with an Energy Demand Similar to That of Alberta in 2019.....	22
Table 4.3 Calculation of Possible Fuel H ₂ Demand for Power Generation in a Future Net-Zero Emission Energy System with a Total Electricity Demand Similar to Present Day.....	26
Table 5.1 Estimate of Fuel H ₂ Demand for Transit Buses in the City of Calgary Should the 2019 Fleet Transition to Net Zero.	29
Table 5.2 Estimate of Fuel Hydrogen Demand for Non-Transit, City of Calgary Vehicles in 2019.....	30
Table 5.3 Estimate of H ₂ Required to Displace NG for Space & Water Heating in City of Calgary Owned Buildings.....	33
Table 5.4 Calculation of H ₂ Demand for Cogeneration from City of Calgary's Largest NG Demanding Facilities Where Cogeneration Is Scaled for Heat Demand.	34
Table 6.1 Transportation Fuel Demand at the Calgary International Airport in 2019.....	37
Table 6.2 Natural Gas Demand for Space & Water Heating at the Calgary International Airport in 2019.....	39
Table 6.3 Grid Electricity Demand of the Calgary International Airport in 2019.	41
Table 7.1 Hydrogen Demand in Total Freight Rail in the Calgary Region.....	43
Table 8.1 Estimation of the Fuel H ₂ Demand for Single Unit (SU) and Tractor Trailer (TT) Trucks Driving on Highways 1 & 2 Running Through Calgary and Around the Ring Road (Highway 201).....	47
Table 9.1 Major Point Sources of CO ₂ in the Calgary Region and High-Level Assessment of the Possible Role They Could Play in an Emerging Net-Zero Emission Energy Future.	52

LIST OF ABBREVIATIONS

ABBREVIATION	DEFINITION
AIH	Alberta Industrial Heartland, a region in Alberta which includes Edmonton, Strathcona, Fort Saskatchewan, Sturgeon, and Lamont counties
AMTA	Alberta Motor Transport Association
ATR	Autothermal Reforming
AZETEC	Alberta Zero-Emission Truck Electrification Collaboration Project
BEV	Battery Electric Vehicle
Blue Hydrogen	Hydrogen produced from natural gas and carbon capture and storage
C	Carbon
CESAR	Canadian Energy Systems Analysis Research
CCS	Carbon Capture and Storage
CCUS	Carbon Capture Utilization or Storage
CN	Canadian National Railway Co.
CO ₂	Carbon Dioxide
CP	Canadian Pacific Railway Company
DTE Ratio	Drivetrain Efficiency Ratio (GJ H ₂ /GJ diesel or gasoline for same distance)
EOR	Enhanced Oil Recovery
FCEB	Fuel Cell Electric Bus
FF	Fossil Fuel
GHG	Greenhouse Gas
GJ	Gigajoule (10 ⁹ joules)
Green Hydrogen	Hydrogen produced by water electrolysis using intermittent zero-carbon electricity generated from wind and solar facilities

H ₂	Hydrogen gas
HDV	Heavy-Duty Vehicle: Vehicles with a gross vehicle weight rating > 15 tonnes
HFCE	Hydrogen Fuel Cell Electric
HHV	Higher Heating Value
HRSG	Heat Recovery Steam Generator
ICE	Internal Combustion Engine
kJ	Kilojoule (10 ³ Joules)
LDV	Light-Duty Vehicle
LH ₂	Liquid Hydrogen
LHV	Lower Heating Value
MDV	Medium-Duty Vehicle
MJ	Megajoule (10 ⁶ joules)
Mt	Megatonne (10 ⁶ metric tonnes)
NG	Natural Gas
PJ	Petajoule (10 ¹⁵ joules)
PSA	Pressure Swing Adsorption
SMR	Steam Methane Reforming
SUT	Single Unit Truck
TJ	Terajoule (10 ¹² joules)
TTC	Tractor Trailer Combination
WGS	Water-Gas Shift Reactor
YYC	Calgary International Airport Authority

ACKNOWLEDGMENTS

The Transition Accelerator is appreciative of its funding partners. Without their support and encouragement, this work would not have been possible.

FUNDING PARTNERS



DISTRIBUTION: Transition Accelerator Reports are available online at www.transitionaccelerator.ca

DISCLAIMER: The opinions expressed in this publication are the authors' alone.

COPYRIGHT: Copyright ©2023 by the Transition Accelerator. All rights reserved. No part of this publication may be reproduced in any manner whatsoever without written permission except in the case of brief passages that may be quoted in critical articles and reviews.

ISSN: Transition Accelerator Reports (Online format): ISSN 2562-6264

COVER IMAGE: Tourism Calgary

MEDIA INQUIRIES: For media inquiries, requests or other information, contact info@transitionaccelerator.ca

MAILING ADDRESS: The Transition Accelerator, 225 Superior Ave. SW, Calgary AB T3C 2J1

WEB: www.transitionaccelerator.ca

VERSION: 2

EXECUTIVE SUMMARY

Global climate change, materializing as severe storms, heat waves, floods, and droughts, are [taking lives](#), [threatening wars](#), and [damaging economies around the world](#). To address this challenge, [more than 70 countries](#), including [Canada](#), have set net-zero greenhouse gas (GHG) emission targets by mid-century.

In Canada, [57% of national GHG emissions](#) are associated with the distributed combustion of fossil fuel-based 'energy carriers', predominantly gasoline, diesel, jet fuel and natural gas. Another 25% of national emissions are associated with the recovery and processing of the oil and gas that is largely used to make these energy carriers.

Clearly, replacing fossil carbon-based energy carriers with zero-emission carriers is one of the major pillars in any transition to a net-zero emission energy system. For a province like Alberta, whose economy depends on oil and gas recovery and use, this transition could be seen as more of a threat than an opportunity.

Hydrogen as a Zero-Emission Energy Carrier. However, Alberta is superbly positioned to take a leadership role in the transition to hydrogen as a zero-emission energy carrier that can be produced with minimal or no GHG emissions. The province already produces over [5000 t H₂/day \(2/3rd of the total produced in Canada\)](#) from natural gas and uses it as an industrial feedstock to crack bitumen, refine oil, and make fertilizer and other materials and chemicals. With some of the production, a portion of the by-product CO₂ (a greenhouse gas) is captured and geologically sequestered. In addition, [some companies](#) are building large new plants where up to 95% of the CO₂ emissions from H₂ production will be permanently sequestered in the subsurface.

Alberta also has excellent wind and solar resources that could be used to make low-cost electricity to split water and make hydrogen without GHG emissions.

[Canada's Hydrogen Strategy](#) and [Alberta's Hydrogen Roadmap](#) agree on the importance of building a new fuel hydrogen economy around regional Hubs that bring together a low GHG supply of hydrogen with new markets for hydrogen in sectors such as transportation, space and industrial heating and even power generation.

Canada's first [hydrogen hub was established in the Edmonton Region](#) in 2021 and has been working to better understand the opportunity and deploy pilots, demonstration projects and new commercialization ventures around the hydrogen economy. The work in Edmonton has highlighted the importance of creating strategically located hubs across Canada that are connected by hydrogen corridors capable of supporting hydrogen-fueled trucks and trains. The hubs can also support return to base transportation needs and the production and use of hydrogen for heat and power generation and export to other jurisdictions.

This report was prepared to explore the feasibility of setting up a hydrogen hub in the Calgary region, which is home to 37% of the provincial population (1.64 million persons).

This report was prepared to explore the feasibility of setting up a hydrogen hub in the Calgary region, which is home to 37% of the provincial population (1.64 million persons).

Targets for Retail Hydrogen Prices. The analysis begins with an understanding that, on the same basis (*i.e.*, C\$/GJ_{h_hv}), Western Canadians currently pay much less for heat energy (C\$8 to C\$13/GJ) than for transportation fuels (C\$25 to C\$45/GJ) or for electricity (C\$20 to C\$50/GJ). This reality was used to set targets for the retail price for hydrogen in current Canadian dollars in a future net-zero emission energy system: C\$2 to C\$3/kg H₂ as a fuel for heat and power generation or export, and C\$5 to C\$8/kg H₂ as a transportation fuel.

These values are proposed as approximate retail prices, so they must include the cost of production, processing and distribution. Also, for use as a transportation fuel, there is a cost associated with building and operating fueling stations. While low GHG hydrogen can be made at a cost equal to or less than the wholesale diesel price, as a gas, hydrogen is more challenging to transport and dispense than liquid fuels. [Techno-economic analyses](#) have shown that the only way to get close to the price targets is to deploy at a relatively large scale. This reinforces the need for strategically placed hydrogen hubs and corridors to build regionally concentrated value chains that can ‘get to scale’ and minimize the need for ongoing public support for an emerging hydrogen economy.

Hydrogen Market Potential in the Calgary Region. Provincial data on end-use energy demand for Alberta in 2019 was scaled by population fraction (37%) for the Calgary region to estimate the market potential for hydrogen use as a fuel in a net zero future. The results for the Calgary region included the following:

- ❑ **Transportation** fuel demand of 1012 t H₂/day, where 53% of demand is from heavy-duty (Class 8, 15+ tonne gross vehicle weight) trucks, 11% from medium-duty trucks (Class 2b to 7), 10% from rail, and 15% from air transport.
- ❑ **Building** energy demand of 1900 t H₂/day, assuming 75% of the current natural gas supply for space and water heating to residential and commercial buildings shifts to hydrogen in a net-zero emission future.
- ❑ **Industrial heat and power generation** of 2130 t H₂/day, assuming that hydrogen is used to provide backup to lower-cost renewable generation when it is not available (at 10% of annual generation), and industrial heat and power supply (20% of annual generation) when the scale of demand or region of need does not justify fossil fuel use coupled to carbon capture and storage (CCS).

The total estimated hydrogen demand for the Calgary region in a net-zero future was estimated to be 5043 t H₂/day based on the 2019 energy system. However, it did not include any allowance for population or economic growth or the potential to serve export markets over the period to 2050. At a wholesale price of \$2.50/kg H₂, this represents a market potential of \$4.6 billion per year.

The total estimated hydrogen demand for the Calgary region in a net zero future was estimated to be 5043 t H₂/day. At a wholesale price of \$2.50/kg H₂, this represents a market potential of \$4.6B/yr.

City of Calgary Hydrogen Potential. As a potential early adopter of fuel hydrogen, we assessed the market potential of the City of Calgary-owned infrastructure. Details on current fuel demand were used to estimate the equivalent demand for hydrogen in a zero-emission future. The results included:

- ❑ **Municipal Bus Fleets.** Market potential of 6.2 t H₂/day, assuming hydrogen is the chosen fuel for 10% of shuttle buses, 60% of 40-foot buses and 100% of 60-foot buses.

- ❑ **Other Municipal Vehicles.** Market potential of 3.5 t H₂/day, assuming only 30% of the current fuel demand shifts to H₂ rather than battery electric.
- ❑ **Facility Natural Gas Demand.** Considering only the 10 city-owned facilities with the largest NG demand, an average of 18.4 t H₂/day would be required to provide zero-emission energy needs for heat only. If the heat requirement for these facilities was supplied by hydrogen cogeneration, the hydrogen demand would increase to 35 t H₂/day, but sufficient electricity would be generated to meet 231% of the needs of those facilities and make it possible to deliver about 113 GWh of low GHG electricity per year to the public grid.

Calgary International Airport (YYC). As another potential early adopter of hydrogen, the 2019 (pre-COVID) fuel use by YYC provided a first approximation of the hydrogen market potential. The results included:

- ❑ **Airport Ground Vehicles.** Assuming all ground vehicles switch to fuel hydrogen in a net zero future, the hydrogen demand would be 1.7 t H₂/day.
- ❑ **Passenger Train to Banff.** The [proposed Calgary-Banff train](#), if implemented, may use about 4 t H₂/day.
- ❑ **Airplanes.** If the transition to net zero shifts to hydrogen-powered planes, the hydrogen demand would be about 480 t H₂/day at YYC.
- ❑ **Space and Water Heating.** Replacing natural gas at YYC with hydrogen would create an average fuel hydrogen demand of 7.5 t H₂/day, ranging from 3.1 t H₂/day in August to 16.4 t H₂/day in January.
- ❑ **Power and Heat Demand.** Using low GHG fuel hydrogen to meet the electricity demand for the airport and provide about half the demand for heat would require about 20 t H₂/day.

Freight Rail. Of the estimated diesel fuel demand for rail transport in the Calgary region, 90% is associated with long-haul locomotives (10% for local switching). If hydrogen fuel cell electric was the desired net-zero option for these vehicles, the hydrogen demand would be about 24 t H₂/day.

Heavy-Duty Road Freight. Class 8 Trucks (15+ tonnes gross vehicle weight, GVW) account for only about 12% of annual sales of all trucks that are 3.9 t GVW (Class 2b) or greater, but they account for 45% of the vehicle kilometres travelled (VKT) per year, and 55% of the annual fuel use and emissions. We used provincial traffic data to estimate the potential fueling station demand for hydrogen in the Calgary region should 50% to 75% of these vehicles transition to equivalent fuel cell electric vehicles. These calculations consider only the fuel used while driving on the highways identified, so the numbers below are expected to be underestimates:

- ❑ City of Calgary Ring Road (Hwy 201): 16 t H₂/day
- ❑ City of Calgary, Okotoks to Balzac (Hwy 2): 16 t H₂/day
- ❑ Highway 1 to Banff National Park: 8 t H₂/day
- ❑ Highway 1 to Saskatchewan Border: 19 t H₂/day
- ❑ Highway 2 to Montana Border: 11 t H₂/day
- ❑ Highway 2 to Edmonton: 52 t H₂/day

In total, the fueling station demand would be 122 t H₂/day. Assuming each station delivers about 7 t H₂/day, the region could support at least 18 stations. We identified 20 existing truck stops/card-locks that serve heavy-duty transportation in the Calgary region today, as shown in **Figure 0.1A**.

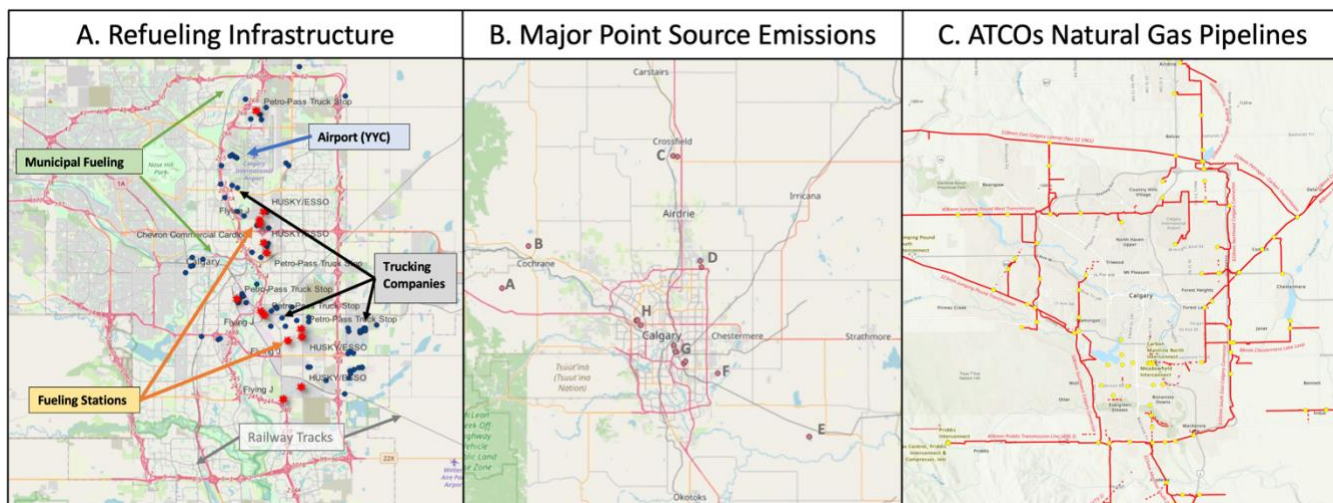


Figure ES.1. The Location of Key Hydrogen-Related Infrastructure in the Calgary Region.

Panel A shows the location of key infrastructure needed to support the transportation sector, including trucking, municipal buses, trains and the Calgary airport. **Panel B** identifies the current location of point source emissions which could be either potential centres for H₂ demand, sources of low GHG H₂ production or potential users of CO₂ pipelines that could enable regional 'blue' hydrogen production. **Panel C** highlights the location of high-pressure natural gas pipelines in the Calgary region (red lines), and the gates (yellow circles) that deliver gas to distribution pipelines. These could be sites to deliver hydrogen to residential and commercial buildings.

Major CO₂ Emitters: Potential Partners in a Net-Zero Future. The major point source emitters of CO₂ in the Calgary region were identified and assessed for their potential to be part of a zero-emission hydrogen future in three possible ways:

- ❑ **Replacing Natural Gas with Fuel Hydrogen.** Facilities like the Bonnybrook Wastewater Treatment Plant (Location G, Figure ES.1B), the University of Calgary or the Foothills Medical Centre (both Location H, Figure 0.1B) could use fuel hydrogen as a low carbon source of fuel energy for space and water heating and other heat requirements to dramatically reduce their emissions.
- ❑ **Carbon Capture and Storage Infrastructure.** Many of the more prominent point sources like the Shepard Power Plant (Location F, Figure ES.1B) or natural gas recovery and processing plants (Location A, B, C & E, Figure ES.1B) could invest in carbon capture technologies and direct the CO₂ into pipelines that would flow to a geological sequestration site. This would support the infrastructure that is needed for blue hydrogen production.
- ❑ **Possible Producer of Blue Hydrogen.** Some of the point source emissions in the Calgary region have the potential to get into the production of blue hydrogen while coupling the by-product CO₂ to geological storage. Examples include the Carseland Nitrogen Plant or other gas plants located in the region (Location A, B, C & E, Figure ES.1B).

Planning for Pipelines. While economically challenging at current prices for transport fuels, liquid hydrogen can be a long-term solution for hydrogen use in supporting heavy-duty transport in Canada. However, the cost of liquid hydrogen production, transport and storage would preclude fuel hydrogen use for heat and power generation. Expanding hydrogen use to these other sectors requires dedicated hydrogen pipelines. The existing natural gas transmission pipeline corridors tend to surround the City of Calgary and reach into 'gates' within the city where the pressure drops to deliver gas to individual buildings (Figure ES.1C). A future network of hydrogen pipelines could follow the same routes, deliver hydrogen for use as a heat/power source, and provide economic benefits to heavy vehicle fueling stations.

Call to Action. The Calgary Region is superbly positioned to take a leadership role in transitioning to a vibrant hydrogen economy that can position Calgary, Alberta and Canada as a key part of the climate change solution. The region has large potential markets for fuel hydrogen and the resources and workforce to produce and make cost-effective, very low GHG hydrogen available where it is needed.

The Calgary region would be an excellent candidate to establish a hydrogen hub and link with other hubs to create transportation corridors supporting heavy-duty trucks and trains across Western Canada, with links to similar initiatives in the USA. Such a start can rapidly grow in scale and then expand to hydrogen use for heat and power generation, attracting new industries.

From the analyses described here, we encourage the Calgary Region to take advantage of this opportunity by:

- A. **Funding and empowering a hydrogen hub** to build a consortium around a shared vision for a fuel hydrogen future. At their core, hydrogen hubs are about economic development, but in a sustainable way to meet regional, provincial, national, and global objectives to mitigate climate change. The consortia should include all levels of government (including First Nations), companies representing the entire value chain, non-profit organizations (universities, environmental groups, industry associations), and others willing to invest both time and resources to build and deploy a strategy that will attract both public and private sector funding. The hydrogen hub requires full-time, dedicated staff resources for a minimum of a three-year commitment (ideally 5+ years) to build on the information provided in this report, connect with the coalition of the willing, identify the most promising industry or municipal government-led initiatives, help them attract resources and then deploy, monitor, communicate and grow. The initial funding for this Hub will need to come from the government (municipal, provincial and federal), but with the successful project launches, there may be opportunities to attract other sources of funding.
- B. **Partnering with the Edmonton Regional Hydrogen Hub.** The [Edmonton Regional Hydrogen Hub](#) was set up almost two years ago, so they now have valuable experience in what should be done or not be done in deploying a fuel hydrogen economy. Rather than competition, they should be seen as partners, especially in creating a Highway 2 corridor for heavy-duty hydrogen truck transport. Insights could be used to develop other corridors along Highway 1 or into Southern Alberta and the USA.
- C. **Connecting with Canadian Pacific, Calgary Transit, YYC and the AMTA to support regional hydrogen vehicle trials.** CP is already building fuel cell hydrogen locomotives and a fuel cell-grade hydrogen production and fueling facility in the region. Explore opportunities to support their efforts and benefit from their initiative. Calgary Transit is already linked to the Alberta Zero Emission Hydrogen Transit (AZEHT) project in Edmonton, and there is a possibility of moving one of those buses for trials in Calgary in 2024. The Alberta Motor Transport Association (AMTA) will be making H₂ trucks available for carriers to trial in 2023 and early 2024, and their focus is on the Edmonton Region. An active hydrogen hub in the Calgary Region could help them expand their initiative to the Calgary Region. The Calgary Airport (YYC) has committed to dramatically reducing its GHG footprint and is strategically located to play a major role as a provider and user of hydrogen in an emerging hydrogen economy. Rocky Mountain GTL has a ready supply of hydrogen in the region and is located less than 1 km from the CP mainline east of Calgary.
- D. **Focusing on smaller-scale, distributed hydrogen production to serve the fuel market.** Unlike Edmonton, the Calgary Region does not have a large (100's to 1000's t H₂/d) nearby source of industrial 'gray' and 'blue' hydrogen production, some of which could be diverted to fuel hydrogen use. Therefore, we propose that the Calgary Region focuses over the next ~5 years on the smaller scale (up to 20 t H₂/d, but mostly ~4 t H₂/d), distributed production of low or zero GHG hydrogen close to emerging demand centres. (Rocky Mountain GTL's Carseland plant fits this scale at about 14 t H₂/d). Local hydrogen production could be 'blue', 'green' or 'turquoise' hydrogen that may cost more to produce than in Edmonton, but there should be significant cost savings associated with processing (e.g., liquefaction) and distribution of the fuel. Ideally, the hydrogen would be produced on-site, but if it does need to be moved to a fueling station, it may be worth

exploring the possibility of using rail since CP is a potential producer and user, and the existing rail network is close to major transportation corridors.

- E. **Developing a carbon capture utilization and storage (CCUS) strategy.** In the transition to net-zero emissions, many companies in the Calgary Region are interested in connecting to a CO₂ pipeline network, where the CO₂ is geologically sequestered. Such pipeline infrastructure is essential for the local production of blue hydrogen: especially as the demand for hydrogen grows and there is interest in deploying hydrogen pipelines that will serve vehicle refuelling, building heat and power generation. Therefore, the region should be helping to build a case for investment in CO₂ pipelines and CCUS storage sites to enable the growth of the hydrogen economy.
- F. **Encouraging renewable generation and green hydrogen production.** Southern Alberta has some of Canada's best conditions for wind and solar generation, and with the declining cost of electrolyzers, green hydrogen production is a promising opportunity for making fuel hydrogen for the region. For example, smaller dedicated wind and solar installations could support individual fueling stations, or large wind and solar farms could feed the grid when electricity prices are high and make hydrogen when the prices are low. Alternatively, power purchase agreements could enable grid-reliant electrolytic hydrogen production at fueling stations.
- G. **Deploying hydrogen for heat and power generation.** Blending hydrogen into natural gas distribution networks can generate GHG benefits while creating a variable buffer in the market demand for hydrogen that is made to support transportation markets.
- H. **Engaging the academic community.** Local colleges and universities can provide valuable training, insights, and technologies to advance a hydrogen economy. Therefore, they should be engaged in the early stages of launching a hydrogen hub.

1 INTRODUCTION

The production and use of fossil carbon-based energy carriers are contributing to the climatic changes that are impacting the quality of life and economy of communities across Canada and around the world. To mitigate these impacts, Canada and dozens of other nations have committed to achieving net-zero greenhouse gas (GHG) emissions by 2050 [1]. The distributed combustion of gasoline, diesel, jet fuel and natural gas accounts for almost half of Canada's GHG emissions, and another 24% is associated with the production of these energy carriers from oil and gas recovery and processing (**Figure 1.1 A**) [2]. In the interim, Canada has reaffirmed its commitment to cut GHGs by 40-45% below 2005 levels by 2030 and has further identified key industrial sectors for emission reductions, such as transportation, oil and gas, electric generation, and agriculture [3].

Clearly, the transition to net-zero emission energy systems needs to involve changing the energy carriers that are used to meet societal needs. Electricity, made from very low or zero-emission sources, is seen by most as a key part of the solution. However, widespread consensus is that a net-zero emission energy future cannot be met by (zero-emission) electricity alone [4,5,6]. Chemical-based fuels are required for sectors such as heavy transport, many thermo-chemical industries, space heating in cold climates and the long-term storage of electricity. Biofuels can help, but their capacity is limited, especially if biological systems are to provide negative emission technologies (i.e., increase the carbon stocks in forests and agricultural soils), while providing even more food and fibre to support the world's growing population and expanding economies.

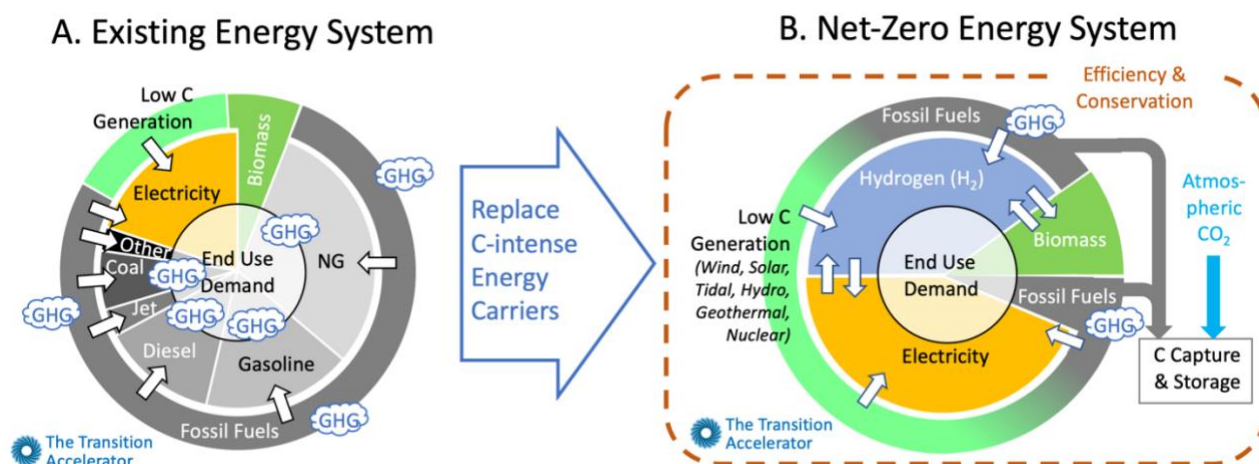


Figure 1.1 Canada's Existing Energy System (A) and the Needed Transition to Net-Zero Emissions (B)

In the existing energy system, energy carriers like gasoline, diesel, jet fuel and NG (natural gas) support end-use demand but generate large emissions. To achieve net-zero commitments, they must be transitioned to zero-emission energy carriers (electricity, hydrogen, biomass) (B). Panel A from NRCan's Comprehensive Energy Use Database.

As a result, nations around the world (e.g. Australia [7], Germany [8], UK [9], USA [10], South Korea [11], and China [12]) are developing strategies and starting to build out a new energy system based on hydrogen and electricity made from very low or zero-emission sources. Hydrogen (H₂) is a carbon-free gas that releases energy when combined with oxygen from the atmosphere. Heat is generated if hydrogen and oxygen are combined through

combustion, but if combined in a fuel cell, half or more of the energy is delivered as electricity and the balance as heat.

Figure 1.1B provides an example of a possible net-zero energy system for Canada in 2050. It envisages an expanded role for electricity and biomass as energy carriers in the future, as well as a major role for hydrogen that is produced with zero or very low GHG emissions.

1.1 Towards a New Value Chain for a Fuel-Hydrogen Economy

Energy carriers used today are inconsistent with net zero. Canada needs energy carriers such as electricity and hydrogen made with low or no greenhouse gases (GHGs); the supply chain for electricity in Canada is established and well utilized, but there is a need to build a new value chain for hydrogen.

Today, hydrogen is primarily used as an industrial feedstock in upgrading and refining hydrocarbons and generating chemicals and fertilizers (such as ammonia and methanol). It also has the potential to be used as an industrial feedstock for steel making from iron ore. In Canada, hydrogen production is estimated at 8,200 t/day (3.0 Mt/year), and Alberta is the largest producer at about 5,800 t/day (2.1 Mt/year). However, most of the hydrogen generated today is derived from natural gas, where the CO₂ by-product of the process is released into the atmosphere, which has associated GHG emissions of approximately 28 Mt CO₂e/year.

To create a new value chain for hydrogen-use as a fuel or as an energy carrier for export markets, it is necessary to understand the energy service hydrogen will provide, where it is needed, where it can be produced cost-effectively, and the options for connecting supply to demand. Like any chain, a value chain is only as strong as its weakest link. Ideally, each link in the value chain helps to enable subsequent links while strengthening preceding links, increasing the overall resilience and economic viability of the entire chain (**Figure 1.2**).

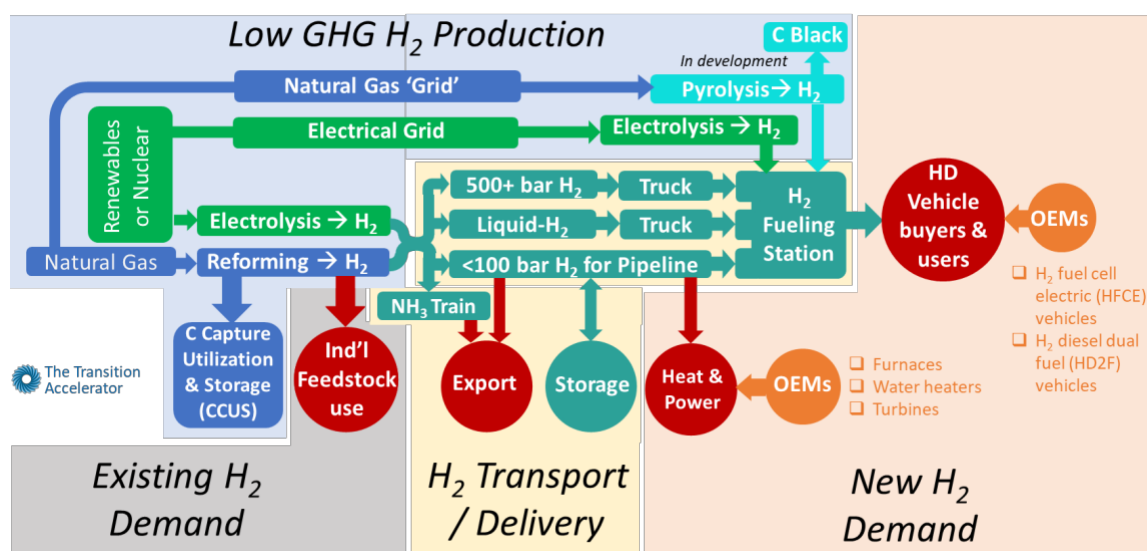


Figure 1.2 New Hydrogen Value Chain

The red circles identify the markets for hydrogen, while the blue-green boxes depict the infrastructure options to serve those markets. The blue, green, and light turquoise boxes show the major options for low-GHG hydrogen production. OEM, original equipment manufacturers.

SOURCE: The Transition Accelerator

The use of hydrogen as an energy carrier is emerging as a choice for heavy vehicle transport (trucks, rail, marine, off-road), space and water heating (especially in cold climates), and industrial heat and power applications. In its gaseous form, hydrogen is much more challenging to transport and store than liquid fuels, such as gasoline or diesel, especially in small quantities. Certainly, it is critical to deploy all parts of a new hydrogen value chain in a coordinated way. This is best achieved in targeted hubs or corridors where the demand and supply can be either co-located or deployed at a scale where economic viability can be achieved without on-going public investment.

Hydrogen will become an important decarbonization fuel because of its flexibility. Its use in hydrogen fuel cells, whether for vehicles or stationary power applications, results in zero CO₂ emissions. Hydrogen can also be burned in vehicles or used in industrial processes, with no or very low GHG emissions. Hydrogen can be blended with natural gas for space and water heating, reducing the GHG footprint of emissions in those sectors. Renewable energy can be used to create hydrogen through electrolysis, and through this process, hydrogen becomes an effective energy storage medium for renewable energy, offsetting concerns about the intermittency of wind and solar power. Aviation companies are working to develop aircraft powered by hydrogen to overcome the challenges of electrification in aircraft; the shipping industry is looking for ways to power ships using hydrogen or ammonia derived from hydrogen.

1.2 The Need for Hydrogen Hubs and Corridors

To capitalize on the environmental and economic potential of hydrogen as a fuel, economies of scale play a key role in creating demand and supply in a coordinated way and at a scale that will quickly become economically viable without the need for on-going public investment. From previous analysis [13] and experience in founding and launching Canada's first hydrogen HUB in the Edmonton Region, the Transition Accelerator recommends that the transition pathway to fuel hydrogen begins with Hubs and corridors that are built around regions with:

- The ability to make low-cost, low-GHG hydrogen
- Substantial nearby markets for hydrogen and the ability to connect the supply to demand
- A scale of supply/demand where the economics works without sustained public investment
- Engaged industry, governments, and academics

The creation of Hydrogen Hubs is a concept that has been endorsed by both the Alberta government; through the release of its Alberta Hydrogen Roadmap [14] in 2021; as well as the federal government in the form of the Hydrogen Strategy for Canada Report [15], released in December 2020 by Natural Resources Canada (NRCan).

[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 hub by NRCan's Hydrogen Hubs Working Group 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".

1.3 The Calgary Region Feasibility Study

This Feasibility Study / Foundation Report is the first step in the 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 Hub Stages are as follows (**Figure 1.3**):

- A. **Foundation Report.** Document the regional ‘assets’ that could be harnessed in a transition to a hydrogen economy and engage 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.** Build on Stage A to engage a ‘coalition of the willing’ to articulate a strategy for building and connecting H₂ supply to H₂ demand. (There is a possibility that the work on 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.** To critically assess 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 pilots, demonstration, and commercialization projects.

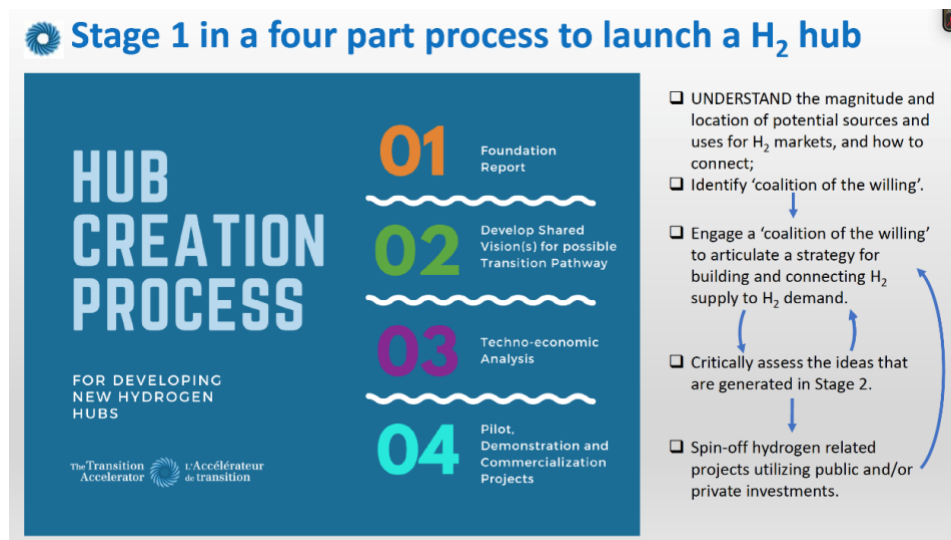


Figure 1.3 The Transition Accelerator’s Hub Creation Process

Throughout this report, we attempt to estimate the energy requirements in the Calgary Region and identify where opportunities lie to shift a portion of demand from traditional energy carriers to hydrogen across various sectors.

Such transitions are long-term investments and while they may seem like a reasonable and justifiable target, numerous challenges need to be overcome.

Within this report, you will find:

- A description of the Calgary Region and its role in the province of Alberta (**Section 2**)
- A 'Hydrogen 101' brief to summarize information about hydrogen that helps to explain the focus and calculation in many of the subsequent sections of the report (**Section 3**)
- The use of government data to estimate the fuel hydrogen potential of the province and the proportion of that which could be assigned to the Calgary Region (**Sections 4**),
- Several assessments of the fuel hydrogen potential for local jurisdictions or sectors to identify potential early adopters or regional initiatives that could be the focus for initiatives in a new value chain for the region (**Sections 5 to 11**),
- A series of recommendations for the next steps (**Section 12**)

The hope is that this report will help to create a shared vision among multiple stakeholders for a transition pathway to a zero-emission hydrogen economy in the Calgary Region. As a technical report, we hope that it will inform and motivate a broad suite of actors that have key roles in accelerating the implementation of the low-carbon hydrogen-as-fuel economy in Canada. They include:

- **Policy Makers:** To inform and encourage the development and implementation of economic and environmental policies critical to attaining a self-sustaining hydrogen economy in Canada.
- **Academics and Students:** Academia can play a much more significant role in making practical, tangible progress to help society attain societal objectives, in addition to the traditional roles of analyses, research and technology development. While technology innovation is important, so is the ability to access the broader implications associated with deploying those innovations in order to address societal needs.
- **Environmental Groups:** By focusing on evidence-based assessments of the environmental footprint associated with the production and use of low-GHG, fuel hydrogen, it is hoped that this report will engage environmental groups in helping to define and support effective solutions.
- **Industry:** Attaining an economically self-sustaining hydrogen economy is a complicated endeavour, requiring new public and private sector roles and outcomes along a new hydrogen value chain. The industry is essential in this venture. The Transition Accelerator is eager to work with a 'Coalition of the Committed', typically led by industries who wish to start on the journey along a transition pathway to a net-zero energy future fueled partly by hydrogen.

2 THE CALGARY REGION

2.1 History & Economy

The Calgary Region (**Figure 2.1**), as defined for this report, includes the City of Calgary, the Rocky View, Foothills and Wheatland Municipal Districts and the cities/towns within their geographic extent, as well as the Tsuu T'ina, Stoney-Nakoda and Siksika First Nations communities. While this region is geographically a small portion of the province, approximately 2.1% by area, it is home to 37% of the province's population [16].

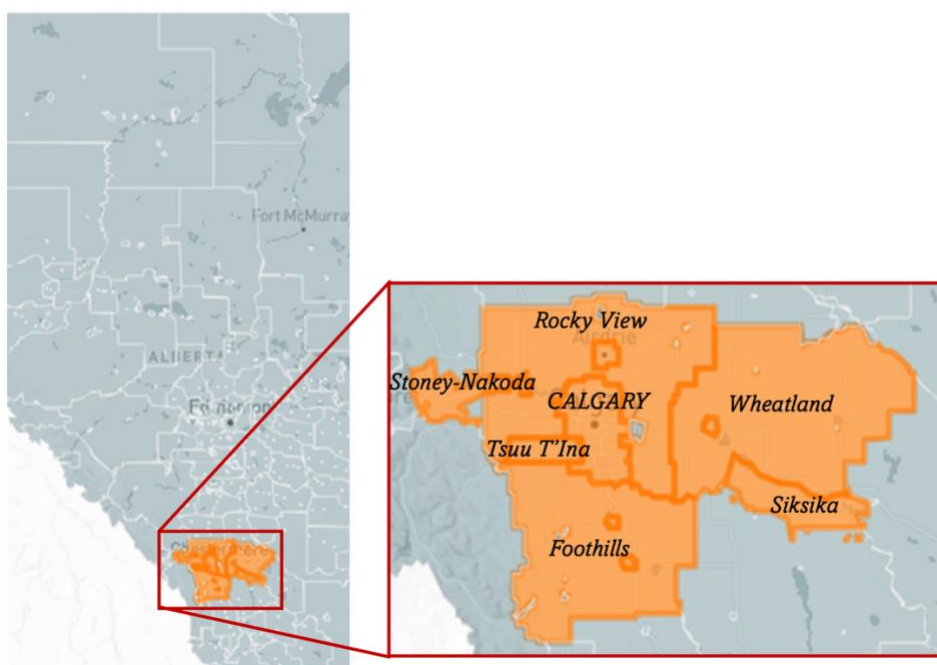


Figure 2.1 The Calgary Region

For more than 10,000 years, the Calgary Region was home to the Plains First Nations and sat in the heart of the Treaty 7 region in Southern Alberta. The Treaty 7 region includes the Blackfoot Confederacy (comprised of the Siksika, Piikani, and Kainai First Nations), as well as the Tsuu't'ina First Nation, and the Stoney Nakoda (including the Chiniki, Bearspaw, and Wesley First Nations). [17] The City of Calgary is also home to the Metis Nation of Alberta, Region III.

Following the arrival of Europeans, the Calgary was established in 1873 by the North-West Mounted Police and would be renamed Fort Calgary in 1876. The transnational railway arrived in Calgary in 1883, linking Calgary to eastern Canada and opening the region for pioneering ranchers. Calgary was incorporated as a town in 1884 and a city in 1894. Oil was discovered in the region in 1914 with the drilling of the Dingman well in nearby Turner Valley, but this first oil boom only lasted a few months until the outbreak of World War I [17].

In 1924, Royalite drilled below the Dingman well and struck oil and natural gas. From that time forward, the City of Calgary and the surrounding area has lived through several boom-and-bust periods in the energy industry but always remained a strong agricultural region. As a result, Calgary has grown over the decades to become an important economic powerhouse for the province.

The Region sits at the crossroads of the Trans-Canada Highway and the Queen Elizabeth II Highway and serves as a major hub for air and rail cargo, making it one of Western Canada's most important distribution hubs. Calgary is home to over 100 head offices, the most per capita of any Canadian city, and has the second-highest concentration of small businesses per capita of Canada's major cities [18]. A 2021 report by the Conference Board of Canada noted that Calgary also has the highest GDP per capita of Canada's major cities, partly due to the province's vast wealth of natural resources [19].

Canada's two major rail companies, CP and CN, have substantial operational centers located in the Calgary Region. In addition to the Company's corporate headquarters, CP operates a large intermodal facility, a major terminal and a maintenance facility within the southeast part of the city. In 2021, the company operated approximately 90 line-haul locomotives within the Calgary region on a daily basis. CN recently constructed and operates a new Intermodal/Logistics Park located just east of the Calgary city limits near the hamlet of Conrich. Both rail companies have direct access to ports on Canada's west coast.

The Calgary International Airport, or YYC as it is commonly referred to, is an important centre for both air travellers and cargo. Data from 2019 shows that the airport received 18 million passengers and 4305 cargo landings [20]. YYC's Sustainability Strategy has set a goal of achieving net zero emissions by 2050 with the knowledge that advancing a hydrogen economy will be a key part of a low-carbon future.

Outside of the urban City of Calgary, smaller towns of Airdrie, Okotoks, Cochrane, and Strathmore in the counties of Rocky View, Wheatland and Foothills offer remote and more rural dwellings in picturesque prairies.

2.2 Demographics & Economy

The Calgary Region is home to 1.6 million people, or 37% of Alberta's population (**Table 2.1**). Of that total, 84.7% live in the City of Calgary, followed by the City of Airdrie at 4.7% (**Figure 2.2**). Cochrane and Okotoks make up about 2% each, followed by the towns of Strathmore and High River. The three Municipal Districts total 5% of the regional population, and the 3 First Nations communities add up to 0.6%. Many of the residents that comprise the populations of the areas surrounding Calgary commute to the city for work, shopping, or other activities. Given the dominance of the City of Calgary in the entire Calgary Region, the primary focus of this report will be on the City of Calgary's energy requirements and opportunities for the development of a hydrogen economy.

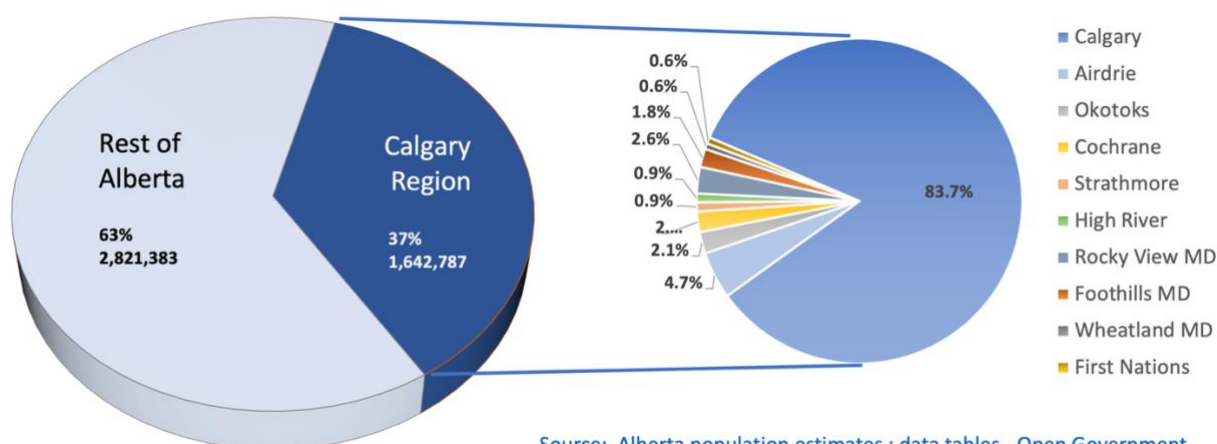
Table 2.1 Regional Demographics

	<i>Calgary Region</i>	<i>Alberta</i>	<i>% of Alberta</i>
Population (2021)	1,639,471	4,421,876	37%
Area (sq km)	14,295	661,800	2.2%
Median Family Income (2020)	\$106,508	\$104,613	102%
Total Dwellings (2021)	616,245	1,624,227	38%
GDP Growth (2021 forecast)	4.2%	6.1%	
Unemployment Rate (2019)	9.3%	8.8%	
Labour Force (2020)	772,920	2,343,000	33%
Aboriginal Population (2016 Census)	51,390	258,640	19.9%
Number of Businesses (2020)	56,359	157,489	35.8%

SOURCE: The Government of Alberta

Demographic markers for the region show that the Median Family Income falls just above the rest of the province at \$106,710 (Table 2.1). In addition, total dwellings, number of businesses and the Labour Force generally fall in line with the Region's portion of the province's population at 38%, 36% and 33%, respectively.

The Region is also home to 12% of Alberta's first nation population within three First Nations communities (Figure 2.2).



Source: Alberta population estimates : data tables - Open Government

Figure 2.2 Proportion of Alberta's Population in Calgary Region (left) and Distribution within the Region(right)

The total population of the Calgary Region is 1.6 million persons.

SOURCE: The Government of Alberta

3 HYDROGEN 101

3.1 Introduction

The use of hydrogen as a zero-emission fuel to replace traditional carbon-based liquid (e.g., gasoline, diesel, jet fuel) or gaseous fuels (natural gas, propane) requires a new value chain with technologies to produce, move, store, and convert to deliver energy services. As a gas, a new hydrogen value chain is likely to be more similar to natural gas than gasoline and diesel fuel, offering both challenges and opportunities.

This section provides a brief overview of how hydrogen can be used as an energy carrier, its physical properties and the economics of its production, transport, and use. To set a bar for the performance of this new value chain, we begin with a summary of the current wholesale and retail costs for energy in Western Canada (**Figure 3.1**). The data presented here do not reflect the sharp rise in energy costs that coincided with the Russian invasion of Ukraine in early 2022.

As shown in **Figure 3.1**, per unit of energy, Canadians pay more for electricity and transportation fuels than heating fuels. In part, this is because:

- ❑ The methane in natural gas that serves as a heating fuel is often a by-product of fossil fuel recovery processes that are more focused on crude oil extraction or the extraction of the heavier hydrocarbon fraction (ethane, propane, butane) of natural gas. Consequently, pipeline-quality natural gas produced in Western Canada (95% methane) is somewhat stranded from the major markets in the USA and available at a lower cost. In fact, between 2016 and 2021, pipeline natural gas in Alberta was about 53% of the Henry Hub price for fuel.
- ❑ Pipelines deliver the fuel in large volumes to virtually every building in Alberta's cities and most buildings in the province. The distribution costs are relatively low, given the scale of the infrastructure and the volume of fuel used. (It is worth noting that Alberta also supplies large volumes of natural gas to other provinces and the USA through and extensive pipeline network.)
- ❑ Pipelined natural gas delivery to residential and commercial buildings is a regulated industry, so the cost to consumers is tied to actual costs to the industry, reducing market volatility and the negative impacts of monopolistic behaviours.
- ❑ Per unit of embedded energy, the wholesale cost of crude oil that is used to make transportation fuels has been much higher than the wholesale cost of natural gas, especially in the last 12+ years.
- ❑ The retail cost of transportation fuels must include the cost of building and operating the fueling stations.
- ❑ The values shown in **Figure 3.1** do not reflect the impact of the projected carbon tax on transportation and heating fuels between now and 2030 when it is expected to rise to \$170/t CO₂e.

The yellow shading in **Figure 3.1** shows the targeted price for hydrogen to provide similar energy service to the current energy system. Note that two price ranges have been identified: one for hydrogen as a heating fuel (C\$2-C\$3/kg H₂) and one for H₂ use in heavy transport (C\$5-C\$8/kg H₂). These calculations take into account the following:

- ❑ Fuel cells convert hydrogen to vehicle movement more efficiently than internal combustion engines convert diesel fuel to vehicle movement.
- ❑ The projected impact of carbon taxes on future retail costs.

- The continuing trend toward improved thermal efficiency in buildings. (In space and water heating, we assume that the hydrogen will be combusted, like natural gas, in high-efficiency furnaces.)
- The need for expensive hydrogen compression and storage and higher purity hydrogen at fueling stations in a hydrogen economy, whereas building heating would be able to use lower quality hydrogen delivered in a repurposed natural gas pipeline network.
- The coordinated, large-scale deployment of infrastructure supporting a hydrogen economy, thereby taking advantage of the efficiencies of scale. (The calculations do not include an equivalent to the current gas tax on transportation fuels that is used to help pay for road infrastructure.)

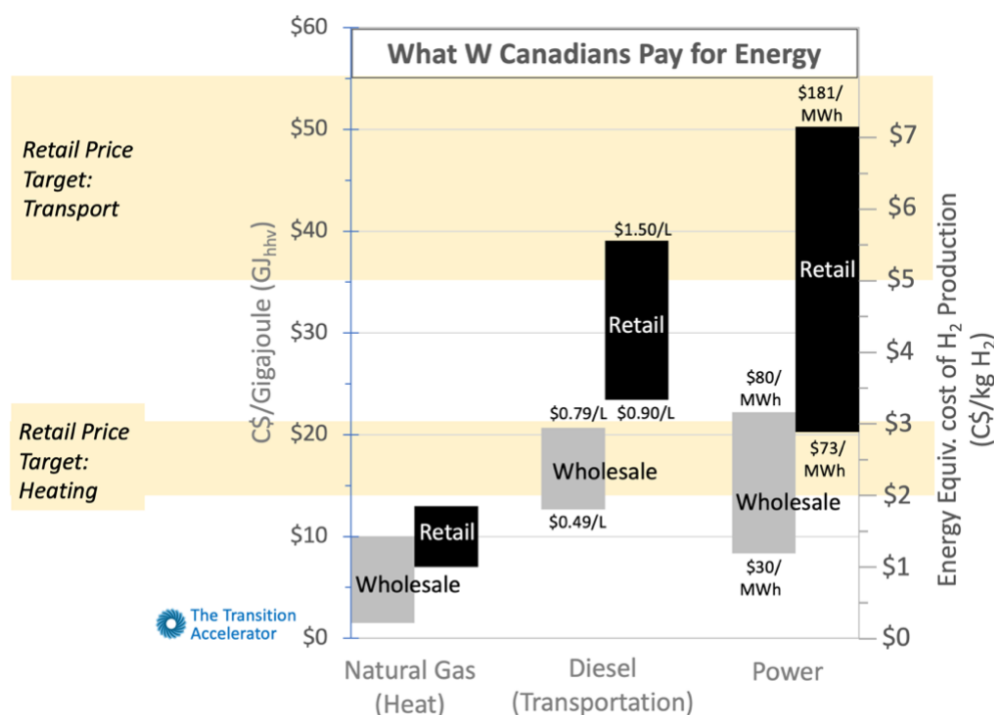


Figure 3.1 Costs (\$/GJhhv) for Fuel Energy Demand in Western Canada

Note that per unit of energy, Western Canadians pay more for transportation fuel and electricity than for heating fuels. The prices represent typical values for the 2016 to 2021 period. The yellow shading shows the target retail price for hydrogen use in heating or transport. For transport, higher compression and rapid refueling is required. Note that the prices shown here reflect recent levels of carbon tax (\$30 to \$50/t CO₂). At the \$170/t CO₂ projected for 2030, natural gas costs would be expected to increase by \$6 to \$7/GJ.

SOURCE: The Transition Accelerator

The higher targeted price for transportation fuels means that in short to medium term, the economics for a transition of heavy-duty diesel vehicles to hydrogen is closer to economic viability than is the use of pure hydrogen for building heat supply. That being said, a strong case can be made for blending hydrogen (up to 20% by volume) into existing natural gas networks as part of a transition strategy to zero-emission energy systems. It is also important to pilot and test pure hydrogen for space and water heating, industrial heat demand and power generation in the next few years.

3.2 Properties of Hydrogen and Its Derivatives

Physical Properties. With a molecular weight of 2 grams per mole, hydrogen gas (H_2) is the smallest and lightest molecule in the universe. Therefore, it is not surprising that the energy density per unit of mass is 2.8 to 3.1 times that of gasoline (**Table 3.1, Items 4 and 5**), making it attractive as a transport fuel where weight is a factor.

Like natural gas, hydrogen is a gas, but each H_2 molecule has only one energy-rich chemical bond, compared to four energy-rich bonds in methane (CH_4), the major constituent of natural gas. Therefore, on a volumetric basis, hydrogen has only one-third the energy density of natural gas (**Table 3.1, Item 7**).

When the temperature of hydrogen gas is dropped to $-253^\circ C$, it becomes a liquid, and the energy density of liquid hydrogen (LH_2) is still only about $1/3^{rd}$ of the energy density of liquefied natural gas (LNG @ $-160^\circ C$) or about one-quarter of that for diesel fuel. Therefore, larger volumes of hydrogen must be moved to deliver the same amount of energy as carbon-based energy carriers.

Like LNG, LH_2 is known to “boil off” while being stored. The boil-off gas can be used as a fuel, reliquefied or compressed and put into a pipeline or compressed tank. Therefore, LH_2 is not usually considered for long-term hydrogen storage, but as a form of hydrogen that can be transported by truck or train, typically to a fueling station. A truck can carry up to four tonnes of LH_2 in a cryogenic container, whereas only about 1 t H_2 can be carried per truck as a compressed gas.

Compared to storing or transporting the same amount of energy as other energy carriers, hydrogen tanks tend to be larger or held at higher pressure. In the case of gas transport in similar pipeline sizes, hydrogen can be transported about three times more rapidly than natural gas before there are concerns about adverse impact on pipeline integrity. Therefore, a similar-sized pipeline can deliver hydrogen energy at about 85% of the capacity of natural gas energy.

Health and Safety Considerations. Like other energy carriers, hydrogen production, transport, storage, and use are associated with important health and safety risks. Being a small molecule, it can escape through small cracks, so tight sealing fittings are essential. Hydrogen is also known to cause embrittlement in some kinds of steel, creating cracks and weakening the steel. It is also a colourless and odourless gas, making it harder for people to detect fires and leaks.

Fortunately, the industry has a lot of experience in how to handle hydrogen gas, an experience that needs to be shared with others and incorporated into regulatory processes if hydrogen is to become an energy carrier in a future net zero emission energy system.

Protocols for the safe handling of hydrogen in pipelines, storage containers and fueling stations are already in place, and companies around the world building vehicles, furnaces, boilers, and gas turbines are now exploring the use of hydrogen as a fuel.

Ammonia is a zero-emission energy carrier produced from hydrogen and nitrogen gas (N_2) extracted from the air. It is highly toxic, flammable and corrosive and so its use as an energy carrier tends to raise more health and safety considerations than hydrogen. Consequently, ammonia’s use as an energy carrier would probably be restricted to professionally trained operators. On the positive side, it has a pungent smell, making leaks easier to detect.

Table 3.1 Physical Properties of Hydrogen

Adapted from the IEA's Future of Hydrogen Report (2019) [21]

#	PROPERTY	HYDROGEN	COMPARISON
1	Density (gaseous)	0.089 kg/m ³ (0C, 1 bar)	1/10 of natural gas
2	Density (liquid)	70.79 kg/m ³ (-253C, 1 bar)	1/6 of natural gas
3	Boiling point	-252.76°C (1 bar)	90°C below LNG
4	Energy per unit of mass (HHV)	141.7 MJ/kg	2.7x that of natural gas 3.1x that of gasoline
5	Energy per unit of mass (LHV)	120.1 MJ/kg	2.5x that of natural gas 2.8x that of gasoline
6	Ratio of Lower (LHV): higher (HHV) heating value	0.85	natural gas (0.90) gasoline (0.94)
7	Energy density (ambient cond., LHV)	0.01 MJ/L	1/3 of natural gas
8	Specific energy (liquefied, LHV)	8.5 MJ/L	1/3 of LNG ¼ of diesel
9	Flame velocity	346 cm/s	8x methane
10	Ignition range	4-77% in air by volume	6x wider than methane
11	Autoignition temperature	585°C	220°C for gasoline
12	Ignition energy	0.02 MJ	1/10 of methane

Notes: cm/s = centimetre per second; kg/m³ = kilograms per cubic metre; LHV = lower heating value; MJ = megajoule; MJ/kg = megajoules per kilogram; MJ/L = megajoules per litre.

Like hydrogen, there is long experience in using ammonia by industry and agriculture since the dominant use for the chemical is as nitrogen fertilizer. Gaseous ammonia can either be injected into soils directly (it is highly water soluble) or converted into ammonia nitrate or urea and applied to soils in solid or liquid form. While a gas at room temperature becomes a liquid at low pressures (7.5 bars at 20°C) or low temperature (-33°C at atmospheric pressure) and can be transported in sealed tanks similar to propane. When combusted, ammonia does not produce greenhouse gases.

Hydrogen can also be reacted with other molecules to form liquid organic hydrogen carriers (LOHC) that have been proposed for long-distance hydrogen transport, especially on ships. Methylcyclohexane is a potential LOHC since it releases hydrogen when heated, creating toluene that can be returned to the hydrogen source, where it is again converted to methylcyclohexane. As liquids at normal temperatures and pressures, toluene and methylcyclohexane are easier and have a lower cost to transport than gaseous energy carriers. Toluene is toxic, and both liquids are flammable, but the industry knows how to handle them safely, and there are no serious concerns about moving them by ship or in pipelines. The main challenge with LOHCs is that hydrogen accounts for only about 6% of the weight, so most of the weight being shipped is the carrier, not the hydrogen.

3.3 The Economics of Hydrogen Production in Canada

The two most commonly deployed technologies for low GHG hydrogen production are the electrolysis of water using very low GHG electricity and the reforming of natural gas coupled to 90% to 95% carbon capture and storage (CCS), where the natural gas is recovered, upgraded and transported with extremely low GHG emissions.

Canada is among the world's lowest-cost producers of low-GHG hydrogen (**Figure 3.2**). In the 2018 Asia Pacific Research Centre paper [22], Canadian electrolysis and steam reformation/CCS projects were shown to be equal to or lower than the wholesale price for diesel (**Figure 3.2**). This has become even more pronounced, with current diesel prices being nearly double the prices utilized in the comparison.

Electrolytic Hydrogen Production. Electrolysis creates hydrogen (H_2) and oxygen (O_2) from water using electricity. If the electricity is from renewables, it is often called 'green' hydrogen. Our analysis focused on the costs for a Polymer Electrolyte Membrane/Proton Exchange Membrane (PEM) electrolyzer rather than Alkaline electrolyzers since a number of studies [23,24] consider them better suited for use with intermittent power sources. In addition, model parameters from the International Energy Agency's Future of Hydrogen report [21] were adapted for Canadian currency to illustrate the effect of electricity price and use factors (number of hours per year) on the cost of hydrogen production today by 2030 and in the future when technology deployment is mature (**Figure 3.3A to C**).

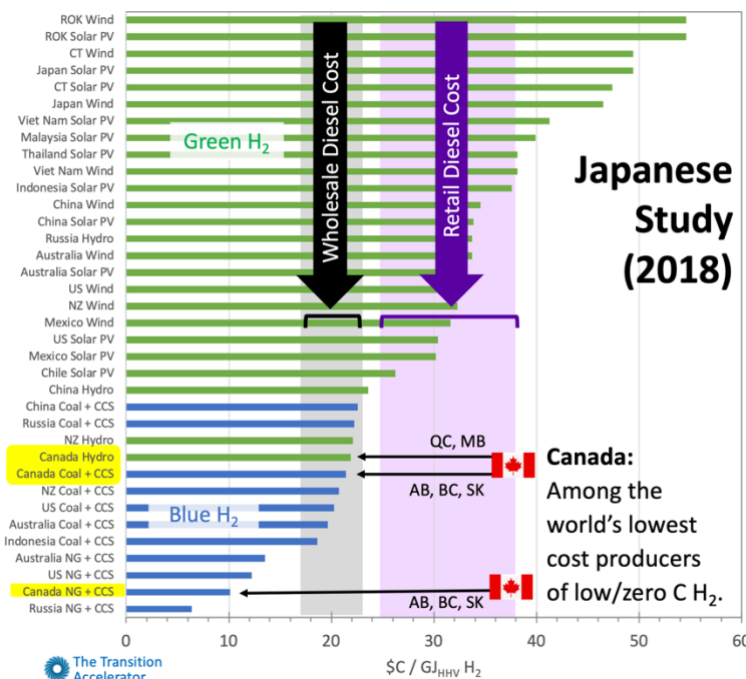


Figure 3.2 A Comparison of the Cost of Blue or Green H₂ Production from Countries in the Asia-Pacific Region

Adapted from Asia Pacific Energy Research Centre's Perspectives on H₂ in the APEC Region [22]. The vertical shaded regions depict ranges for recent wholesale and retail costs of diesel use in Canada.

Using the IEA model, three case studies were explored, and the results are shown on the surface plot and bar charts in **Figure 3.3**:

- ❑ **Dedicated intermittent renewable** (e.g., wind) with a capacity factor of 34% (3,000 hr/year) where the levelized cost of electricity (LCOE) is \$40/MWh now but will decline to \$30/MWh by 2030.
- ❑ **Low carbon grid power** accessed for 6,000 hr/year (68% capacity factor for electrolyzer) at a delivered electricity price of \$80/MWh.
- ❑ **Low carbon grid power** accessed for 6,000 hr/year (68% capacity factor for electrolyzer) at a delivered electricity price of \$20/MWh. This is the least likely of the three alternatives, only being possible in jurisdictions that often have excess large hydro or nuclear power.

For electrolytic hydrogen production over the next 10 years, the wholesale cost for green hydrogen may decline to as little as C\$3/kg (C\$21/GJ_{HHV}), assuming a low carbon electricity cost of about C\$30-35/MWh. To drop to less than C\$2/kg H₂ and be competitive with hydrogen reformed from natural gas with CCS, low-cost, more efficient electrolyzers would help, but the most important factor would be the near-continuous supply of electricity under C\$30/MWhr. For regions of the world with superb wind and solar resources and low-cost land, such a price target may be possible [25], but perhaps not in Canada.

In most places, the cost of water is not a major contributor to the cost of hydrogen production since the electrolysis of a cubic meter of water can produce over 100 kg H₂, which is worth many hundreds of dollars. However, access to water that can be purified for use in an electrolyzer is still an issue in some places.

It is important to note that the cost of hydrogen production is only one factor in economic viability. Hydrogen transportation and fueling infrastructure are often more important, and electrolytic hydrogen production can deploy at smaller scales, nearer to demand, so long as there is water and low-cost electricity.

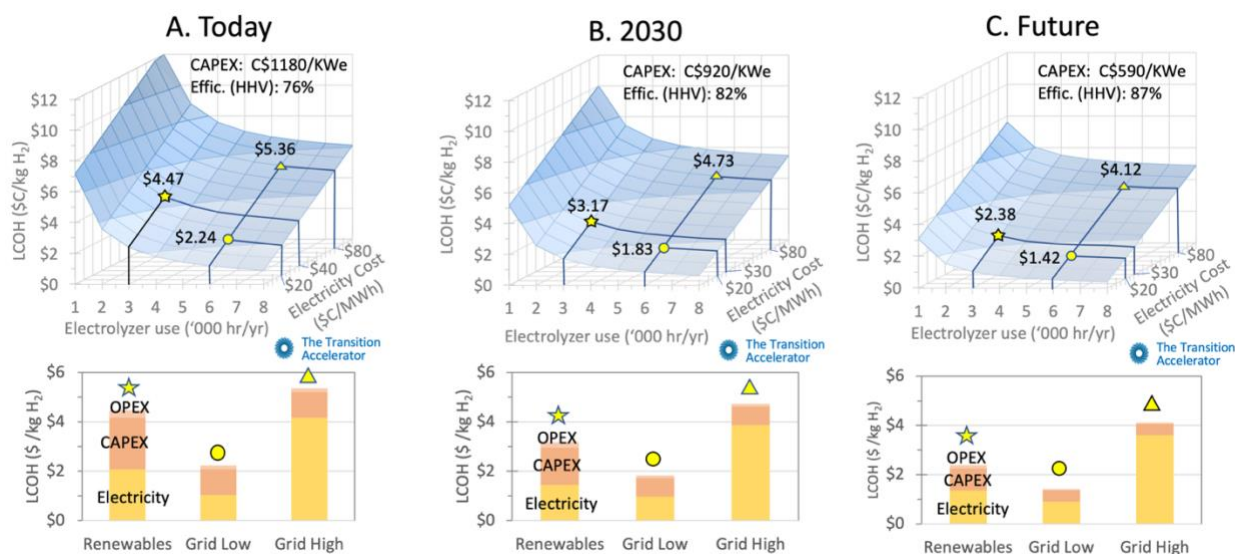


Figure 3.3 The effect of electricity cost & capacity factor on the levelized cost of H₂ (LCOH) production for a 4.2 MW PEM electrolyzer today (A), in 2030 (B) and in the future (C) when the market is mature.

Symbols refer to the three cases described in the text. Model adapted from the IEA's Future of Hydrogen Report [21].

Hydrogen Production from Methane Reforming with CCS. The reforming of natural gas (predominantly methane) dominates hydrogen production in Canada, and the process can be modified to prevent the atmospheric release of 90% or more of the by-product CO₂. When methane reforming is coupled to carbon capture and utilization/storage (CCUS), the product is often called 'blue' hydrogen.

There are two major technologies for blue hydrogen production: steam methane reforming (SMR) with CCS and auto-thermal reforming (ATR) with CCS. The SMR technology dominates industrial 'gray' hydrogen production in Canada today, releasing to the atmosphere about 9.6 kg CO₂ per kg H₂. SMR generates a large volume of by-product flue gas in which the CO₂ concentration is relatively low, resulting in the need for an expensive add-on CCS technology to produce 'blue' hydrogen with a carbon intensity of less than 1.5 kg CO₂/kg H₂. The ATR process generates a more concentrated CO₂ stream, reducing the cost and improving the efficiency of CCS. While the electricity demand is higher in the ATR process, 'blue' hydrogen can be produced at a similar or slightly lower cost than SMR + CCS, and the carbon intensity of the produced hydrogen is less than 1 kg CO₂/kg H₂.

Other hydrogen production technologies from carbon-based feedstocks include biomass, bitumen or coal gasification coupled to CCS or methane pyrolysis to hydrogen and carbon black. While coal and bitumen gasification are mature technologies, the others are not yet as mature or economically viable as ATR-CCS in regions with the geology for carbon storage.

Figure 3.4 provides a breakdown of the estimated costs for blue hydrogen production (including CCS) from natural gas today (**Figure 3.4A**) by 2030 (**Figure 3.4B**) and in a future, mature hydrogen economy (**Figure 3.4C**).

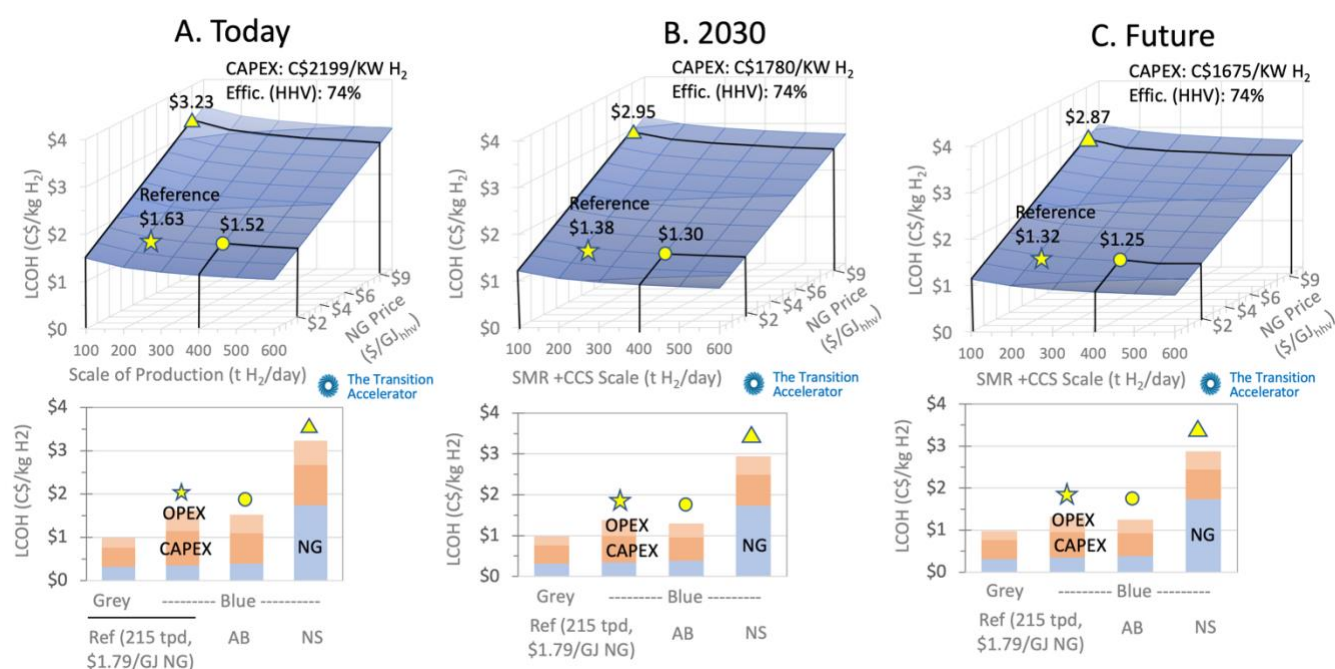


Figure 3.4 The effect of natural gas cost & scale of production (tH₂/d) on the levelized cost of H₂ (LCOH) from a steam methane reformer coupled to carbon capture and storage today (A), in 2030 (B) and in the future (C) when the market is mature.

Model adapted from the IEA's Future of Hydrogen Report [21].

The calculations were based on the International Energy Agency's 'Future of Hydrogen' [21] model assuming a Canada-US dollar exchange rate of \$C0.76 per \$US1 and an 8% return on capital cost investment. The upper plots in **Figure 3.4** show the effect of natural gas price (\$0 to \$10/GJ_{HHV}) and the scale of hydrogen production (100 to 600 t H₂/d) on the levelized cost of H₂ production. On each surface plot, three case studies are highlighted:

- A reference case based on a 215 t H₂/day reformer (based on the IEA model) and a NG feedstock price of \$1.79/GJ_{HHV} NG (average of Alberta prices over the last 5 years, **Figure 2.3**).
- An Alberta (AB) scenario assuming a 400 t H₂/day reformer and a NG feedstock price of C\$2/GJ_{HHV}.

- A high NG price (i.e., Nova Scotia (NS)) scenario which takes into account a C\$9/GJ_{h_hv} price for natural gas and a smaller (100 t H₂/day) reformer.

With proven technologies today and a natural gas cost typical of the 2015-2020 period (C\$1.79/GJ_{h_hv}), the levelized cost of hydrogen (LCOH) for the reference scenario is C\$1.63/kg H₂ (**Figure 3.4A**). However, with improvements in larger-scale deployment of technologies linking H₂ production to carbon capture and storage, the LCOH is projected to decrease to C\$1.38/kg H₂ by 2030 (**Figure 3.4B**) and eventually to C\$1.32/kg H₂ (**Figure 3.4C**).

Note that even in markets like Nova Scotia with high prices for natural gas, the LCOH for blue hydrogen is similar to, or lower than, the cost of green hydrogen (**Figure 3.3**), assuming that the geology can be found nearby for permanent geological storage. However, the cost reductions for green hydrogen production over the next 10-20 years are projected to be steeper than that for blue hydrogen, so green hydrogen could out-compete blue hydrogen production costs in such markets by 2030 and beyond.

The bar charts in **Figure 3.4A** compare today's LCOH for gray and blue hydrogen production, showing a differential cost of C\$0.65/kg H₂. This translates to a CCS cost of C\$74.37/t CO₂. This CCS cost is low compared to many estimates for post-combustion CCS costs from coal etc., and it does not consider the potential for other income that could be generated by selling the CO₂ into markets that could use it or in generating CO₂ credits from government programs.

3.4 The Economics of Moving Hydrogen and Building Fueling Stations

Production costs are only one component of the hydrogen value chain. Transportation and delivery costs must be considered when assessing the challenge of achieving a retail cost for hydrogen that is competitive with the incumbent fuel supply (**Figure 3.1**).

The total delivered cost at a fueling station for heavy-duty vehicles includes the cost of hydrogen production, the cost of compressing or liquefying the hydrogen and moving it by truck or pipeline to the station, and the cost of building and operating the fueling station. **Figure 3.5** summarizes the findings from a recent study [26] that calculated the costs of hydrogen production, processing & transport of the hydrogen, and the cost of fueling station construction and operation. The yellow shading in the

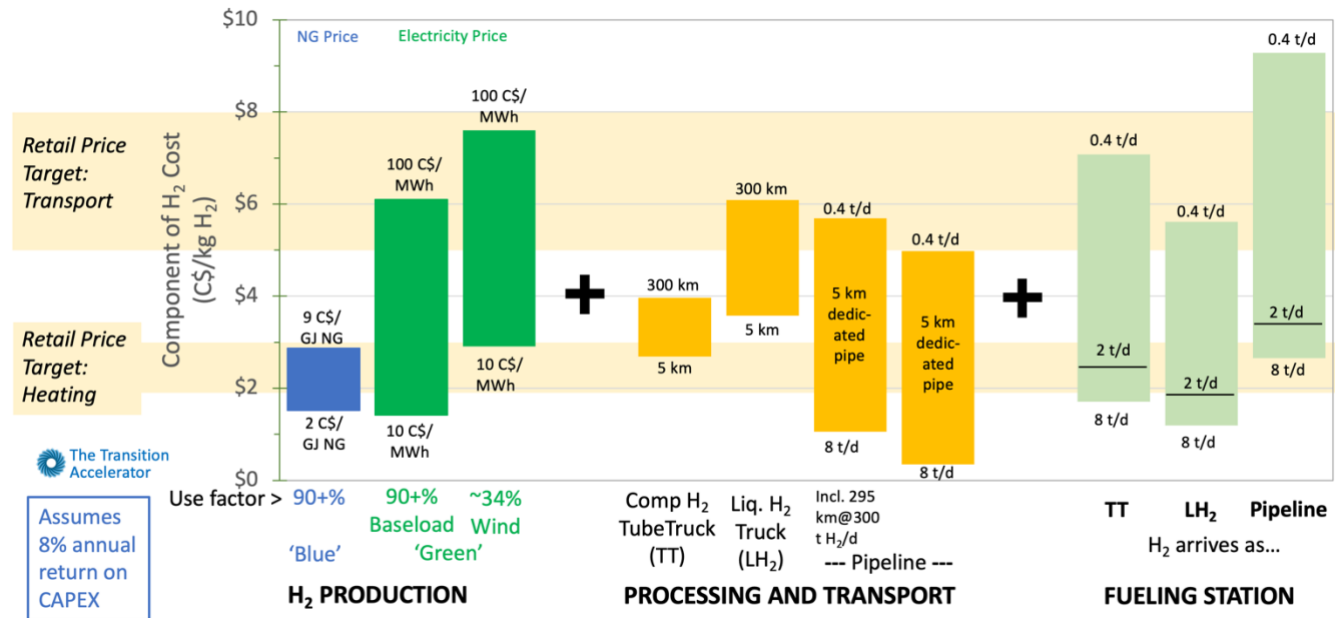


Figure 3.5 An Overview of the Economics for Producing, Processing and Transporting Hydrogen and for Providing Fueling Stations for HD Vehicles

Comparison of fuel cost for heating, transport, and power generation on an energy basis with the energy equivalent value for hydrogen, to demonstrate the range of hydrogen cost required to maintain retail cost parity. Current production cost range for blue and green are indicated, with blue having the lowest production cost.

SOURCE: The Transition Accelerator

Background of the figures shows the target price ranges for hydrogen as a heating fuel (C\$2-C\$3/kg H₂) or as a transportation fuel for heavy-duty vehicles (C\$5-C\$8/kg H₂) as discussed previously (**Figure 3.1**). These retail target prices are higher than the US Department of Energy (Office of Scientific and Technical Information) target price for hydrogen of US\$1 per 1 kg in one decade [27], but they include more than just the production cost.

Lessons from **Figure 3.5** and the Transition Accelerator's Value Chain report [26] include:

- ❑ In addition to the cost of hydrogen production, how the gas hydrogen is delivered and the size of the fueling stations have a significant impact on the economic viability.
- ❑ Smaller demand and short-haul distances are best served by truck transport of compressed or liquified hydrogen. While liquid hydrogen production adds significant cost, the fueling station costs with liquid hydrogen are lower.
- ❑ Long distance and large-scale hydrogen delivery is most economically serviced by pipeline, but this is only feasible if the pipeline's throughput is substantial. Generally, keeping the H₂ transport cost below \$1/kg, a demand of 1 t H₂/d is needed for each km distance [34]. Therefore, if hydrogen needs to be transported 50 km, a demand of at least 50 t H₂/d is needed.
- ❑ For heating applications, pipeline transport of hydrogen is the only economically viable alternative.
- ❑ For fueling stations, the scale has the most dramatic impact on cost, but how the hydrogen arrives at the station also plays a role due to the cost of compression of the gas to the 450 bars or more that is required to fill the 350 bar tanks on vehicles. In addition, liquified hydrogen has a benefit since as it warms, it generates its own pressure without a compressor.

- These calculations assume the hydrogen will be stored on the vehicles as a compressed gas at 350 bar, but it is worth noting that considerable effort is being invested to allow liquid hydrogen onboard storage for vehicles that use a lot of fuel and drive long distances [28], [29]. As a result, such vehicles should be able to carry more fuel with less weight and travel up to 1000 km between refuelling.
- Internal combustion diesel engines tend to be relatively efficient (perhaps 40% efficient), especially when running continuously at 90 km/yr, so the drivetrain advantage of a hydrogen fuel cell electric vehicle (estimated efficiency of 47%) delivers a relative efficiency of about 0.85 J H₂/J diesel.
- Gasoline engines in smaller vehicles tend to be less efficient (20% to 25%), especially in stop-and-go traffic. Therefore, similar hydrogen fuel cell electric vehicles can outperform them and deliver relative efficiencies of 0.4 to 0.5 J H₂/J gasoline. However, plug-in battery electric vehicles show even better efficiencies of 0.25 J electricity/J gasoline, so they tend to be preferred as the net-zero option unless there is a need for long distances and rapid refuelling.
- If a typical truck stop/card-lock station serves 150 Class 8 trucks per day (10 vehicles per hour for a 15 hr day), and each vehicle purchases an average of 200L fuel, fuel demand will be 30,000 L/station per day. A hydrogen fuel cell station of a similar size serving 150 trucks would supply each vehicle with about 45.9 kg H₂ per filling for a total of 6.9 t H₂/day. If serving municipal buses that use 23 kg H₂/day, a station of this size would support 300 hydrogen fuel cell buses. Such a station should be highly profitable.
- The Transition Accelerator estimates that a truck fueling station delivering 4 t H₂/day (to allow for variability in demand with a day of week and season, the station would need to be larger than that) and serving an average of 87 Class 8 long haul trucks per day (45.9 kg H₂/refill) is a good target for efficiency of scale to achieve minimal economic viability. Smaller stations are possible, but certainly not smaller than 1 or 2 t H₂/day unless substantive public subsidies are available.

The value chain study is based on low-cost, centralized production of hydrogen and then moving it to strategically located fueling stations. An alternative approach that needs more study is the smaller-scale, distributed hydrogen production adjacent to where fueling stations are required. The additional cost of this hydrogen production could be offset by savings in the cost of hydrogen processing (e.g. liquefaction) and transport. Specific opportunities currently being explored by the Transition Accelerator include:

- Dedicated wind and solar farms supporting electrolytic hydrogen production for strategically located fueling stations
- Grid-operated electrolytic hydrogen production backed by power-purchase agreements with wind and solar electricity producers
- Methane pyrolysis production of hydrogen, with and without access to a low carbon electricity supply, and with and without a market for the carbon black by-product.
- Municipal waste or residual biomass production of hydrogen with or without carbon capture and geological storage
- Small-scale steam methane reforming of hydrogen with or without carbon capture and geological storage, and the possibility of purchasing “blue hydrogen credits” from centralized auto thermal reforming plants that will be deployed in Canada in the next few years.
- The use of other low GHG energy carriers (renewable methanol, low-carbon ammonia, biogas from landfills or anaerobic digesters) to make hydrogen

The techno-economic analyses associated with these studies will consider recent policy initiatives like the [Investment Tax Credit for CCS](#), the [clean fuel regulations](#), and the [clean hydrogen investment tax credit](#).

4 TOP-DOWN ESTIMATES OF FUEL HYDROGEN MARKET IN A NET-ZERO FUTURE

4.1 Introduction

In Alberta, the majority of energy use and emissions are associated with oil and gas recovery and processing. Much of the fossil energy recovered in Alberta is exported to other jurisdictions in Canada or the USA as crude oil or natural gas, but some are also processed to produce carbon-intense energy carriers like gasoline, diesel, jet fuel and natural gas consumed in the province.

In this section, we focus on the end-use demand for fossil-fuel-based energy carriers and the potential for hydrogen to be a zero-emission energy carrier in a net zero-emission energy future. Through its Office of Energy Efficiency, Natural Resources Canada maintains a Comprehensive Energy Use Database [2] on the end use of energy and the associated greenhouse gas (GHG) emissions by sector and region of Canada.

When combusted, these energy carriers release carbon dioxide (CO₂) into the atmosphere, a powerful greenhouse gas known to contribute to climate change. That reality has nations and companies worldwide looking for zero-emission alternatives, like electricity and hydrogen, so long as the alternatives are produced with little or no GHG emissions. The shift to a net zero energy system does not necessarily mean the end of Alberta's oil and gas sector, but it would dramatically change the sector by altering how and what energy carriers it produces for domestic and export markets. It could create new opportunities and businesses in evolving clean energy supply chains.

In this section, we quantify the market potential for fuel hydrogen based on the 2019 (pre-COVID) data for the province of Alberta extracted from the Comprehensive Energy Use Database (CEUD) and prorated for the Calgary Region. This assessment is a first look at the region's market potential for fuel hydrogen.

4.2 Transportation

In 2019, energy use by all vehicular transportation in Alberta was 455 Peta Joules (PJ), as summarized in **Table 4.1 (Column A)**. NRCAN consumption data is categorized by various sizes and functions of the vehicle, with the largest shares in transportation being medium (MD) and heavy-duty (HD) at 45% of fuel energy demand, light-duty (LD) vehicles at 35%, and air transport at 9%; the rest is split between rail, buses, and off-road vehicles (**Table 4.1**).

In the transition to net-zero, plug-in battery electric vehicles are typically seen as the technology of choice for personally owned, light-duty vehicles and even for most MD vehicles, but not HD vehicles. Challenges with range, refuelling time, vehicle weight and winter performance have focused the HD vehicle market on hydrogen fuel cell electric (HFCE) vehicles, especially for long haul applications that dominate, especially in Alberta.

Federal government policies have set a target for 2030 whereby 35% of MD and HD vehicles sales are zero-emission (ZEV), and by 2040, nearly 100% of MD and HD sales are ZEV. Since the half-life (i.e., 50% survival rate) for HD vehicles is about 8-10 years, meeting these targets should bring this sector to be near zero GHG emissions by 2050.

Looking at the 2019 transportation demand data for Alberta, not considering future population growth, economic growth or behaviour change over the period to 2050, we generate a low estimate for the potential hydrogen demand in Alberta's transportation sector. However, given that the Calgary Region has 37% of the Alberta population, the provincial number can be prorated for the Calgary Region.

Table 4.1 Calculation of the Possible Fuel Hydrogen Demand for Transportation in a Future Net-Zero Emission Energy System with the Energy Demand of Alberta in 2019.

Transportation			A	B	C	D	E	F	G	H
			PJ hhv/yr	% to H ₂	H ₂ displaces PJ hhv	Rel Effic J H ₂ /J FF	H ₂ Demand: Alberta			Calgary
							PJ/yr	kt H ₂ /yr	t H ₂ /d	t H ₂ /d
1		Cars	41.2	10%	4.12	0.4	1.65	11.6	31.9	11.8
2	LD	Passenger Light Truck	74.2	10%	7.42	0.4	2.97	20.9	57.4	21.2
3	Vehicles	Motorcycles	0.9	5%	0.04	0.7	0.03	0.21	0.59	0.2
4		Freight Light Trucks	42.2	10%	4.22	0.4	1.69	11.9	32.6	12.1
5		School Buses	2.2	10%	0.22	0.59	0.13	0.93	2.55	0.94
6	Buses	Urban Transit	6.8	60%	4.09	0.59	2.41	17.0	46.6	17.2
7		Inter-City Buses	0.8	80%	0.62	0.8	0.50	3.52	9.64	3.57
8	MD trucks	MD Trucks	94.8	20%	18.95	0.85	16.1	114	311	115.2
9	HD Trucks	HD Trucks	111	80%	88.77	0.85	75.5	533	1459	540
10	Rail	Passenger Rail	0.6	50%	0.31	0.55	0.17	1.19	3.26	1.2
11		Freight Rail	25.8	100%	25.80	0.55	14.2	100	274.3	101
12	Air	Passenger Air	40.3	50%	20.14	1	20.1	142	389.4	144
13		Freight Air	0.9	50%	0.43	1	0.43	3.00	8.23	3.05
14	Off road	Off-Road	13.2	50%	6.60	0.85	5.61	39.6	108	40.1
15		Marine	0.0	0%	0.00	0.85	0.00	0.00	0.00	0.0
16	TOTAL		455		182		141	998.4	2735	1012

Footnotes:

A. From Comprehensive Energy Use Database for Alberta in 2019. Transportation Table 7

(https://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/menus/trends/comprehensive_tables/list.cfm)

B. Assumes net-zero Transportation options include battery Electric, Biofuel or Hydrogen fuel cell electric. Percent allocated to hydrogen was based on limitations in biofeedstock availability for and poor fit for service for battery electric.

C. Column A X Column B

D. Estimated efficiency of H₂ fuel cell electric vehicles compared to the incumbent internal combustion engine. Lower values (= improved efficiency) was assigned to vehicles that would benefit from regenerative braking and electric drive. For Air transport, h₂ is assumed to be used in jet engines with similar efficiency to current technology.

E. Column C X Column D

F. Column E ÷ 141.7 TJ hhv/kt H₂ (energy content of hydrogen)

G. Column F ÷ 365 days/yr

H. Column G X 37% (proportion of Alberta population living in Calgary region)

Assuming net-zero transportation options for energy carriers include electric, drop-in biofuels or hydrogen, we allocated a percentage of each vehicle type to hydrogen (**Table 4.1, Column B**). The chosen values ranged from 10% or less (light-duty vehicles, school buses, etc.) to 80% or more (HD trucks and trains). The smaller percentages were

assigned to vehicle types where plug-in electric should be the most competitive, and the higher values were assigned to vehicle types requiring onboard fuel, rapid refuelling, long travel distances and heavy load, but the scale of demand eliminated biofuels as a credible option.

In the bus vehicle class, most school and smaller intercity buses could be BEV, whereas longer haul intercity buses and urban transit buses were projected to be HFCE. Biofuels were projected to be a good fit for up to 50% of air transport and off-road vehicles, with hydrogen accounting for the other 50%.

Applying these assumptions, hydrogen was calculated to displace the diesel energy equivalent values shown in **Table 4.1, Column C**. However, when paired with a fuel cell and electric motor, a hydrogen-fueled vehicle can be significantly more efficient in converting chemical energy into motive force than a diesel-ICE vehicle. Therefore, we defined the term 'Relative Efficiency' to define the joules of H₂ needed to provide the same energy service as a joule of diesel.

A lower number for relative efficiency (in **Column D**) reflects a more efficient hydrogen electric drivetrain of a fuel cell electric engine compared to diesel consumption in an internal combustion engine. The drivetrain advantage tends to be greater when compared to gasoline vehicles or vehicles that stop and go since HFCE can benefit from regenerative braking and no idling. In planes, we assume hydrogen would be combusted in a jet engine similar to jet fuel, so relative efficiency was set to equal one.

Utilizing these transition assumptions and the detailed transport fuel use in 2019, it can be estimated that 40% (or 182 PJ) of transportation demand in Alberta will be satisfied by hydrogen, with the total potential demand for hydrogen being an average of 2,735 t/day (or 998 kt/year). This is equivalent to about half of the current industrial hydrogen production in the province. More than half (53%) of the total potential demand

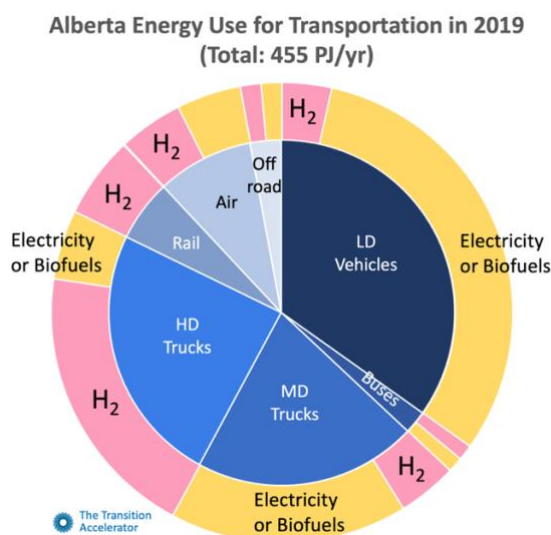


Figure 4.1 The energy use for transportation in Alberta in 2019 (pie chart) and the projected zero-emission fuel alternatives that the authors suggest are most appropriate in a net zero future (doughnut chart).

See [Table 4.1](#) and text for calculations and assumptions.

is generated in HD (Class 8) vehicles; when taken together, MD and HD trucks, trains, air, and buses account for 92% of hydrogen demand. Prorating to a population base of 37% for the Calgary Region, the regional estimate for H₂ use in **transportation is 1,012 t H₂/day**.

Drawing on the discussion in **Section 3.4**, above, and assuming a typical fueling station delivers 7 t H₂/day, the Calgary Region would need 145 fueling stations. Assuming a conservative hydrogen retail price of \$6.50/kg H₂, the 1012 t H₂/day would result in sales of \$2.4 Billion/yr.

4.3 Buildings

Alberta utilized 448 PJ of energy in 2019 for residential and commercial building heating and space and water heating (**Table 4.2**). Of 448 PJ/year, space and water heating (typically provided by natural gas) account for 87% of building energy for residential and 71% for the commercial sector; the remaining balance is for electricity and cooking.

As with the transportation sector discussed previously, the potential for hydrogen use in residential and commercial buildings was estimated using the 2019 energy system, not counting future population growth, economic growth or behaviour change over the period to 2050. However, energy efficiencies due to improved building standards and retrofits of existing buildings could balance population growth. If so, these 2019 estimates may be a reasonable 2050 projection for the energy use by this sector in a business-as-usual energy future.

Table 4.2 Calculation of Possible Fuel H₂ Demand for Building Space & Water Heating in a Future Net-Zero Emission Energy System with an Energy Demand Similar to That of Alberta in 2019.

Buildings		A	B	C	D	E	F	G	H
		PJ hhv/yr	% to H ₂	H ₂ displaces PJ hhv FF/Yr	Rel Effic J H ₂ /J FF	H ₂ Demand: Alberta PJ/yr	kt H ₂ /yr	t H ₂ /d	Calgary t H ₂ /d
1	Space heating	149	75%	112	1	112	791	2166	802
2	Residential Water heating	43.6	75%	32.7	1	33	231	632	234
3	Other	27.9	0%	0.0	-				
5	Space heating	148	75%	111	1	111	785	2151	796
6	Commercial Water heating	12.9	75%	9.66	1	10	68	187	69
7	Other	66.1	0%	0.0	-				
16	TOTAL	448		266		266	1875	5136	1900
Footnotes:									
A. From Comprehensive Energy Use Database for Alberta in 2019. Residential and Commercial Tables 2 (https://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/menus/trends/comprehensive_tables/list.cfm)									
B. NG currently accounts for over 90% of building space and water heating in Alberta. The potential for heat pumps is limited, especially with existing infrastructure, and the repurposing of NG infrastructure to hydrogen seems to be the most credible net zero strategy									
C. Column A X column B									
D. Assumes hydrogen would be combusted with a similar efficiency to natural gas									
E. Column C X Column D									
F. Column E ÷ 141.7 TJ hhv/kt H ₂ (energy content of hydrogen)									
G. Column F ÷ 365 days/yr									
H. Column G X 37% (proportion of Alberta population living in Calgary region)									

In the transition of the building sector to net-zero emission, continued distributed combustion of natural gas will not be possible. Therefore, we considered renewable natural gas made from biological feedstocks, but a quick analysis shows that the province lacks sufficient feedstock to supply this demand without dramatically reducing the biosphere carbon stocks and increasing net GHG emissions.

We also considered using heat pumps, electricity-powered devices that move heat from outside to inside buildings with less energy than that needed to generate heat through electricity or fuel combustion. However, Alberta's cold winter temperatures make air source heat pumps more challenging than more temperate climates. Ground source heat pumps have potential applications in Alberta but are very expensive to install and require land areas that would be challenging for many communities in Calgary. While there is likely to be an increased role for heat pumps in Alberta, widespread uptake would significantly increase demand for zero-emission electricity, especially in the winter months (**Figure 4.2**), when renewables tend to be less available.

While more work needs to be done to explore Alberta's zero-emission space and water heating options, this study assumed 75% of 2019 demand would be met by retrofitting the existing natural gas distribution system for use with hydrogen. This would also require changing the control valves and fuel burners in furnaces and boilers. Such changes have been done in the past in other countries [35], and compared with other retrofit solutions, fuel hydrogen for space/water heating is probably the lowest cost.

In the calculations in **Table 4.2**, we assumed that 75% of the 2019 demand for space and water heating shifts from natural gas to low GHG hydrogen (**Column B**). There would probably be a staged transition to hydrogen for heating, starting with pure hydrogen being mixed (up to 20% v/v) with natural gas at the city's gas 'gates', where high-pressure gas drops to low-pressure for distribution to homes. Once the infrastructure is in place, communities would be switched to hydrogen with a replacement of burner tips, valves, and fittings [35].

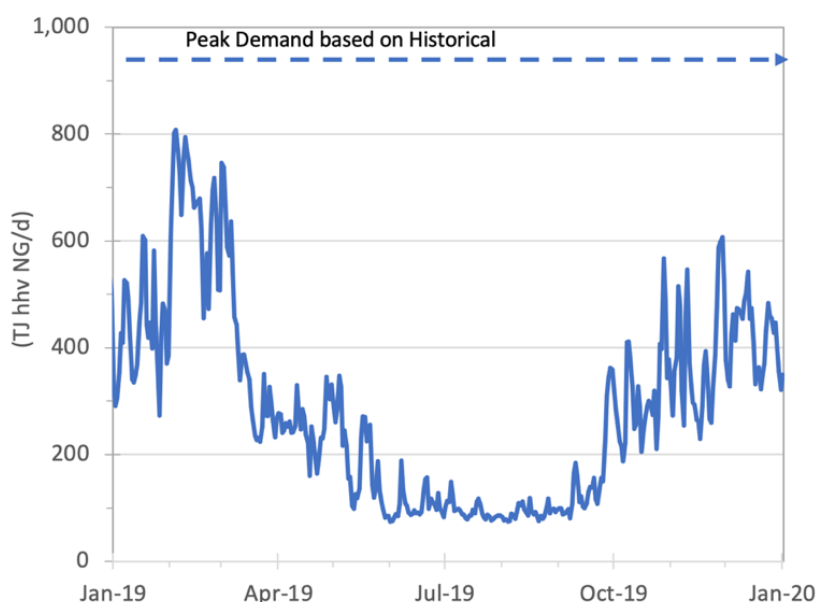


Figure 4.2 Calgary Region NG Demand (Space & Water Heating and Industrial Consumption)

NG demand for power generation excluded. Values from ATCO by scaling from Calgary and Airdrie data.

The relative efficiency for hydrogen in this role is set at 1.0 since hydrogen would be combusted for heat in a similar way to heat energy from natural gas (**Table 4.2, Column D**). As a result, the total estimated hydrogen demand for residential and commercial space and water heating in Alberta is 5,136 t/day (or 1,875 kt/yr), replacing the use of natural gas (**Table 4.2 and Figure 4.3**). As Calgary Region is 37% of Alberta, a regional estimate for hydrogen demand in the residential and commercial sectors is 1,900 t H₂/day (**Table 4.2, Column H**).

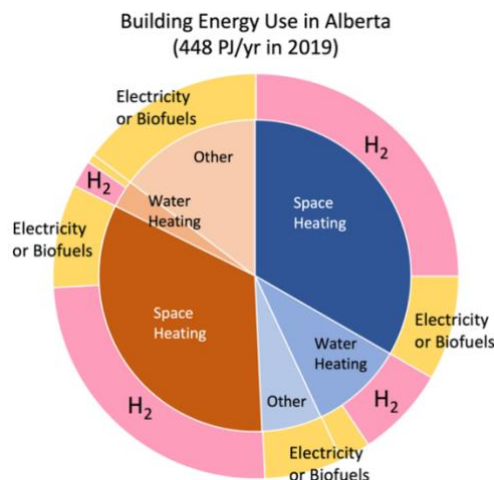


Figure 4.3 Energy use by Residential (blue shaded sections in the pie chart) and Commercial buildings in Alberta in 2019 (pie chart), and the projected zero-emission fuel alternatives that the authors suggest are most appropriate in a net zero future (doughnut chart).

See [Table 4.2](#) and text for calculations and assumptions.

4.4 Electrical Generation

Alberta used 86 terra-watt hours (TWh) of electrical generation in 2021, which represents **310 PJ** of energy consumption where about one-third of the generation is produced and consumed “behind the fence,” and two-thirds is delivered to users via the public grid (**Figure 4.4**). At present, natural gas provides over 75% of the electricity demand in Alberta, but this is rapidly changing and will likely change even more rapidly if the province is to meet federal commitments for a net zero grid by 2035 [36]. In 2021, wind, hydro and solar represented 15% of the generation; and almost 8% is ‘Other’ generation that includes biomass generation and power imports through interties with British Columbia, Saskatchewan, and Montana.

Hydrogen could play an essential role in the transition of Alberta’s electrical grid to zero emissions. First, it could support the build-out of intermittent renewables like wind and solar by providing a lower price for the electricity they generate when it exceeds grid demand. That excess, low-value electricity could be made into hydrogen, supporting the heavy transport sector.

Alternatively, hydrogen can be a zero-emission fuel that can be used to generate baseload power, peak power or combined heat and power.

Power Generation in Alberta (86 TWh/yr or 310 PJe/yr in 2021)

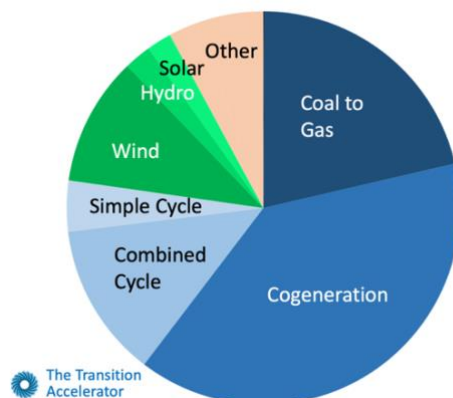


Figure 4.4 Electricity Generation in Alberta in 2021, Attributed to the Conversion Technology.

All blue-shaded technologies are fueled with natural gas. 'Other' includes imported power and biomass generation. Data from Alberta Electrical System Operator (AESO).

As a source of base load power generation, in a province like Alberta with geological resources for carbon capture and storage, there are some promising alternatives to hydrogen use in power generation. For example, carbon capture and storage (CCS) could be added to existing natural gas-fueled combined cycle power plants, and the by-product CO₂ could be permanently sequestered in the sub-surface. Alternatively, natural gas could be combusted with pure oxygen in a new kind of power plant (e.g., net power [37]) that uses the Allam Power Cycle [38]. It produces a pure CO₂ stream that can be sequestered. In many places in Alberta, these technologies should be more cost-effective than using hydrogen as a fuel. However, where geological sequestration is unavailable and low GHG baseload power is needed, hydrogen can be combusted in a combined cycle gas turbine to produce electricity.

As a source of peak power or a backup to intermittent renewables, hydrogen-fueled single-cycle gas turbines or solid oxide fuel cells could provide the necessary electricity. In our calculations, we have assumed that 10% of provincial generation could be served by Peaker Plants using hydrogen (**Table 4.3**).

Thermal demand of Alberta's industrial sector accounts for the large role of cogeneration (e.g., combined heat and power), and it will be challenging to meet this demand in a net-zero future. Post-combustion CO₂ capture and storage could work in facilities close to a geological storage site or pipelines; however other solutions are needed. Small modular nuclear reactors are being considered for deployment [39,40], and hydrogen is a credible option for cogeneration. In our calculations, we have assumed that 20% of electricity from industrial cogeneration could be served by hydrogen (**Table 4.3**).

Based on these assumptions, 93 PJe/yr would be generated yearly from low-carbon hydrogen. Assuming gas turbine technology for Peaker Plants and cogeneration facilities [41,42,43], 3 to 3.3 GJ H₂ would be needed to generate each GJ of electricity (**Table 4.3, Column B**), resulting in a fuel hydrogen demand of 298 PJ H₂/yr that would be required, equivalent to an average demand of 5,757 t H₂/day.

Assuming the Calgary Region generates a population-weighted fraction of that electricity, the hydrogen demand would be 2,130 t H₂/d.

Table 4.3 Calculation of Possible Fuel H₂ Demand for Power Generation in a Future Net-Zero Emission Energy System with a Total Electricity Demand Similar to Present Day.

Power Generation	A	B	C		E	F
	PJe/yr	Conv. Effic. GJ H ₂ / GJ e-	H ₂ Demand: Alberta			Calgary
			PJ H ₂ /yr	kt H ₂ /yr	t H ₂ /d	t H ₂ /d
Peaking to firm intermittent renewables (est. at 10% of Generation)	31	3	93	657	1799	666
Cogeneration (estimated at 20% of generation)	62	3.3	205	1445	3958	1464
Total	93		298	2101	5757	2130
Footnotes:						
A. Based on 310 PJe/yr (86 TWhr/yr) power generation in Alberta in 2021 (from AESO) as per Fig 3.4						
B. Assumes gas turbine peaker generation at 33% efficiency (0.33 GJe / GJ H ₂) and gas turbine cogeneration at 30% efficient for power generation only						
C. Column A X Column B						
D. Column C X 141.7 GJ hhv/t H ₂						
E. Column D ÷ 365 days/yr						
F. Column E X 37% (fraction of Alberta's population in the Calgary Region)						

4.5 Top-Down Summary

Bringing together the calculations from **Tables 4.1, 4.2 and 4.3**, this sums to a total fuel hydrogen potential for the province of 13,629 t H₂/d, of which the population-based allocation for the Calgary Region is 5,043 t H₂/d (**Figure 4.5**).

In the short term (*i.e.*, next decade), transportation markets for fuel hydrogen seem to be the most promising given technology readiness and economics. During this period, many pilots and early demonstration projects to explore hydrogen use for heating applications (space, water, and industrial processes) and power applications are likely to be deployed. Larger-scale commercial deployment of hydrogen for heat and power generation is thought to occur in the mid-2030s, as this will require pipeline delivery of low-cost, low-GHG fuel hydrogen.

Assuming a wholesale price of \$2.50/kg H₂, Alberta's domestic fuel hydrogen market could represent a \$12.4 billion/year economic opportunity.

It is important to note that this estimated demand does not account for the potential use of hydrogen in provincial industrial sectors (e.g., oil and gas, cement, fertilizers, *etc.*), nor does it account for future population or economic growth of the province, or potential for export to other markets, whether to the other Canadian provinces, United States or overseas. Hence, the market size for fuel hydrogen presented here is conservative, especially considering export markets.

Current hydrogen production in Alberta for use as an industrial feedstock has been estimated to be about 5,400 t H₂/d, so that the domestic fuel hydrogen market would be about 2.5 times larger than today's industrial feedstock market. This new market demand for low carbon fuel hydrogen could be supplied by 11 large (about 500 t H₂/day) Autothermal Reformers that would each produce a pure CO₂ stream of 4200 t CO₂/d (1.5 Mt CO₂/yr), requiring a total geological sequestration potential of 17 Mt CO₂/yr.

Total Fuel H₂ Demand Potential

Alberta (AB): 13,629 t H₂/d

Calgary Region (Cal): 5043 t H₂/d

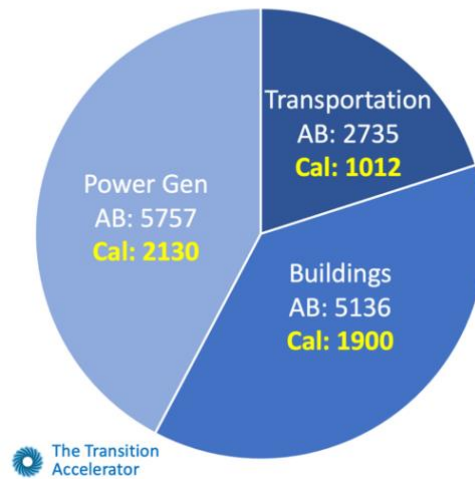


Figure 4.5 Estimate of Potential Domestic Market for Fuel H₂ in Alberta in a Net-Zero Emission Energy Future

Based on the current size of the energy systems in the province. Values from Tables 4.1, 4.2 and 4.3.

Alternatively, to produce just the 2,735 t H₂/day needed for the projected heavy transportation market from water electrolysis (*i.e.*, 'green hydrogen') would require about 52 TWh/year of new generation, equivalent to a 90% increase in the size of the current public electricity grid in Alberta, and all of that generation would need to be with minimal or no GHG emissions. This is why energy systems analysis for regions like Alberta with sizeable natural gas reserves and geological storage capacity see blue hydrogen dominating the fuel hydrogen market.

5 CITY OF CALGARY-OWNED INFRASTRUCTURE

5.1 Introduction

In the transition to a future, net-zero emission energy system, **Section 4** of this report made a case that the Calgary Region has the potential to use over 5,000 t H₂/day. While most of this regional demand will be associated with energy use by individuals and corporations [44], municipalities are also major energy users, often seen as ideal ‘early adopters’ for a new fuel hydrogen economy. This is especially true in regions that see opportunities for economic development and new market opportunities.

In November 2021, the City of Calgary declared a Climate Emergency [45], and in July 2022, the city council [approved their Climate Strategy](#) that included a commitment to achieve net zero emissions by 2050. With such a commitment, the City of Calgary has the potential to be an early adopter of fuel hydrogen in four areas where the city has the infrastructure and uses energy. These will be considered in the following sections.

5.2 Municipal Transit

In 2019 (pre-COVID), Calgary Transit had 1024 buses that consumed 23 million L (ML) of diesel (**Table 5.1, Column C**), 3.4 ML of gasoline (**Table 5.1, Column D**) and 1.3 ML–diesel equivalent (ML-de) of compressed natural gas (CNG, **Table 5.1, Column E**). Note that 2019 was the first year for CNG buses in the city fleet, and CNG consumption in 2021 was 2.1 times the amount used in 2019.

The energy embedded in the transportation fuel supplying these buses totalled 1045 TJ_{h_hv}/yr (**Table 5.1, Column I**). In the transition to a net zero future, some of these buses will be plug-in electric and others (the larger vehicles travelling longer distances) will be hydrogen fuel cell electric (HFCE). For more than 50% of the vehicles projected to transition to HFCE (**Table 5.1, Column J**), the drive train efficiency improvements (**Table 5.1, Column L**) result in a fuel hydrogen demand of only 322 TJ_{h_hv}/yr, equivalent to 6.2 t H₂/d. (**Table 5.1, Column O**).

To manage the changes in the transit fleet, the City of Calgary will need to construct and operate hydrogen fueling infrastructure. This would likely occur at one or more of the existing Calgary Transit garages. The location of the Calgary Transit bus garages, as shown in **Figure 5.1**, are along major traffic corridors, except for the Victoria Park garage (#3). The Stoney garage (#1) is located near the Stoney Trail and Deerfoot Trail intersection in NE Calgary. With its CNG fueling capabilities, it may be a natural choice for a hydrogen fueling station. Likewise, the Spring Gardens garage (#2) is located very close to Deerfoot Trail and 32nd Avenue NE, which is along a primary traffic corridor. Finally, the Anderson garage (#4) is located in the City’s SW and serves as both a transit bus garage and a large LRT station. Future construction of hydrogen pipelines may be possible along these major traffic corridors if the City has sufficient Right of Way access and land ownership.

Table 5.1 Estimate of Fuel H₂ Demand for Transit Buses in the City of Calgary Should the 2019 Fleet Transition to Net Zero.

#	A Transit Fleet	B # Buses	C Fuel use (ML or ML-de/yr)			F Fuel Use (TJ hmv/yr)				J Share to H ₂	K # H ₂ Buses	L Rel Effic J H ₂ /J	M Total Fuel H ₂ demand		
			Diesel	Gasoline	CNG	Diesel	Gasoline	CNG	Total				TJ _{hmv}	kt H ₂ /y	t H ₂ /d
1	Standard 40'	746	18.9	-	1.3	731	-	52.0	783	60%	448	0.53	249	1.76	4.82
2	Articulated 60'	95	3.2	-	-	123	-	-	123	100%	95	0.53	65.2	0.46	1.26
3	Shuttle buses	183	0.6	3.4	-	23.7	116	-	139	10%	18	0.53	7.4	0.05	0.14
4	TOTAL:	1024	22.7	3.4	1.3	878	116	52.0	1045	-	561	-	322	2.27	6.22

Footnotes

1. Total fleet of 746 40 foot buses. A 40 foot H₂ bus would carry 37.5 kg of H₂, but typically use about 20-25 kg H₂/d

2. Total fleet of 95 60 foot, articulated buses. A similar H₂ bus would carry about 60 kg of H₂, but typically use about 30 to 35 kg H₂/d

3. Total fleet of 183 community shuttles, each with a capacity of up to 20 riders. Most are likely to be plug-in electric.

A to E: Data provided by City of Calgary

F to H. Calculated from Columns B to D using energy contents of 38.6 MJ hmv/L for diesel or Diesel equivalent(de) and 34.2 MJ/L for gasoline.

I: Sum of Column F to H.

J. Assumptions based on a fleet transition study completed for the City of Edmonton by Zen Clean Energy Solutions in 2022.

K. Column B * Column J.

L. From Barclays Official California Code of Regulations (Westlaw, 2022)

M. Calculated from Column I X Column J X Column L.

N. Column M divided by 141.7 TJhmv H₂/kt

O. Column N * 1000/365 days/ year.

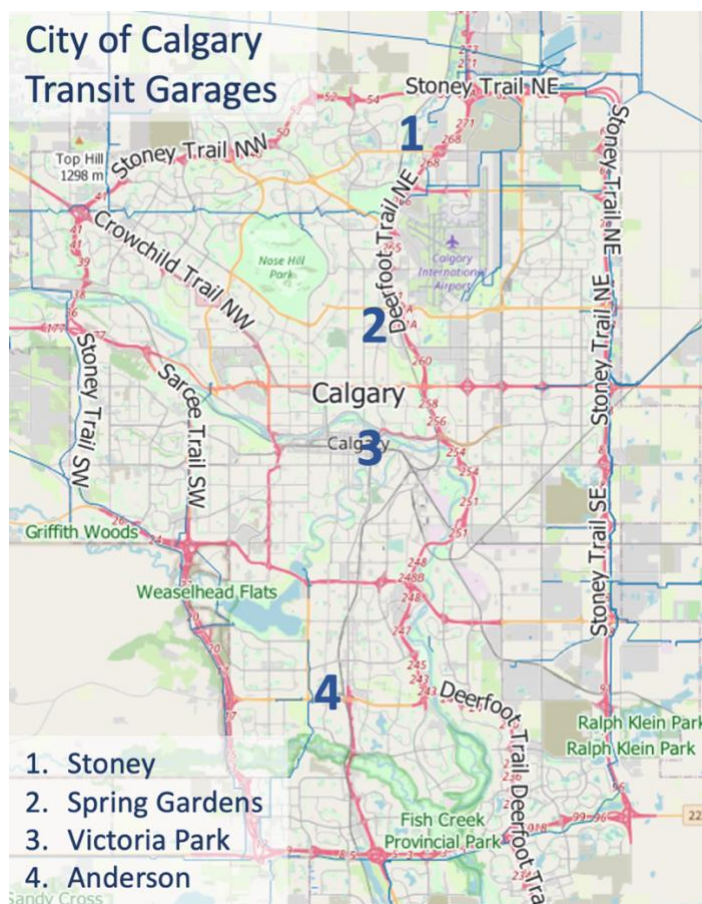


Figure 5.1 Location of Calgary Transit Garage, Fueling and Maintenance Facilities.

5.3 Other Municipal Vehicles

The City of Calgary owns another 3929 vehicles that used 699 TJ_{hvh} of diesel and gasoline fuel in 2019 (**Table 5.2, Columns A to F**), not counting police and fire services. Of this total, there are 1037 heavy-duty vehicles such as gravel trucks, graders, waste and recycling trucks, and road cleaning and repairing units. In addition, the fleet also includes 1798 light-duty vehicles and 1094 motorized/specialized equipment pieces. While we did not receive a breakdown of types of trips or distance (km) travelled per year, the vehicle numbers and average fuel use suggest that their fuel requirements per vehicle are low compared to the bus fleet. Consequently, we assumed that most vehicle types could transition to battery electric in a net zero-emission future.

However, some heavy-duty vehicles and those requiring long service hours (e.g., snowplows and garbage trucks) may benefit from HFCE drivetrains. Here we assume that 30% of the energy needs for these non-transit vehicles transition to HFCE vehicles (i.e., typically those vehicles that drive longer distances and/or carry a heavier load and require rapid refuelling).

Table 5.2 summarizes the findings. Using the 2019 data, an assumption on the share of hydrogen and relative efficiency, fuel hydrogen demand for other non-transit city-owned vehicles could amount to 3.5 t H₂/day.

Figure 5.2 provides a summary figure showing the proportion of the 2019 transportation fuel use that could be displaced by hydrogen. Considering the efficiency improvements of fuel cell electric drive vehicles compared to internal combustion engine vehicles, the total hydrogen demand was projected to be 9.7 t H₂/day.

Table 5.2 Estimate of Fuel Hydrogen Demand for Non-Transit, City of Calgary Vehicles in 2019.

Assuming a transition to net zero GHG emissions. Vehicles belonging to Calgary Police and Fire Services are not included.

A	B	C	D	E	F	G	H	I	J	K
# Veh	Fuel use (ML/yr)		Fuel use (TJ _{hvh} /yr)			Share	Rel Effic	Total Fuel H ₂ demand		
	Diesel	Gasoline	Diesel	Gasoline	Total	to H ₂	J H ₂ /J FF	TJ _{hvh} H ₂ /yr	kt H ₂ /yr	t H ₂ /d
3929	11.4	7.62	439	261	699	30%	0.86	180	1.27	3.49
Footnotes										
A to C: Data provided by City of Calgary. Count excludes Calgary transit, police and fire department vehicles										
D & E. Calculated from Columns B to C using a energy content of 38.6 MJ _{hvh} /L for diesel and 34.2 MJ _{hvh} /L for gasoline.										
G. Assumes only larger vehicles with extensive use										
H. Estimated for HD vehicles on longer trips (not stop and go). Other vehicles would be plug in battery electric										
I. Column F * Column G * Column H.										
J. Column I divided by 141.7 TJ _{hvh} H ₂ /kt										
K. Column J * 1000/365 days/year										

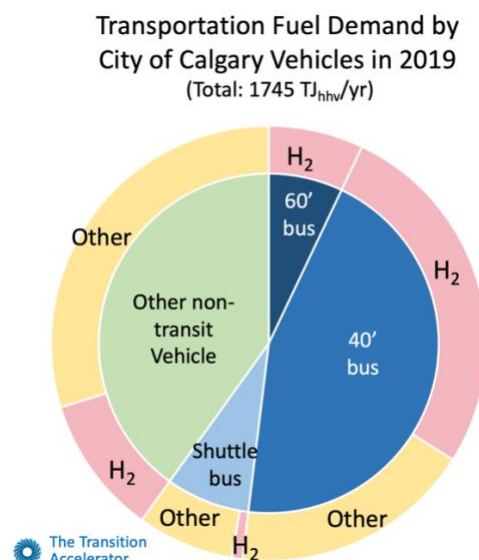


Figure 5.2 Summary of Fuel Use by City of Calgary Vehicles in 2019.

Pie chart (total 1745 TJ_{hhv}/yr) and our estimate of the proportion for which hydrogen (red shading in doughnut chart) could be the zero-emission fuel of choice in a net zero future. 'Other' zero emission fuels (yellow shading in doughnut chart) include electricity and biofuels.

5.4 Natural Gas & Electricity Demand for Built Spaces

The City of Calgary also uses large amounts of natural gas and electricity within its built spaces. In 2019, natural gas (1876 TJ_{hhv}/yr) and electricity use (1768 TJe/yr) by the City were similar to the levels of City-owned transportation (1745 TJ_{hhv}/yr). **Figure 5.3** summarizes the major City-owned facilities that are responsible for this energy use.

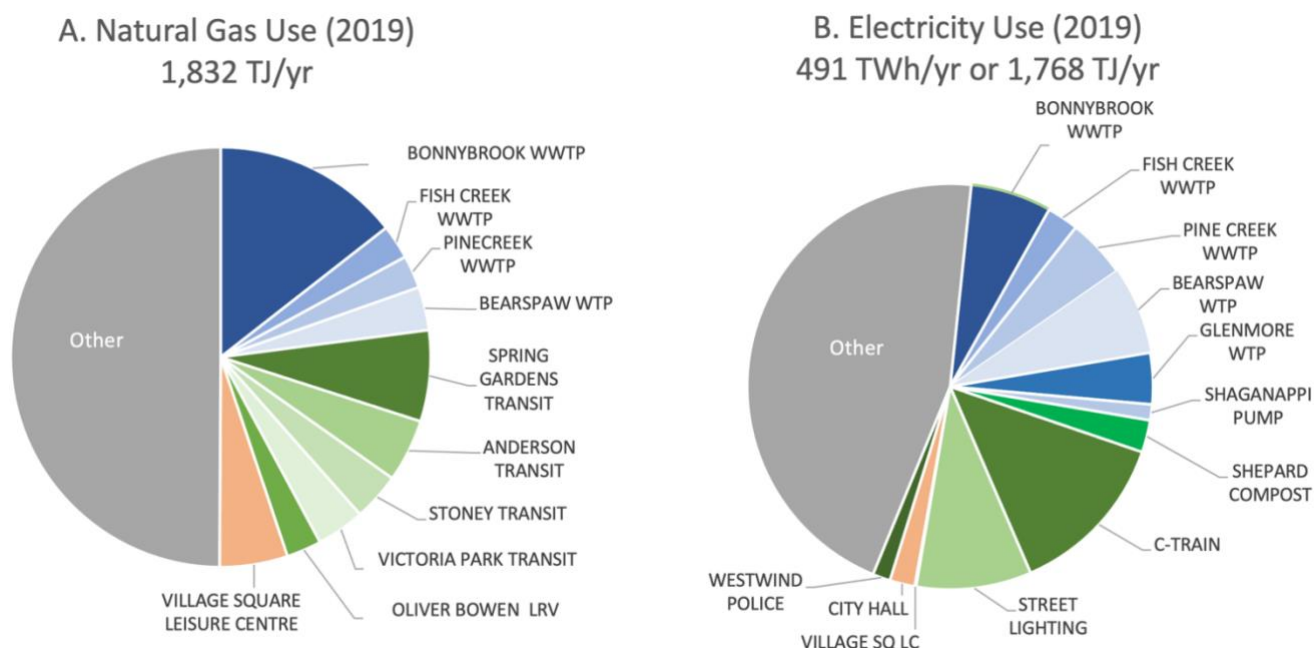


Figure 5.3 Natural Gas (A) and Electricity (B) Use by City of Calgary Owned Infrastructure in 2019.

Data from the City of Calgary.

For electricity demand, the City's water and wastewater treatment facilities draw the most power (**Figure 5.3B**) and are also major natural gas users (**Figure 5.3 A**). In addition, the C-Train and street lighting have significant demands for electricity. On the natural gas side, Calgary's transit facilities collectively use the most gas, followed by the water and wastewater treatment facilities.

The largest single-demand location for natural gas is the Bonnybrook Wastewater Treatment facility, followed by the Spring Gardens Transit garage. The wastewater and water treatment facilities and the transit garages collectively consume 43.5% of the City's natural gas use annually. The other large stand-alone structure, the Village Square Leisure Centre, is also a significant demand source, consuming 5% of the City's total natural gas demand.

In **Figure 5.2B**, the wastewater and water treatment facilities represent a large collective demand (26%) for electricity amongst City-owned infrastructure, followed by the C-train and street lighting.

In the transition to net-zero emission energy systems, low GHG fuel hydrogen could provide an alternative to natural gas use, especially for space and water heating. Hydrogen can also be a fuel for combined heat and power generation and help to decarbonize electricity demand by City-owned infrastructure. Both options are explored here.

In a net zero emission energy future, regions with cold winter temperatures and that lack large hydropower reservoirs that can store electricity for winter heating may need to use hydrogen for space and water heating. In this case, the natural gas distribution system in cities would be repurposed to deliver hydrogen to each building, a concept that is being explored in the H21 project [46] and in the UK Hydrogen for Heat initiative [35].

However, prototyping and testing hydrogen for space and water heating will be needed, and municipal buildings are ideal for this purpose. Larger buildings with substantial heat demand (ideally year-round) that are near pipeline corridors or hydrogen fueling stations would be desirable.

The City of Calgary owns and provides natural gas for space and water heating in many buildings, but the ten most significant fuel users account for almost half (49%) of the total natural gas demand by the City of Calgary infrastructure. For example, of the 1832 TJ_{hvh}/yr of natural gas (NG) demand in City buildings, the 10 largest facilities use 895 TJ_{hvh} NG/yr (**Table 5.3, Column C**) and include:

- Three waste-water treatment facilities
- One water treatment facility
- Four transit bus garages
- One light rail maintenance facility
- A recreational center

Assuming, like natural gas, the hydrogen is combusted to deliver heat energy, only the fuel's lower heating value (lhv) can be accessed. With this adjustment, an estimated 954 TJ_{hvh} H₂/yr would be required to provide heat energy for the City-owned facilities with the largest natural gas demand (**Table 5.3, Column E**). This is equivalent to 18.4 t H₂/day (**Table 5.3 column G**), or about twice the projected hydrogen demand for City-owned vehicles.

Table 5.3 Estimate of H₂ Required to Displace NG for Space & Water Heating in City of Calgary Owned Buildings.

#	A Top Ten NG Consuming Facilities	B C Natural gas use		D E F G Hydrogen Use			
		TJ _{h_hv} /yr	TJ _{l_hv} /yr	TJ _{h_hv} /yr	TJ _{h_hv} /yr	kt H ₂ /yr	t H ₂ /d
1	BONNYBROOK WWTP	271	244	244	289	2.0	5.6
2	FISH CREEK WWTP	49	45	45	53	0.4	1.0
3	PINE CREEK WWTP	47	43	43	51	0.4	1.0
4	BEARSPAW WTP	63	56	56	67	0.5	1.3
5	SPRING GARDENS TRANSIT	131	119	119	140	1.0	2.7
6	ANDERSON TRANSIT	91	82	82	97	0.7	1.9
7	STONEY TRANSIT	25	22	22	26	0.2	0.5
8	VICTORIA PARK TRANSIT	70	63	63	74	0.5	1.4
9	OLIVER BOWEN LRV	50	45	45	54	0.4	1.0
10	VILLAGE SQ LEISURE CTR	98	89	89	105	0.7	2.0
11	Sub-Total	895	808	808	954	6.7	18.4
12	OTHER	936	845	845	998	7.0	19.3
13	Total Municipal Demand	1832	1653	1653	1951	13.8	37.7

Footnotes:

7. Stoney Transit NG demand is for Space and Water Heating (not for bus fueling)

A-B. Data from City of Calgary (<https://data.calgary.ca/Environment/Primary-Natural-Gas-Usage/s5g9-8sgf>)

C. Column B times ratio of LHV:HHV for natural gas (0.9023)

D. Set equal to Column C

E. Column C ÷ ratio of LHV:HHV for hydrogen (0.8469)

F. Column E divided by energy content of H₂ (141.7 TJ_{h_hv}/kt H₂)

G. Calculated as Column F * 1000 ÷ 365 days / year

Cogeneration with Hydrogen to Produce Low GHG Heat and Power

Municipal buildings also consume significant amounts of electricity delivered from Alberta's public grid, which is known to have a high carbon intensity (about 680 kg CO₂e/MWh in 2019 [47]). Therefore, to decarbonize the City's buildings, there is the potential to use fuel hydrogen with a cogeneration unit to meet the heat and electricity requirements of municipal buildings.

Table 5.4 provides a calculation of the hydrogen demand scaled to meet the heat requirements of the ten City of Calgary facilities with the largest natural gas consumption. In these calculations, we assumed that the heat requirements were similar in all months of the year and, therefore, not tied to space heating (note: further work would be required to assess whether this assumption is valid). In addition, the cogeneration unit was assumed to be a reciprocal engine that rotates a generator to make electricity (efficiency: 40% of fuel higher heating value), and the water supplied to cool the engine is used to meet the heating requirements (efficiency: 40% of higher heating value), resulting in an 80% (h_hv) efficiency.

For the 10 buildings, the annual natural gas heat and grid electricity demand is 895 TJ_{h_hv} NG/yr and 310 TJ_{h_hv} electricity/yr, respectively (**Table 5.4, Columns B and C**). To meet that heat demand using a cogeneration unit, the natural gas demand would double to 1791 TJ_{h_hv} NG/yr (**Table 5.4, Column D**), but some heat would be lost in the flue gas, and only about 1661 TJ_{h_hv} heat/yr (**Table 5.4, Column E**) would be useful. However, if that useful heat was provided by hydrogen, more fuel would be required because when hydrogen burns, there is more water vapour/lost

heat in the flue gas compared to natural gas, resulting in a hydrogen requirement estimate of 1908 TJ_{hhv} H₂/yr (Table 5.4 Column G), equivalent to 34.6 t H₂/day (Table 5.4, Column I).

Table 5.4 Calculation of H₂ Demand for Cogeneration from City of Calgary's Largest NG Demanding Facilities Where Cogeneration Is Scaled for Heat Demand.

The calculation assumes useful heat and electricity recovery of 40% and 40% of the higher heat value of natural gas, respectively.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
	Top Ten NG Consuming Facilities	NG use	Power use	NG use in Cogen		H2 use in Cogen				Power Generation from Cogen				LC GHGs	CI-power	CI-thermal
				Fuel NG	Heat	Heat	Fuel H2		electricity							
#		TJ _{hhv} /yr	TJ _e /yr	TJ _{hhv} /yr	TJ _{hhv} /yr	TJ _{hhv} /yr	TJ _{hhv} /yr	kt H ₂ /yr	t H2/d	TJ _e /yr	GWhe/yr	MWe Cap	% demand	kt CO2e/yr	kg CO ₂ /MWh	kg CO2/GJ
1	BONNYBROOK WWTP	271	114	542	489	489	577	3.8	10.5	217	60.2	7.6	190%	5.7		
2	FISH CREEK WWTP	49	45	99	89	89	105	0.7	1.9	40	11	1.4	89%	1.0		
3	PINE CREEK WWTP	47	83	95	86	86	101	0.7	1.8	38	11	1.3	46%	1.0		
4	BEARSPAW WTP	63	2	125	113	113	133	0.9	2.4	50	14	1.8	2475%	1.3		
5	SPRING GARDENS TRANSIT	131	18	263	237	237	280	1.9	5.1	105	29	3.7	570%	2.8		
6	ANDERSON TRANSIT	91	15	181	164	164	193	1.3	3.5	73	20	2.6	476%	1.9	37	13
7	STONEY TRANSIT	25	6	49	45	45	53	0.3	1.0	20	5	0.7	331%	0.5		
8	VICTORIA PARK TRANSIT	70	12	139	125	125	148	1.0	2.7	56	15	2.0	470%	1.5		
9	OLIVER BOWEN LRV	50	13	101	91	91	107	0.7	1.9	40	11	1.4	314%	1.1		
10	VILLAGE SQUARE LC	98	1.9	197	177	177	209	1.4	3.8	79	22	2.8	4207%	2.1		
12	Total Municipal Demand	895	310	1791	1616	1616	1908	12.6	34.6	716	199	25.2	231%	19.0		
Footnotes:																
B. From Column B in Table 4.3																
C. Data from City of Calgary Portal. https://data.calgary.ca/Environment/Primary-Electricity-Usage/aphy-m9us																
D. Column B X 2.0 which is the ratio of assumed boiler efficiency for heat recovery (80% of hhv) : cogen efficiency for heat recovery (40% of hhv)																
E. Column D X ratio of LHV:HHV for natural gas (0.9023)																
F. Set as equal to Column E																
G. Column F ÷ ratio of LHV:HHV for hydrogen (0.8469)																
H. Column G divided by Hydrogen higher heat value of 141.7 GJ/kt H2.																
I. Column E times 1000 divided by 365 days per year.																
J. Column D X 40% energy recovery as electricity																
K. Column J divided by 3.6 TJ/GWh.																
L. Column K divided by 7884 hours per year. Assumes a 90% Capacity Factor.																
M. Column J ÷ Column C. Cigeneration expressed as percentage of facility demand																
N. Column H X 1.5 kg CO2/kg H2. Aassumes H2 production via autothermal reforming with CCS to give 0.5 t CO2/t H2, and upstream CH4 emissions reduced to 1 tCO2/t H2, equivalent to a 1% NG leak rate on recovery and processing.																
O. Carbon intensity of Power Generation. (Column N * 1000) ÷ Column K X (25% ÷ (40%+25%))																
P. Carbon intensity of heat production. (Column N * 1000) ÷ Column B X (40% ÷ (40%+25%))																

While that is considerably more than the 18.4 t H₂/day needed for a simple replacement of natural gas for heating (Table 5.3, Column G), the cogeneration unit also produces 199 GWh/yr of low GHG electricity (Table 5.4, Column K). The electricity generated can meet 231%, on average, of the annual demand of these buildings for power (Table 5.4, Column M). The life cycle carbon intensity of the produced electricity was estimated to be 37 kg CO₂e/MWhr (Table 5.4, Column O), while the heat provided by this system was estimated to have a carbon intensity of 13 kg CO₂e/GJ (Table 5.4, Column P).

The wastewater treatment facilities in the City of Calgary showed a reasonably good balance between their heat and power demand for deployment of a hydrogen-fueled cogeneration system, so such units may be worth exploring with these facilities. Figure 5.4 shows the location of three wastewater facilities in the City. They are along the Bow River and close to the Highway 2/Deerfoot Trail corridor. These facilities could help to anchor a north/south hydrogen distribution system that would also serve fueling stations for bus and heavy transport.

Location of Wastewater Facilities in the City of Calgary



Figure 5.4 Potential Sites for H₂ Cogeneration Facilities in Calgary Wastewater Treatment Facilities.

6 THE CALGARY INTERNATIONAL AIRPORT

6.1 Introduction

The Calgary Region is home to the Calgary International Airport, commonly referred to as YYC. On an annual basis, the Airport receives 18 million passengers and 4,305 cargo landings (2019) [20]. YYC has recently issued its Sustainability Strategy [48] that commits it to Net-Zero Scope 1 & 2 GHG emissions by 2050, with an 18% reduction over 2018 baseline Scope 1 & 2 emissions by 2025. As part of its strategy to reduce GHG emissions and energy use, YYC is focusing on low-carbon fleets and fuels.

The Airport is viewed to be a potential early adopter of hydrogen in the concentrated demand areas of transportation, space and water heating and electricity generation.

It is also advantageously located – near provincial Highway 2 and the Stoney Ring Road (Highway 201) – where potential exists to attract infrastructure that can support return to base operations and vehicles travelling on the corridor to Edmonton and the east-west corridor linking Winnipeg to Vancouver.

In this section, the pre-COVID (2019) energy use at the Calgary airport will be used to estimate the potential market opportunity for fuel hydrogen to meet the transportation (ground and air), space and water heating and electricity needs of the airport.

6.2 Airport Transportation

Ground Vehicles. At the Calgary International Airport, fleets of ground vehicles are owned and operated by the airport itself and by the FSM Group on behalf of some airlines.

Over the year, these ground vehicles consumed 4.26 ML/yr of gasoline and diesel fuel (**Table 6.1, Column B**), equivalent to 156 TJ_{hhv}/yr (**Table 6.1, Column C**), and generating life cycle GHG emissions of about 11 kt CO_{2e}/yr (**Table 6.1, Column D**).

Assuming all these vehicles transition to fuel hydrogen-supporting fuel cell electric (HFCE) vehicles, the fuel H₂ demand was estimated to be 87.4 TJ_{hhv}/yr (**Table 6.1, Column G**). The lower fuel energy demand for these vehicles compared to the existing gasoline and diesel vehicles can be attributed to the more efficient fuel cell electric drivetrain in HFCE than what is found in Internal Combustion Engine (ICE) vehicles. A Relative Efficiency of 0.56 was assumed here (**Table 6.1, Column F**) since many of the ICE ground vehicles idle between periods of use, and that is a condition where electrical drivetrains have a significant advantage. Electric vehicles also can use regenerative braking, a major benefit in the stop-and-go movements of airport ground vehicles.

Using these assumptions, the ground vehicles at the Calgary airport were projected to use an average of about 1.7 t H₂/day (**Table 6.1, Column I**). If that hydrogen is produced from natural gas with autothermal reforming coupled to CCS, and government programs to dramatically reduce upstream methane emissions to <1% are successful, the life cycle GHG emissions would be 0.93 kt CO₂e/yr, equivalent to a 92% reduction (**Table 6.1, Column J and K**).

It is essential to note the seasonal variation in fuel use by ground transportation. For example, the current monthly fuel use for ground vehicles in the winter is more than twice that in the summer, so sizing a hydrogen fueling station for the airport would need to take that into consideration.

Table 6.1 Transportation Fuel Demand at the Calgary International Airport in 2019.

Including that for ground vehicles (Rows 1-7), jet fuel for planes (Row 8), and a proposed passenger train to Banff (Row 9). These values were used to estimate the fuel hydrogen demand and greenhouse gas (GHG) reductions in a zero-emission energy system.

Item #	A YYC Vehicles	B Fuel Use ML/yr	C TJ _{hwh} /yr	D FF GHGs kt CO ₂ e/yr	E Share to H ₂	F Rel Effic J H ₂ /J FF	G TJ _{hwh} /yr	H H demand kt H ₂ /yr	I t H ₂ /d	J GHGs ktCO ₂ e/yr	K GHG Red'n ktCO ₂ e/yr
1	FSM Group Vehicles										
2	Gasoline	1.64	56.02	3.78	100%	0.56	31.4	0.221	0.61	0.33	3.45
3	Diesel	1.80	69.65	5.05	100%	0.56	39.0	0.275	0.75	0.41	4.64
4	Airport owned vehicles										
5	Gasoline	0.21	7.10	0.48	100%	0.56	4.0	0.028	0.08	0.04	0.44
6	Diesel	0.61	23.36	1.69	100%	0.56	13.1	0.092	0.25	0.14	1.56
7	Ground Veh. Demand:	4.26	156	11.0			87.4	0.617	1.69	0.93	10.08
8	Jet fuel uploaded to planes	656	24844	1685	100%	1	24844	175	480	263	1422
9	Passenger Train to Banff								4.06		
10	Total Fuel H₂ Demand:								486		

Footnotes

B. Data provided by Calgary Airport and FSM groups.

C. Column B X 34.2 (gasoline) or 38.6 (diesel) MJ_{hwh}/L or 37.9 (jet fuel) MJ_{hwh}/L

D. Column B X combustion emissions (2.3, 2.8, 2.6 kt CO₂e/ML for gasoline, diesel, jet fuel, respectively) X 1.40 to account for upstream emissions. Emission factors from <https://open.alberta.ca/dataset/2a41f622-5ae4-4985-838f-497e6afd110c/resource/0ba7b3dc-0658-43dc-b977-4c9c35637f49/download/aep-carbon-offset-emissions-factors-handbook-v-2-2019-11.pdf> and <https://ihsmarkit.com/products/energy-industry-oil-sands-dialogue.html?ocid=cera-osd:energy:print:0001>

E. The need for most vehicles operate long days and refuel quickly increases role for hydrogen. We have assumed 100% transition to H₂ in net zero future

F. H₂ fuel cell vehicles have better drive train efficiency when idling and in stop and go traffic; for jet planes, the H₂ is assumed to have a similar efficiency to jet fuel in a jet engine

G. Column C X column D X Column E

H. Column F ÷ 141.7 MJ_{hwh}/kg H₂

I. Column H X 1000 ÷ 365 d/yr

J. Column H X 1.5 ktCO₂e/kt H₂. (assumes autothermal reforming with CCS to give 0.5 t CO₂/t H₂, and upstream CH₄ emissions reduced to 1 tCO₂/t H₂, equivalent to a 1% NG leak rate on recovery and processing).

K. Column D - Column J

9. Proposed new passenger train. Assumes 1.95 kg H₂/km X 260 km/round trip/day X 8 round trips/day (M Demisse, pers Comm)

Airplanes. Hydrogen, especially cryogenic liquid hydrogen, is being explored as a zero-emission fuel for air transport [49,50,51] because of its high gravimetric energy density (i.e., 142 MJ_{hwh}/kg H₂), which is about 3.1 times higher than diesel (45.6 MJ_{hwh}/kg diesel). However, the volumetric energy density of liquid hydrogen (10 MJ_{hwh}/L) is only about 26% of the volumetric energy of diesel (38.3 MJ_{hwh}/L). Therefore, hydrogen-fueled planes of the future could be larger but lighter than the planes in use today.

Planes being used for fewer passengers and shorter distances would likely use propellers, with hydrogen-powered fuel cells providing electric propulsion to turn the propellers. Larger planes, especially for long-distance flights, could burn hydrogen in jet engines [52].

Pre-COVID (2019) jet fuel use at the Calgary airport was 656 ML/year (**Table 6.1, Column B**), equivalent to 24,844 TJ_{h_hv}/yr (**Table 6.1, Column C**). Therefore, life cycle emissions associated with the production and combustion of these fuels is about 1,685 kt CO₂e/yr (**Table 6.1, Column D**).

Assuming hydrogen replaces jet fuel as the zero-emission aviation fuel of the future, and it has the same efficiency in energy use per km travelled, the airport would need 480 t H₂/day (**Table 6.1, Column I**), 285 times more than that needed by the ground vehicles. The life cycle emissions associated with this hydrogen production were estimated to be 263 kt CO₂e/year, resulting in GHG reductions of 1422 kt CO₂e/yr (**Table 6.1, Column K**) or 84%.

Note that this estimate for fuel hydrogen demand is higher than that projected for all Alberta air transportation, as shown in **Table 4.1 (Column G, Row 12+13)**. The difference is partly due to the fact that **Table 4.1** assumed that only 50% of the jet fuel would be replaced by hydrogen (compared to 100% here). In addition, the jet fuel demand in **Table 4.1** is only for domestic aviation, whereas the values presented in **Table 6.1** include fuel used for domestic and international flights.

Despite this considerable market potential for hydrogen-fueled airplanes, technologies are not yet ready for widespread deployment. A key issue is the availability of fuel at airports around the world. That will probably begin with fuel hydrogen supplying ground vehicles and perhaps airport heat and power generation. Once the fuel hydrogen is available at airports, planes could tap into/expand that infrastructure to access zero-emission hydrogen as jet fuel.

In the meantime, 'drop-in' bio-based jet fuel can play an essential role in the decarbonization of air travel, and it is worth noting that hydrogen can play a critical role in the production of this fuel, either by hydrogenation of plant and animal fatty acids or in helping to upgrade/refine syngas produced from the gasification of lignocellulosic biomass (e.g. wood and straw).

Trains. To reduce the GHG emissions associated with visitors travelling to the Banff National Park, two passenger trains have been proposed to run from the Calgary airport through downtown Calgary and then on to Cochrane, Canmore, and Banff, a distance of about 130 km each way.

While funding for these trains has not yet been approved, there have been discussions that the train could be fueled by hydrogen [53] fuel cells. The Calgary airport would be an ideal place to refuel the train. Preliminary estimates of fuel use are provided in **Table 6.1, Row 9**, at 4.06 t H₂/day.

6.3 Space & Water Heating

The YYC's energy demand for space and water heating is met by natural gas delivered to the Airport by the ATCO system that delivers gas throughout the City of Calgary. **Figure 6.1** provides the monthly demand for natural gas (NG) at the Airport in 2019. In the winter months, demand can be up to 65 TJ_{h_hv} NG per month, but this drops to only about 10.6 TJ_{h_hv}/month in the summer (**Table 6.2, Column C**). Averaged over a year,

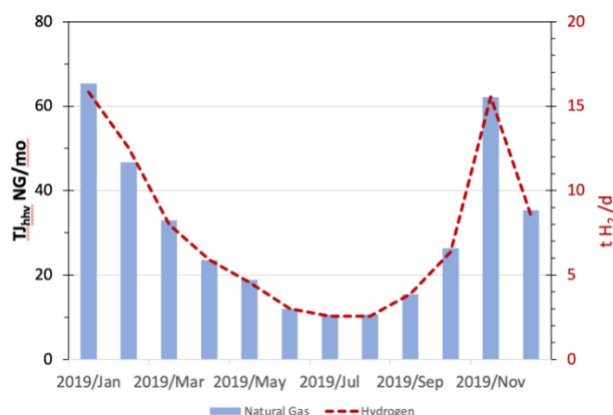


Figure 6.1 Monthly NG Demand for Space & Water Heating at the Calgary International Airport in 2019 (bars) and the Estimate of Fuel H₂ Demand in a Zero-Emission Energy System (dashed line).

the NG use contributes about 21.4 kt CO₂/yr in life cycle emissions to the atmosphere (Table 6.2, Column D).

In a net-zero emission future, zero-emission energy carriers will be needed to provide space and water heating. Electricity made without GHG emissions could provide the energy, but this would be particularly challenging in Alberta, which is struggling to find zero-emission sources of electricity to meet its current needs. Also, the peak in demand coincides with the time of year when renewables are least available. Moreover, seasonal electricity storage is expensive.

Table 6.2 Natural Gas Demand for Space & Water Heating at the Calgary International Airport in 2019.

And the estimate of fuel hydrogen demand and greenhouse gas (GHG) emission reductions in a zero-emission energy system. Note seasonal variation (Row 2 and 3).

Item #	A Calgary Airport NG demand for space & water heating	B NG Use TJ _{hhv} /yr	C NG Use TJ _{hhv} /mo	D NG GHG kt CO ₂ e/yr	E Share to H ₂	F H ₂ demand TJ _{hhv} /yr	G H ₂ demand TJ _{hhv} /mo	H H ₂ demand kt H ₂ /yr	I H ₂ demand t H ₂ /d	J GHGs ktCO ₂ e/yr	K GHG Red'n ktCO ₂ e/yr
1	Average Annual	360	30.0	21.4	100%	383	31.9	2.70	7.5	4.1	17.3
2	January average	-	65.4	-	100%	-	69.5	-	16.4	-	-
3	August average	-	10.6	-	100%	-	11.3	-	3.13	-	-

Footnotes

B, C. Data provided by Calgary International Airport

D. GHG from combustion of natural Gas. Calculated as (Column B X 50.16 t CO₂e/TJ_{hhv} NG) X 1.184 to account for upstream emissions associated with a 2% leak rate. The upstream emissions were calculated using a 100year global warming potential of 25 g CO₂e/g CH₄.

E. Assumed proportion of the airport's natural gas use that would be transition to hydrogen in a net zero emission energy future

F. Column B ÷ 0.940 J_{hhv} CH₄/J_{hhv} H₂, where the 0.94 value takes into account the ratio of LHV/HHV for NG and H₂ with an understanding that fuel combustion can only deliver the LHV of fuels.

G. Column C ÷ 0.940 J_{hhv} CH₄/J_{hhv} H₂, where the 0.94 value takes into account the ratio of LHV/HHV for NG and H₂ with an understanding that fuel combustion can only deliver the LHV of fuels.

H. Column F ÷ 141.7 TJ_{hhv}/kt H₂

I. Column G ÷ 141.7 TJ_{hhv}/kt H₂ X 1000÷30d/mo

J. Column H X 1.5 ktCO₂e/kt H₂. (assumes autothermal reforming with CCS to give 0.5 t CO₂/t H₂, and upstream CH₄ emissions reduced to 1 tCO₂/t H₂, equivalent to a 1% NG leak rate on recovery and processing.

K. Column D - Column J

Fuel hydrogen provides a zero-emission solution that could use much of the existing natural gas infrastructure. Table 6.2 provides a calculation for the potential fuel hydrogen demand for space and water heating at the Calgary International Airport.

Replacing the 360 TJ_{hvh}/yr of NG demand (**Table 6.2, Column B**) would require about 7.5 t H₂/day, peaking in the winter at about 16.4 t H₂/day and dropping to about 3.1 t H₂/day in mid-summer (**Table 6.2, Column I**). Therefore, the life cycle GHG emissions associated with producing this hydrogen was estimated to be 4.1 kt CO₂e/year (**Table 6.2, Column J**), assuming that blue hydrogen is being made with auto-thermal reforming coupled to 95% CCS and federal programs to reduce upstream methane emissions are successful, resulting in life cycle emission of only 1.5 g CO₂e/g H₂.

At this life cycle, GHG intensity for hydrogen production, the reduction in GHG emissions should be 17.3 kt CO₂e/yr (**Table 5.2, Column K**), equivalent to an 81% emission reduction based solely on a change in the fuel supply. In addition, improvements in the thermal efficiency and operation of the buildings could result in additional reductions.

6.4 Power Generation (and Cogeneration)

In 2019, the Calgary International Airport consumed about 116 GWh/yr of grid electricity (**Table 6.3, Column A**). Using the GHG intensity of the Alberta public grid (680 t CO₂e/GWh [47]), the emissions associated with the Airport's electricity use would be about 79 kt CO₂e/year. In addition, upstream methane emissions are associated with the recovery and upgrading of the natural gas used for power generation. Assuming a 2% leak rate and a 100-year global warming potential of 25, that adds another 14 kt CO₂e/yr to give life cycle emissions associated with the Calgary International Airport at 93 kt CO₂e/yr (**Table 6.3, Column C**).

Fuel hydrogen creates an opportunity to decarbonize the electricity supply to the Calgary airport and potentially reduce the carbon intensity of space and water heating. A hydrogen fuel cell would have a very high conversion efficiency (**Table 6.3, Column E**) and be able to deliver the required electricity for a hydrogen demand of about 14.6 t H₂/d (**Table 6.3, Column I and Item 1**). The life cycle GHG emissions from this electricity generation would be about 8 kt CO₂e/year, resulting in a 92% reduction in GHG emissions (**Table 6.3, Column K vs. C**). However, utility-grade fuel cells are not a mature technology, and the capital costs remain high.

If a hydrogen-fueled reciprocal engine [54] is used to generate the 116 GWh/yr, the fuel hydrogen demand would be about 20.1 t H₂/day (**Table 6.3, Column I, Row 2**), assuming a 40% conversion efficiency. Therefore, the life cycle GHG emissions from this electricity generation would be about 11 kt CO₂e/year, resulting in an 88% reduction in GHG emissions from power generation for the Calgary airport (**Table 6.3, Column K vs. C**).

Reciprocal engines can also provide heat energy if deployed in a cogeneration mode (**Table 6.3, Row 3 and 4**). For example, assuming 40% of the fuel energy could be captured and used for space and water heating, a power generation facility at the Calgary airport could deliver 417 TJ_{hvh}/yr (1042 TJ_{hvh}/yr X 0.4), sufficient to meet the annual NG demand at the Calgary airport. However, unlike electricity demand, the demand for heat energy is highly seasonal (**Figure 6.1**), and long-term thermal energy storage is challenging. Hence, assuming only 50% of this thermal energy can be used, there would be an additional GHG reduction of 8.7 kt CO₂e/yr (**Table 6.3, Column K**).

While installing a power generation unit fueled by hydrogen is a significant capital undertaking, there are ways to offset some of the cost (e.g., carbon offset credits). Other opportunities for hydrogen, in connection with the Airport but not modelled for this report, would include taxi fleets, third-party delivery vehicles and buses that travel to and from the Airport.

Table 6.3 Grid Electricity Demand of the Calgary International Airport in 2019.

Estimated hydrogen demand and greenhouse gas (GHG) emission savings if the electricity were generated on-site using fuel cells (Row 1), reciprocal engine (Row 2) or reciprocal engine cogeneration (Rows 3&4).

Item #	A	B	C	D	E	F	G	H	I	J	K
	Grid Demand GWh/yr	TJe/yr	Grid GHGs kt CO2e/yr	Gen'n Technol.	RE-elect J _e -/J _{h_hv} H ₂	RE-thermal J _{th} /J _{h_hv} H ₂	Fuel H ₂ Demand TJ _{h_hv} H ₂ /yr	kt H ₂ /yr	t H ₂ /d	GHG's ktCO ₂ e/yr	GHG Red'n ktCO ₂ e/yr
1	116	417	93	Fuel cell	0.55		758	5.35	14.6	8.0	85.2
2				Recip.-Elect.	0.40		1042	7.4	20.1	11.0	82.2
3				Recip.-Elect.	0.40		1042	7.4	20.1	11.0	82.2
4				Recip.-Heat		0.40	1042	7.4	20.1	11.0	8.7
Footnotes:											
A. Data provided by YYC Group.											
B. Column A X 3.6 GJ/MWh											
C. Column A X 680 t CO2e/GWh (i.e. grid C intensity in 2019, as per National Inventory Report (ECCC, 2022)). Since most of these emissions are from natural gas combustion the product was multiplied by 1.184 to account for upstream emissions associated with a 2% leak rate (assumes a 100 year global warming potential of 25 g CO2e/g CH4).											
D. Three possible technologies for conversion of H2 to electricity. Rows 3+4 represent a reciprical engine combined heat and power system.											
E. Assumed relative efficiencies for power generation (RE-elect) from https://energyknowledgebase.com/topics/heat-rate.asp and https://www.energy.gov/sites/prod/files/2015/11/f27/fcto_fuel_cells_fact_sheet.pdf											
F. Assumed relative efficiencies for heat generation (RE-thermal) from 2G (https://2-g.com/)											
G. Column B ÷ Column D											
H. Column E ÷ 141.7 TJ/kt H2											
I. Column F ÷ 365 d/yr											
J. Column H X 1.5 ktCO2e/kt H2. (assumes autothermal reforming with CCS to give 0.5 t CO2/t H2, and upstream CH4 emissions reduced to 1 tCO2/t H2, equivalent to a 1% NG leak rate on recovery and processing.											
K. Column C - Column J. For the cogen case (Row 4), the cogen heat generated (Column G X Column F= 417 TJth/yr) would be sufficient to meet the annual thermal needs of the airport (Table 5.2), but given challenges for seasonal storage of heat energy, we assumed cogen would only account for half of the heat demand (i.e. Table 5.2, Column K ÷ 2)											

7 FREIGHT RAIL DEMAND

7.1 Introduction

According to a March 2021 report from the Association of American Railroads [55], rail usage is three to four times more fuel efficient than moving freight by truck. In terms of greenhouse gas (GHG) savings, a single freight train can remove the equivalent of several hundred heavy-duty trucks from the road [56]. While rail may be a more efficient way to move freight, it still requires large volumes of diesel fuel for the locomotives. Retrofitting diesel-electric locomotives with hydrogen tank storage and fuel cells is a promising strategy to decarbonize the freight rail sector. The rail sector could be an early adopter of hydrogen fuel cell technology in transitioning to a net-zero future.

Rail could also provide a cost-effective strategy for distributing low-carbon hydrogen fuel. Canada's rail lines tend to follow the same corridors as the major highways, so moving the compressed gas or cryogenic liquid could provide a valuable service for both road and rail transport.

Canadian Pacific and Canadian National operate rail lines within the Calgary Region and provide services for multiple sectors. The main CP rail lines serving the region run parallel to Highway 1; both east and west of Calgary, and along Highway 2; north and south of Calgary. The CP systems continue west through British Columbia, connecting to west coast ports. In addition, CP has a large classifying yard and maintenance facility in southeast Calgary [57].

CN has an Intermodal/Logistics Park located 9 miles east of Calgary [58] and has two lines that run east and north from Calgary's eastern boundaries. One line travels north to the Edmonton area, primarily following Alberta Provincial Highway 21, and the second line travels northeast through the Drumheller region, connecting to Saskatoon and Saskatchewan. This ensures effective connectivity between CN's Intermodal facilities in Calgary, Edmonton, and Saskatoon. CN's system then continues west through Alberta and British Columbia, terminating in both Vancouver and Prince Rupert on the west coast.

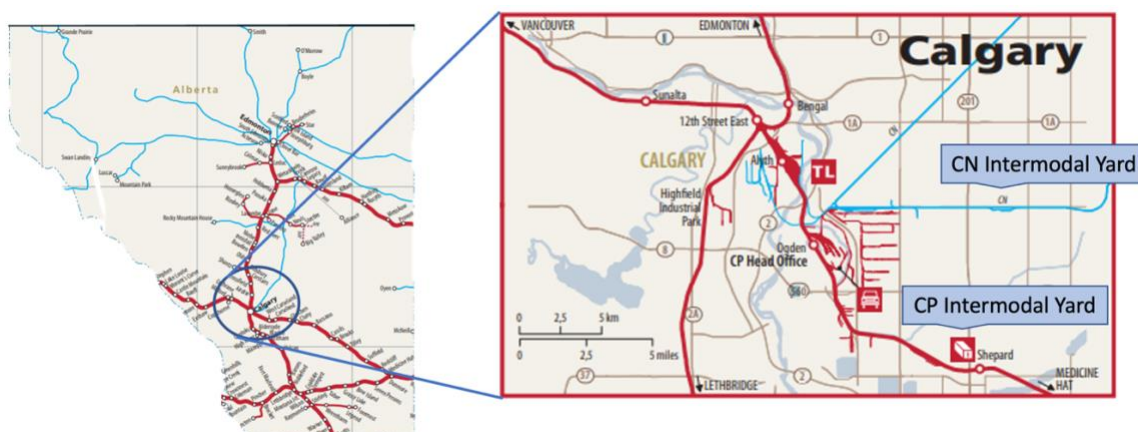


Figure 7.1 Location of CP (red lines) and CN (blue lines) Infrastructure in Calgary Region [57,58, 59]

7.2 Fuel Use and Emission Reduction Potential

In the Calgary Region in 2019, the freight rail sector consumed 58 ML diesel fuel, where ~90% is used by line-haul locomotives and 10% by switching locomotives (**Table 7.1, Column B**). The life cycle GHG emissions associated with fuel production and use accounts for about 229 kt CO₂e/year (**Table 7.1, Column D**).

The diesel-electric drivetrains on most freight locomotives today make it possible to retrofit these long-lasting vehicles to hydrogen fuel cell electric drivetrains, realizing a significant reduction in life cycle emissions and improved conversion efficiency compared to ICE locomotives. For example, if all of the locomotives in the Calgary Region were to transition to hydrogen (**Table 7.1, Column E**) and achieve a relative efficiency of 0.55 J H₂/J diesel, the resulting fuel H₂ demand would be 24 tH₂/d (**Table 7.1, Column I**) with life cycle emissions of 13.1 kt CO₂e/yr (**Table 7.1, Column J**), equivalent to a 94% reduction in GHG emissions by the sector (**Table 7.1, Column K**).

Converting from diesel-electric to hydrogen fuel cell electric will have meaningful impacts on GHG emissions and local air quality.

Table 7.1 Hydrogen Demand in Total Freight Rail in the Calgary Region.

Item #	A Calgary Region Rail Demand	B Diesel Fuel Demand ML/yr	C TJ hhv/yr	D Diesel GHGs kt CO ₂ e/yr	E Share to H ₂	F Rel Effic J H ₂ /J diesel	G TJ hhv/yr	H H ₂ Demand kt H ₂ /yr	I tH ₂ /d	J GHGs ktCO ₂ e/yr	K GHG Red'n ktCO ₂ e/yr
1	Line Haul Locomotives	52.7	2032	206	100%	0.55	1118	7.9	21.6	11.8	195
2	Local Switching	5.85	226	23	100%	0.55	124	0.9	2.4	1.3	21.6
3	Total	58.5	2258	229.3			1242	8.8	24.0	13.1	216

Footnotes
A-B. Data provided by rail companies.
C. Column B ÷ 38.6 TJ hhv / L diesel
D. Column B X 2.8 kt CO₂e/ML (combustion emissions) X 1.40 to account for upstream emissions. Emission factors from <https://open.alberta.ca/dataset/2a41f622-5ae4-4985-838f-497e6afd110c/resource/0ba7b3dc-0658-43dc-b977-4c9c35637f49/download/aep-carbon-offset-emissions-factors-handbook-v-2-2019-11.pdf> and <https://ihsmarkit.com/products/energy-industry-oil-sands-dialogue.html?ocid=cera-osd:energy:print:0001>
E. Assumes all trains will transition to low carbon fuel H₂ in a net zero future
F. Estimated improvement in efficiency for hydrogen fuel cell electric trains
G. Column C X Column E X Column F
H. Column G ÷ 141.7 TJ hhv/kg H₂
I. Column H X 1000 ÷ 365 d/yr
J. Column H X 1.5 ktCO₂e/kt H₂. (assumes autothermal reforming with CCS to give 0.5 t CO₂/t H₂, and upstream CH₄ emissions reduced to 1 tCO₂/t H₂, equivalent to a 1% NG leak rate on recovery and processing).
K. Column D - Column J

7.3 CP's Hydrogen Locomotives

In December 2020, Canadian Pacific (CP) announced the company's intentions to develop North America's first line-haul hydrogen-powered locomotive [60]. Through its Hydrogen Locomotive Program, CP is retrofitting a line-haul locomotive with hydrogen fuel cells and battery technology to drive its electric traction motors. CP is currently conducting service trials and qualification testing to evaluate the technology's readiness for the freight-rail sector.

To support hydrogen locomotive operations, ATCO and CP announced a joint project that includes the installation of hydrogen production and fueling facilities at CP railyards in Calgary and Edmonton. The Calgary fueling facility will include an electrolysis plant to produce hydrogen from water. This facility will operate on renewable power from solar panels at CP's headquarter campus and produce zero greenhouse gas emissions. The Edmonton facility will also include an electrolysis plant powered by Alberta's electricity grid. [60,62,63,64].

Utilization of rail for hydrogen and carbon dioxide transport may be a key to providing export and delivery service in the short term while physical pipeline infrastructure is being constructed and in the long term where pipeline infrastructure cannot be economically constructed.

8 HEAVY-DUTY ROAD FREIGHT

8.1 Introduction

Government policies to encourage the transition away from internal combustion engines and electrifying transportation vehicles have helped drive 8% of new personal vehicle registrations across Canada to be battery-electric by early 2022 [65], and the upward trend is expected to continue and accelerate as new models become available.

Battery electric medium-duty vehicles (Class 2B to 7 trucks, up to 15 t gross vehicle weight (GVW)) are also becoming available [66], and a new \$547M federal program [67] has recently been launched to help zero-emission drivetrains gain market share in the medium and heavy-duty (Class 8, 15+ t GVW) vehicle sectors.

While battery electric vehicles should be able to serve most of the needs for light and medium-duty vehicles, the heavy loads, long trips, and rapid refuelling requirements of heavy-duty vehicles (HDV) have positioned hydrogen as the zero-emission fuel of choice.

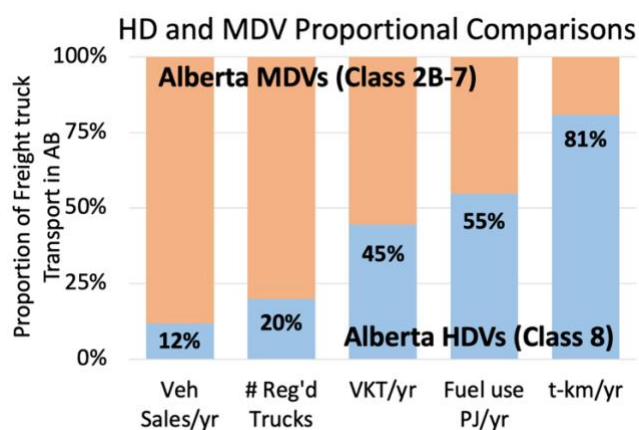


Figure 8.1 Comparison of Medium Duty (MDV) and Heavy Duty (HDV) Vehicles Supporting Freight Transportation in Alberta.

Values from NRCan's comprehensive energy use database for 2019 [68], VKT, vehicle kilometres travelled, PJ, and petajoules.

In Alberta in 2019, compared to all MDVs and HDVs, HDVs were only 12% of new vehicle sales but accounted for 20% of the registered vehicles that drive 45% of the vehicle km travelled (VKT) per year and consume 55% of fuel use (generating 55% of emissions) to move 81% of the tonne-kilometres of freight (**Figure 8.1**). From these numbers, the decarbonization of the HDV sector is clearly critical to meeting climate change objectives and doing so will create a significant market for fuel hydrogen.

This section will explore this opportunity in the Calgary Region.

8.2 Truck Traffic on Major Highways

Alberta Transport provides data and maps on vehicle traffic for all provincially managed highways and secondary roads [69]. For example, figure 8.2 shows a heat map of the Calgary Region showing traffic loads from all vehicle types, including Personal Vehicles (PV), Recreational Vehicles (RV), Buses (BU), Single Unit Trucks (SU) and Tractor Trailers (TT).

Unfortunately, these vehicle categories differ from those used by the federal government and are highlighted in this chapter's introduction (see **Figure 8.1**). The Class 8 trucks would be included in both the SU and TT categories described above, and many of these vehicles on the major highways in the region are likely to be long-haul, so to be zero emission would require a transition to hydrogen fuel cell electric (HFCE).

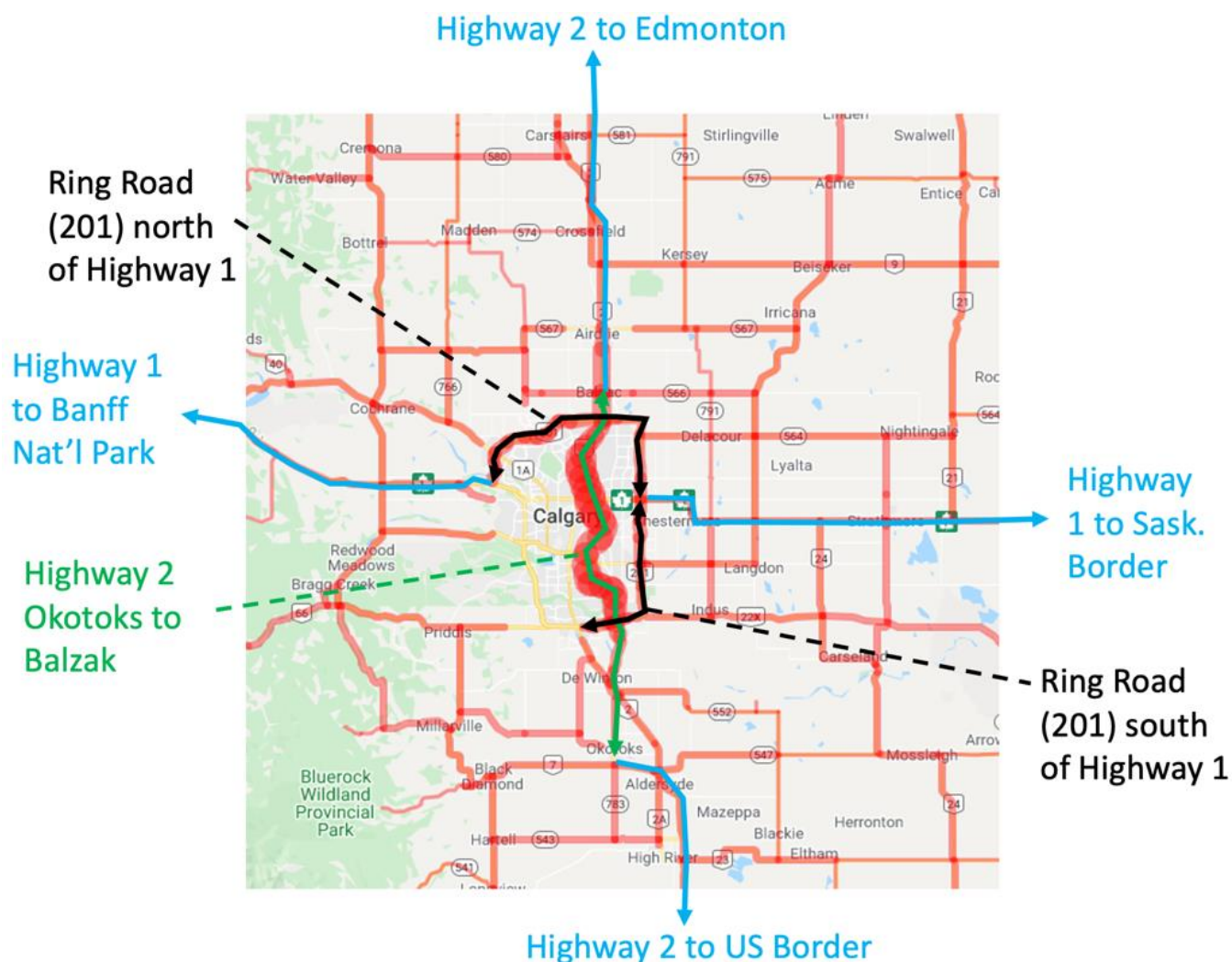


Figure 8.2 Heat Map Depicting Traffic Flows Along Provincial Highways in Calgary Region (red colour), with Specific Highways Identified for More Detailed Analysis.

The thickness of the red lines indicates the volume and km travelled. Image from [69]. The routes marked with black, green, and blue lines are further assessed in **Table 8.1**.

In **Figure 8.2**, three major highways have been identified where Calgary is centrally located. These include the TransCanada Highway (#1), Highway #2 that begins at the border with Montana and passes through Calgary on the

way to Edmonton, and the partially built (in 2019) Ring Road (Highway #201) in Calgary. Together, these highways cover 1030 km (**Table 8.1 Column A**) and support 1154 million vehicle kilometres travelled (VKT) per year by SU and TT Vehicles (**Table 8.1 Column D**).

In a net-zero future, we assumed that 75% of the truck VKTs travelling outside the urban centre would be carried out by HFCE vehicles, but for vehicles, within the city, this proportion would be only 50% (**Table 8.1 Column E**). **Furthermore**, assuming the hydrogen vehicles have a more efficient drivetrain than diesel vehicles (**Table 8.1 Column F**), the fuel demand for the vehicles travelling only on these roads would be 212 t H₂/d (**Table 8.1 Column I**).

Since the VKT data is for two-way traffic on these highways and since the vehicles driving into the Calgary Region would be expected to have refuelled elsewhere, the minimum refuelling potential to support this traffic would be about 122 t H₂/day (**Table 8.1 Column M**). To put this number in perspective, we estimate that a fueling station delivering 4 t H₂/d should be able to generate a profit without government subsidies, so the Calgary Region could theoretically support 30 such stations. In reality, a fewer number of larger, more profitable stations would probably be the better solution.

It is worth noting that this bottom-up assessment of the Calgary Region's fuel H₂ demand for road freight is only about 19% of the top-down assessment of the fuel market demand for medium and heavy-duty trucks in the Calgary Region (**Table 4.1, Rows 8 + 9**), and neither of these assessments include any allowance for population or economic growth in the region. Nor do they consider the potential hydrogen demand for trains, buses, taxi fleets, off-road vehicles, or planes. This projected scale of demand for fuel hydrogen suggests that the Calgary Region should be able to support a significant number of large and profitable hydrogen fueling stations that could anchor the infrastructure investments (like pipelines) needed to enable the economic use of hydrogen in other sectors besides transportation.

Table 8.1 Estimation of the Fuel H₂ Demand for Single Unit (SU) and Tractor Trailer (TT) Trucks Driving on Highways 1 & 2 Running Through Calgary and Around the Ring Road (Highway 201).

The calculations were based on 2019 (pre-COVID) traffic patterns and numbers and only accounted for fuel that would be consumed by the vehicles while on the roads identified.

Item #	Highway	Highway Segment	A	B	C	D	E	F	G	H	I	J	K	L	M
			Distance	Million VKT/yr		H2 Share % of VKT	Rel Effic J H2/J diesel	H2 Demand (t H2/d)			% Refuel demand	H2 Refueling (t H2/d)			
			km	SU	TT			Total	SU	TT		Total	SU	TT	Total
1	#1	Banff Gate to Calgary Ring Road West side	91	15.7	64.5	80.2	75%		2.3	14.0	16.2	50%	1.1	7.0	8.1
2		Calgary Ring Road East side to Sask Border	336	31.8	157	189	75%		4.6	34.1	38.7	50%	2.3	17.1	19.3
3	#2	Montana Border to Okotoks	217	23.6	86.2	110	75%	0.86	3.4	18.7	22.1	50%	1.7	9.3	11.0
4		Okotoks to Balzac	53	69.6	63.5	133	50%		6.7	9.2	15.9	100%	6.7	9.2	15.9
5		Balzac to Edmonton Ring Road	263	104	406	510	75%		15.0	88.0	103.0	50%	7.5	44.0	51.5
6	#201	Calgary Ring Road, north of Hwy 1	42	33.4	46.4	79.8	50%		3.2	6.7	9.9	100%	3.2	6.7	9.9
7		Calgary Ring Road, south of Hwy 1	28	24.1	28.1	52.3	50%		2.3	4.1	6.4	100%	2.3	4.1	6.4
8	Total		1030	302	853	1154			37	175	212		25	97	122

Footnotes

A, B & C. From Alberta Transport Traffic Data (<http://www.transportation.alberta.ca/mapping/>) VKT values are for two way traffic

D. Sum of Columns B and C

E. Assumed to be higher (75%) for vehicles driving outside the metropolitan area and lower (50%) for those vehicles driving in the city.

F. A conservative value since the diesel vehicles are more efficient at highway speeds.

G & H. Calculated from Columns B & C plus E and F using the following additional assumptions and conversion factors: Diesel fuel efficiency 30 and 45 L/100 km for SU and TT vehicles respectively; H₂ energy content of 141.7 MJ/hv/kg H₂, and 365 days per year.

I. Sum of Columns G and H

J. For Roads entering or leaving the region, we assumed that H₂ refueling in the Calgary region would only support 50% of the vehicles (i.e. those leaving)

K. Column G X Column J

L. Column H X Column J

M. Sum of Columns K and L

8.3 Trucking Companies and Fueling Stations

An important factor in developing a fuel hydrogen economy for heavy-duty road freight is to determine where in the region are the trucking companies, where are the fueling stations, and what strategies could be used to transition to a fuel hydrogen economy.

In the Calgary Region, there are about 86 registered trucking companies, 80 of which are located within the City of Calgary (**Figure 8.3**). In addition, Calgary currently has about 20 truck stop/cardlock locations in the region. While most fueling stations seem to congregate along the Highway 2 corridor through the middle of the city, the trucking companies are both there and on the east side of Calgary (**Figure 8.3**).

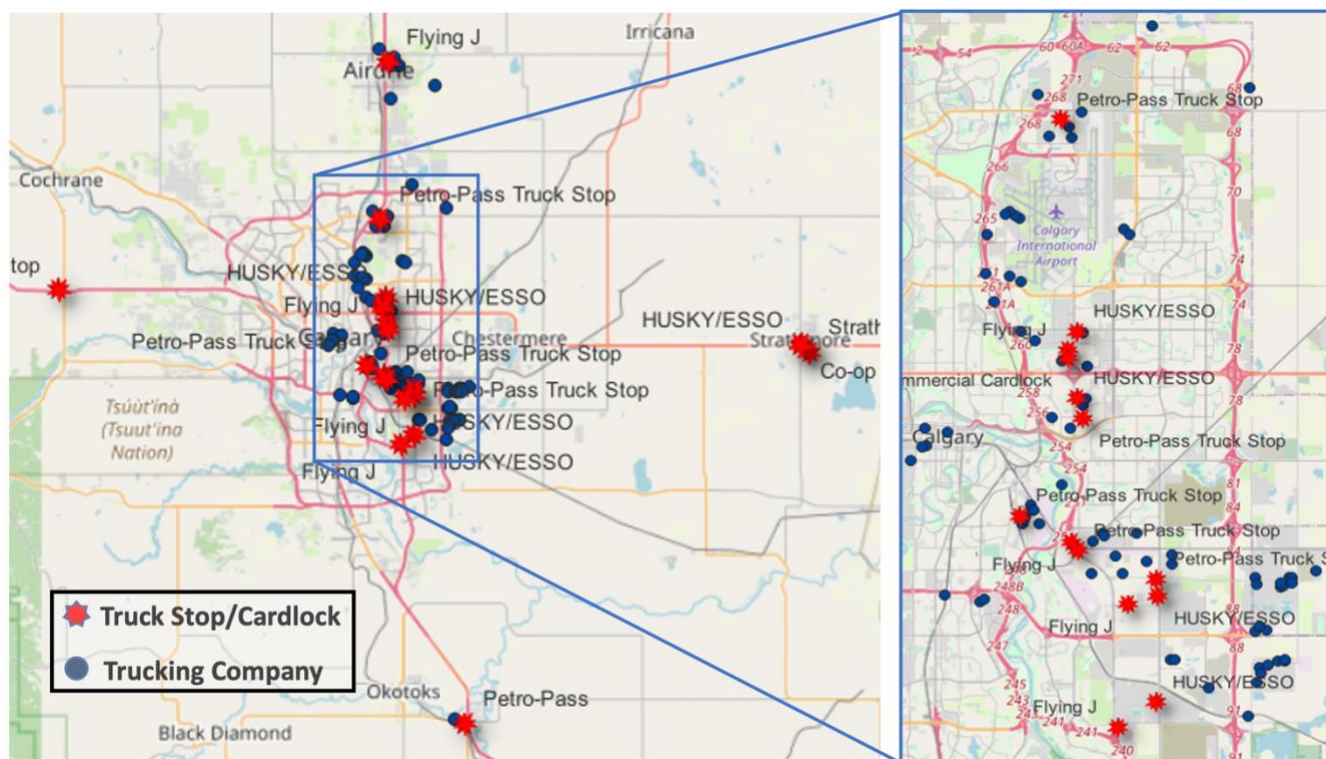


Figure 8.3 Location of Truck Stop/Cardlocks & Trucking Companies in the Calgary Region.

If these 20 stations serve 37% (the Calgary Region's proportion of the Alberta population) of the annual heavy-duty vehicle demand for fuel in Alberta (**Table 4.1, Row 9**), the average annual diesel sales per station would need to be about 54 million litres or 147 kL/station/day. Moreover, if each truck receives an average of 200 L diesel per fill, the average station must serve about 734 trucks per day (an average of 31 trucks per hour over a 24-hour day). These numbers seem too high to be realistic. While we were unable to collect data on the fuel use by truck stops and cardlocks in the Calgary Region, it seems more likely that these 20 stations serve only a fraction (perhaps 20% to 40%) of the Class 8 fuel use in the region.

It seems more reasonable that a typical truck stop/cardlock station would serve 150 to 300 vehicles per day (an average of 10-13 trucks per hour for 15 and 24 hr/day stations, respectively) and assuming each truck purchases an average of 200 L diesel per refuel, each station would deliver 30 to 60 kL diesel fuel per day.

Given these numbers and a net-zero emission energy future, a similar number of stations could serve a similar number of HFCE heavy-duty vehicles providing a similar freight service. Since HFCE vehicles are slightly more efficient than the incumbent diesel (assumed relative efficiency of 0.85 J H₂/J diesel), the average station would need to dispense about 7 to 14 t H₂/day (average of 45.9 kg H₂/vehicle fill). At a fill rate of 7 kg H₂/minute, refuelling would take under 10 minutes. It is worth noting that recently the US National Renewable Energy Laboratory was successful in demonstrating a refuelling system that averaged over 13 kg H₂/minute [72].

Hydrogen fueling stations delivering 7 to 14 t H₂/day would be 2 to 4 times larger than the largest hydrogen fueling stations in construction today, including a 4.8 t H₂ per day station in China [70], and a 3.2 t H₂/day station that Hydra Energy is currently building in Prince George, BC [71].

Further analyses are needed to determine whether the footprint of the existing heavy trucking fueling stations could be transitioned for hydrogen fueling or whether the demands of a hydrogen fueling station would require them to be built in a new location.

While fueling stations can be built to deliver fuel hydrogen at virtually any scale, our analysis suggests that economic viability for stations without ongoing government subsidies requires a station to deliver at least 4 t H₂/day. Moreover, given that there is variation in station demand with days of the week or month of the year, the maximum station capacity would need to be greater than this.

RAPID REFUELING FOR HEAVY-DUTY TRUCKS

The National Renewable Energy Laboratories (NREL) in the USA have recently reported success in building a fast flow fuel delivery system for Heavy-Duty Trucks [72].

They report a 75.9 kg fill from the station into all nine tanks of the HD vehicle simulator in 5 min 43 s, with mass flow rates of 13.2 kg/min average and 23.6 kg/min peak.

Planning for the future of hydrogen fueling stations for heavy-duty transport must also consider the other trends/disruptive forces that are taking place in the heavy freight sector. In particular, there is the question of autonomous trucking. For many years now, there has been a shortage of truck drivers [73], and many companies see a solution with autonomous trucking, especially for long-haul, intercity freight movement [74,75]. Such vehicles will require rapid refuelling and minimal maintenance. The trucks could be on the road 23 hours per day, laying down over 650,000 km per year, with each vehicle displacing 3 conventional long-haul tractors. New large 'truck ports' near major road interchanges could offer both hydrogen fueling and the ability to transfer loads to human-driven vehicles for local distribution [76].

The Transition Accelerator recognizes the importance of strategic planning for the future of the long-haul freight sector, especially if public funding is to be accessed to build out the infrastructure. Therefore, many stakeholders are required to be involved in the discussion, including the carriers, fueling station owners, government regulators, transport ministries, and regional planners.

9 POTENTIAL PARTNERS IN THE FUEL HYDROGEN SUPPLY CHAIN

9.1 Introduction

Previous Chapters have focused on the possible demand for fuel hydrogen in the Calgary Region. In this Section, we will explore possible regional supplies for low-GHG fuel hydrogen, potential partners in the infrastructure needed for local production of fuel hydrogen, and some potential industrial users of fuel hydrogen in a net-zero future.

Alberta is a centre for hydrogen production in Canada today, producing about 5400 to 6000 t H₂/day or two-thirds of all hydrogen production in Canada today [31]. Virtually all of this hydrogen is used as an industrial feedstock for the production of fertilizer ammonia, for the cracking of bitumen into synthetic crude oil, or the upgrading of oil and gas into refined petroleum products such as transportation fuels, chemicals and materials. Until recently, little hydrogen has been produced close to the Calgary Region. In 2022, the Rocky Mountain GTL plant was commissioned and it could provide a hydrogen supply up to 14 t H₂/d, expandable to 30 t H₂/d. It is located 35 km east of Calgary. Larger centers for hydrogen production in Alberta include:

- ❑ The Alberta Industrial Heartland, north-east of Edmonton (for fertilizer production and oil upgrading/refining)
- ❑ Fort McMurray and Fort McKay (for the production of synthetic crude oil)
- ❑ Medicine Hat (for carbon black, methanol, and fertilizer production)
- ❑ Joffre, AB near Red Deer, AB (a by-product of chemical production)

Most of the hydrogen produced in these regions is associated with significant GHG emissions. Projects in the Edmonton Region like Quest [77], the Sturgeon Refinery [78], and the Nutrien Redwater plant [79] are capturing a portion of the byproduct CO₂ from their hydrogen production, concentrating it, and then injecting it into the subsurface [80]. The new Rocky Mountain GTL Carseland facility captures near 40% of its CO₂ production for the manufacture of liquid fuel products.

Other companies such as Air Products [81] and Suncor/ATCO [82] have announced plans for the large-scale (800-900 t H₂/d, each plant) production of hydrogen from natural gas using auto-thermal reforming [83], which can capture up to 94% of the byproduct CO₂ to create low GHG hydrogen that can either be used as an industrial feedstock or as a fuel. As discussed in **Section 3**, such 'blue' hydrogen production can be made for about one-half to one-third the cost of electrolytic hydrogen production, given typical costs for low-carbon electricity.

The Calgary Region could import low GHG 'blue' hydrogen from other Alberta regions producing the gas. However – as mentioned in **Section 3** – the costs of compressing, liquefying, and moving hydrogen are substantial, even more than the cost of production. Therefore, it would be ideal for the Calgary Region to secure a more regional supply of low-carbon hydrogen.

9.2 Point Source CO₂ Emissions

One approach to identify possible future sources for blue hydrogen is to identify the location, nature, and magnitude of point source CO₂ emissions in the region. These are mapped in **Figure 9.1** and summarized in **Table 9.1**. In an economy transitioning to net-zero GHG emissions, all these facilities will need to reduce their emissions to near zero. The opportunities open to the facilities vary with the nature and magnitude of their emissions. We have identified three strategies:

- A. **Replacing Natural Gas with Fuel Hydrogen.** Facilities like the Bonnybrook Wastewater Treatment Plant, the University of Calgary or the Foothills Medical Centre need a low-carbon source of fuel energy for space and water heating and other heat requirements (**Table 9.1**). Therefore, they could dramatically reduce their emissions by switching to fuel hydrogen. Also, peaker power plants, cogeneration facilities and even some baseload combined cycle power plants could reduce their emissions by shifting to NG-hydrogen blends or even pure hydrogen with modified gas turbines. However, the economics of decarbonizing base load power generation using natural gas tends to favour post-combustion capture or the switch to the Allam cycle (e.g. [37]) for power generation rather than the use of hydrogen.

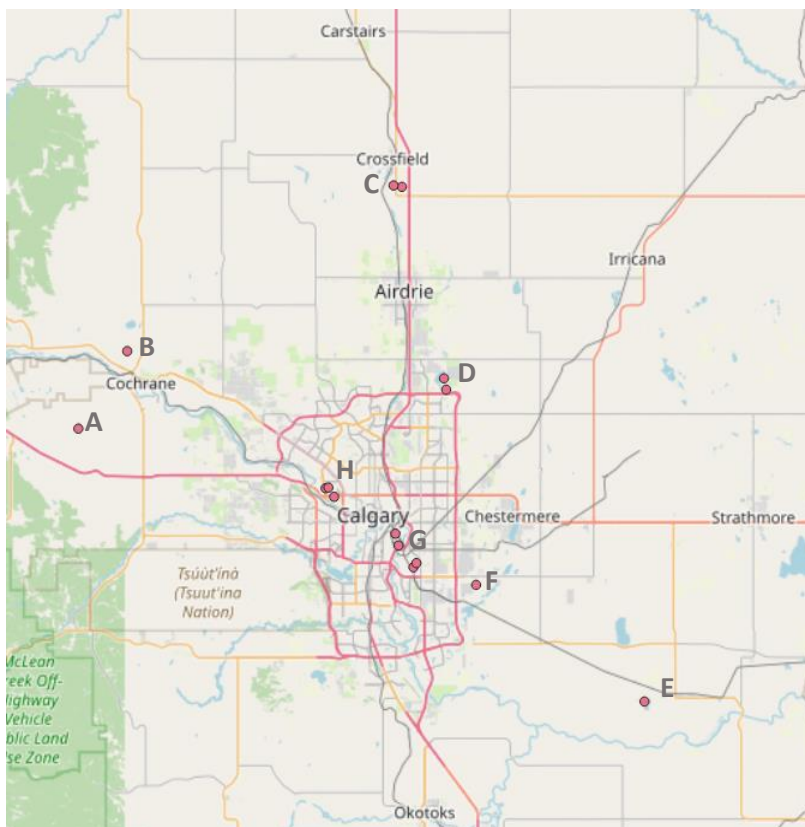


Figure 9.1 Map Showing the Major GHG Emitters in the Calgary Region.

Table 9.1 Major Point Sources of CO₂ in the Calgary Region and High-Level Assessment of the Possible Role They Could Play in an Emerging Net-Zero Emission Energy Future.

Map location	Facility	Annual Emissions t CO ₂ e/yr	Potential in a Net-Zero Future			Comment
			CO ₂ for CCUS	H ₂ Producer	H ₂ User	
A	Jumping Pound Gas Plant	222,727	YES	YES	NO	NG could be made into H ₂ and CO ₂ sequestered
B	Cochrane NGL Extraction Facility	499,909	YES	YES	NO	NG could be made into H ₂ and CO ₂ sequestered
C	East Crossfield Gas Plant	107,348	YES	YES	NO	NG could be made into H ₂ and CO ₂ sequestered
	Enmax Crossfield Power	102,556	YES	NO	YES	Either post combustion capture or use H ₂ to generate power
D	Enmax Calgary Energy Centre	741,038	YES	NO	YES	Either post combustion capture or use H ₂ to generate power
	Enmax Balzac Power Stn	203,255	YES	NO	YES	Either post combustion capture or use H ₂ to generate power
E	Carseland Nitrogen Plant	477,609	YES	YES	NO	Already makes H ₂ , so could use CCS & make extra for fuel
	TC Energy Carseland Cogen	358,446	YES	NO	YES	Either post combustion capture or use H ₂ to generate power
F	Enmax Shepard Power Plant	2,136,185	YES	NO	YES	Either post combustion capture or use H ₂ to generate power
G	Bonnybrook Waste Treatment	86,689	NO	NO	YES	Could use low GHG H ₂ to replace NG demand
H	University of Calgary	71,494	NO	NO	YES	Could use low GHG H ₂ to replace NG demand
	Foothills Medical Centre	61,347	NO	NO	YES	Could use low GHG H ₂ to replace NG demand
Total		5,068,603				

- B. Carbon Capture and Storage Infrastructure.** Many of the more significant point sources, like the Shepard Power Plant or gas plants, could invest in post-combustion carbon capture technologies and direct the CO₂ into a pipeline that would flow to a geological sequestration site. Since CCUS is best done at a large scale (millions of tonnes of CO₂ per year), the pipeline and sequestration infrastructure are typically shared. The presence of such infrastructure could be a significant asset for a company wanting to build a blue hydrogen production facility near Calgary, especially if the market was the provision of fuel hydrogen for transportation, heating, or power generation.

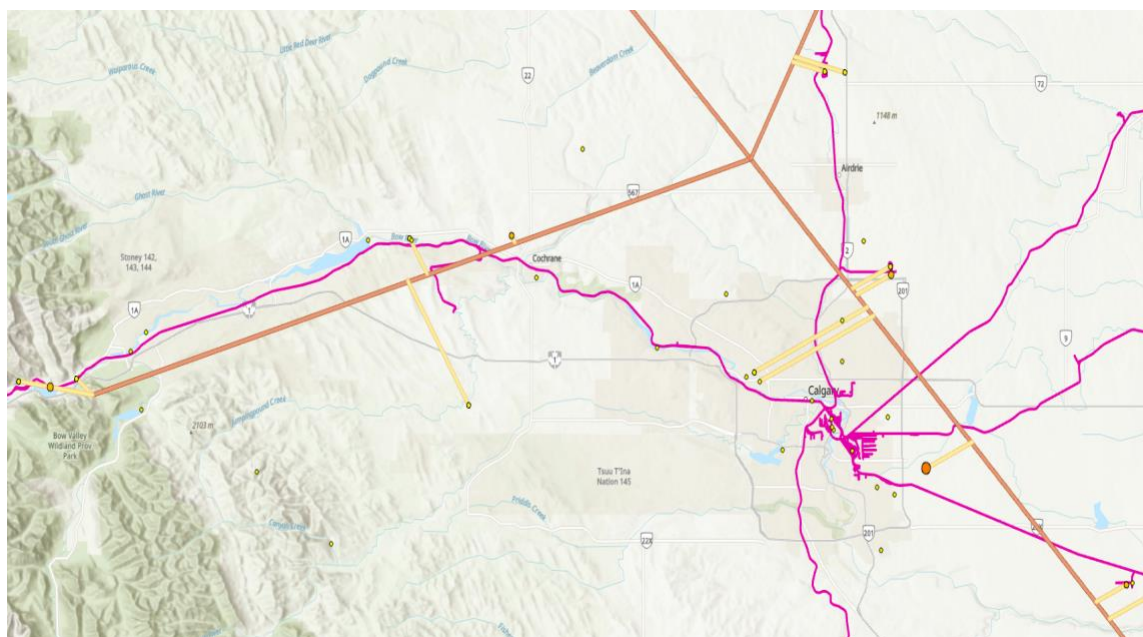


Figure 9.2 Possible Placement of CO₂ Pipeline Infrastructure (yellow and orange) and Rail Corridors (purple) That Could Be Used for CO₂ Gathering.

Charts from Robin Hughes, Natural Resources Canada.

Figure 9.2 shows an example pipeline network and the existing rail network that could be used for CO₂ gathering and transport to injection sites. The Calgary Region is fortunate in that the region's geology is consistent with the presence of porous rock into which CO₂ could be injected for permanent sequestration (**Figure 9.3**). In addition, CO₂ can be stored in depleted oil and gas wells and saline aquifers.

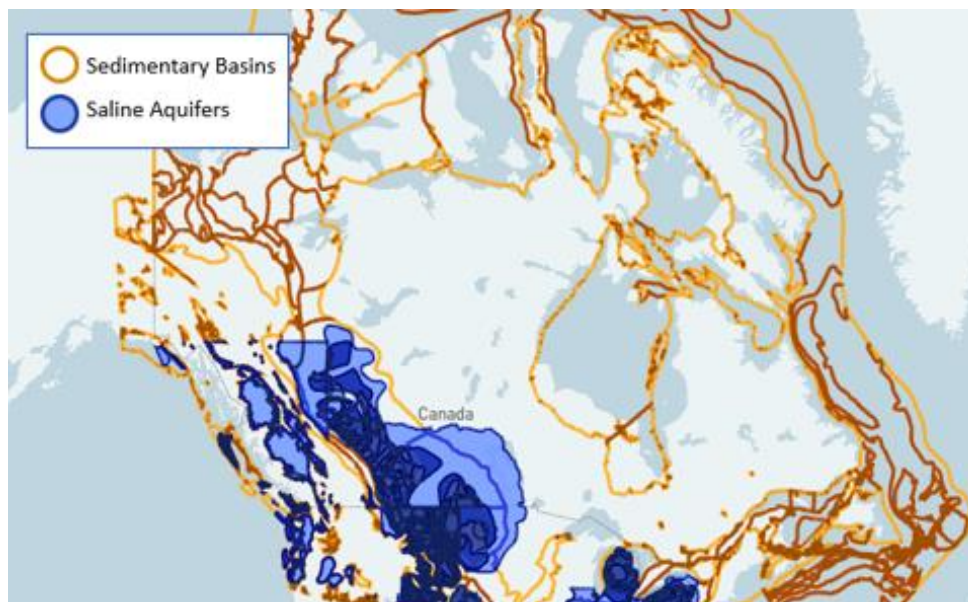


Figure 9.3 Map of CCS Reservoir Potential in Saline Aquifers.

- C. **Possible Producer of Blue Hydrogen.** Some of the point source emissions in the Calgary Region have the potential to get into the production of blue hydrogen while coupling the by-product CO₂ to geological storage. Examples include the Carseland Nitrogen Plant or the gas plants located in the region. For example, TC Energy has recently announced [84] their plan to build a 60 t H₂/day facility at East Crossfield Gas Plant, where some or all of this hydrogen would support heavy trucking in the region [85,86].

10 PLANNING FOR PIPELINES

10.1 Introduction

In the early stages of the transition to a zero-emission hydrogen economy, the primary target market will probably be transportation fuels, and the fuel hydrogen will be moved as a compressed gas or liquid hydrogen. As noted previously (**Figure 4.5**) in Alberta, the transportation market for hydrogen is not as large as the potential market for heating fuel or power generation. The challenge is that the price point for fuel hydrogen in heating or power generation is significantly lower than for its use as a transportation fuel (**Figure 3.1**). To date, the only economically viable way to serve these larger but lower-margin markets is to move hydrogen in large volumes through dedicated pipelines.

Over the next 5-10 years, pilot, demonstration, and early commercialization projects can be carried out to test the use of hydrogen for space heating and power generation. However, realizing the full value of a fuel hydrogen economy will require large-scale deployment of dedicated hydrogen pipelines for both transmission and distribution. Ideally, it would be possible to repurpose natural gas pipelines for use with hydrogen.

In Canada, most of the distribution pipelines are already compatible with hydrogen (*i.e.*, cast iron or plastic). However, many valves, fittings, meters, and burner tips would need to be changed.

There is a more significant challenge in repurposing the natural gas transmission pipelines for use with hydrogen where the metallurgy is such that in the presence of high concentrations of hydrogen, the pipeline can become embrittled, ultimately resulting in failure.

Much work is currently being done to explore the repurposing of natural gas transmission pipelines for use with hydrogen [87,88,89,90,91].

While there is hope that a cost-effective solution will be found, it is essential to know the existing pipeline corridors in a region, especially the location of the 'gates' where the natural gas transmission pipeline pressure is dropped to a lower pressure and the gas enters the distribution pipelines. These gates offer an opportunity to blend hydrogen into the distribution network and partially decarbonize the building sector while the technologies are being developed and tested for 100% hydrogen.

10.2 Transmission Pipeline Network

Significant transmission pipeline infrastructure within the Calgary Region could provide a pathway for hydrogen delivery to support heavy-duty vehicle refuelling, building heat, power generation and other industrial use for hydrogen. **Figure 10.1** shows the existing natural gas high-pressure transmission network in the Calgary Region, including the location of the 'gates' that provide access to the distribution pipelines serving virtually every building in the city. It is interesting to note that the high-pressure NG pipelines do not travel along Highway 2 (Deerfoot Trail) through the city's centre, but they tend to follow the Ring Road.

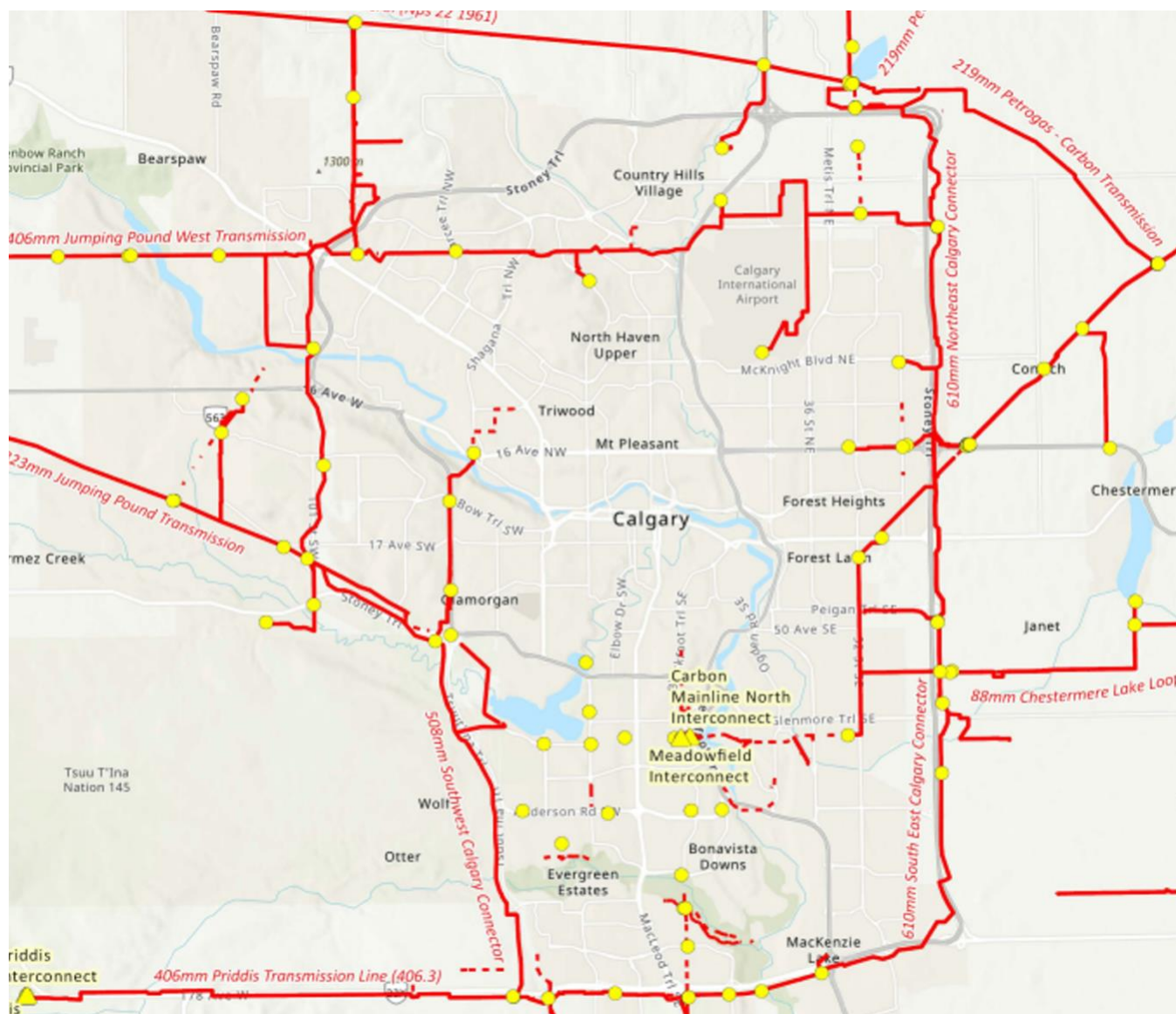


Figure 10.1 ATCO South Integrated Transmission System with High to Low-Pressure Gates.

RED denotes high-pressure transmission pipelines. YELLOW dots are the locations of Hi -> Lo Pressure Gates where H₂ could be injected.

Figure 10.2 shows the locations of abandoned and discontinued natural gas and discontinued jet fuel pipelines in the region. This pipeline infrastructure is primarily concentrated in the north edge of Calgary, with some lines running south along the Ring Road with shorter runs into the city from the Ring Road. In the case of abandoned pipelines, they could offer a pipeline corridor for which it may be possible to lay new pipes. In the case of the discontinued pipeline, they may provide a cost-effective strategy to repurpose or upgrade with liners, especially if the pipelines can help connect new hydrogen supplies with demand for zero-emission transportation, heat, or power generation.

As with the existing pipelines (**Figure 10.1**), they do not parallel Highway 2 through the city but tend to follow the ring roads. However, as discussed in **Section 8** above, there could be real value in planning for the large-scale deployment of most new hydrogen fueling stations/transfer stations around the Ring Road, where major highways enter and leave the city (**Figure 10.3**). This would not only be strategic for serving the long-haul vehicles that are

expected to require hydrogen fuel, but it would position the fueling stations in locations that can benefit from access to pipeline hydrogen when it eventually becomes available.

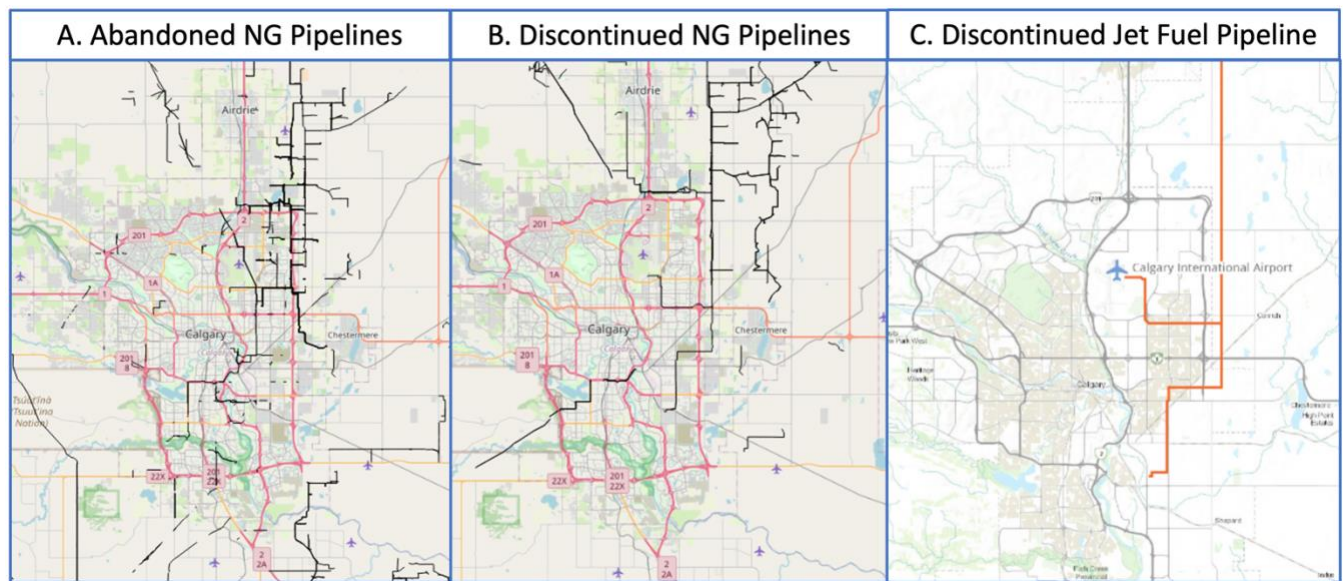


Figure 10.2 Location of Abandoned (A) and Discontinued (B) Natural Gas Pipelines and Discontinued Jet Fuel Pipeline (C).

Data from the Alberta Energy Regulator.

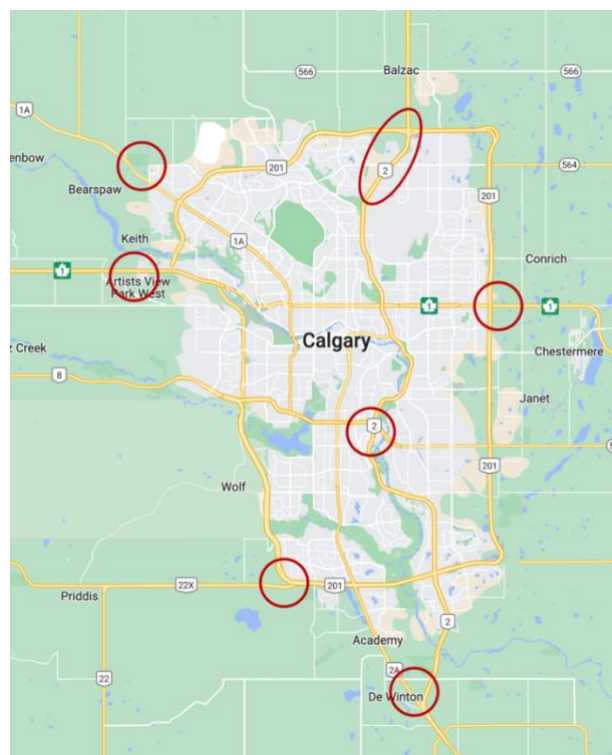


Figure 10.3 Possible Locations for Initial H₂ Fueling Stations That Could Later Benefit from Pipeline Access to the Gas.

11 CALL TO ACTION

The Calgary Region is superbly positioned to take a leadership role in transitioning to a vibrant hydrogen economy that can position Calgary, Alberta and Canada as a key part of the climate change solution. The region has large potential markets for fuel hydrogen and the resources and workforce to produce and make cost-effective, very low GHG hydrogen available where it is needed.

The Calgary region would be an excellent candidate to establish a hydrogen hub and link with other hubs to create transportation corridors supporting heavy-duty trucks and trains across Western Canada, with links to similar initiatives in the USA. Such a start can rapidly grow in scale and then expand to hydrogen use for heat and power generation, attracting new industries.

Figure 11.1 suggests what a hydrogen hub could begin to focus on in the Calgary Region. There is an opportunity to draw on initiatives that are already underway (Green shaded area, **Figure 11.1**) to create both demand and supply for fuel hydrogen in 2023. With a coordinated effort, this could grow rapidly over the next 5 years, setting a foundation for substantial fuel hydrogen supply and demand by the end of this decade.

PHASE 1 STRATEGY. 2023 - 2027

Existing Initiatives that Could be Leveraged

- ☐ CP H₂ Project
- ☐ ATCO-CP Fueling Facility

- ☐ AZETEC (HFCE Truck) Project
- ☐ Hydra (HD2F Truck) Projects
- ☐ Suncor – AMTA Fueling Stations

AMTA
"Road
Show"

- ☐ AZEHT (HFCE Bus) Project
- ☐ TA and Univ. Calgary Projects

Import from Edmonton

Produce H₂ in region:

- ☐ Water electrolysis
- ☐ By-product H₂
- ☐ Steam-methane reforming with CCUS
- ☐ From waste/biomass
- ☐ From Bio-methanol
- ☐ Methane pyrolysis

Low
GHG H₂

Original Equipment Manufacturers

HFCE & HD2F Vehicles

- ☐ Locomotives
- ☐ Class 8 trucks
- ☐ Transit Buses
- ☐ Airport Vehicles
- ☐ Airport Taxi Fleet

Strategically Located H₂ Refueling Facilities

Research, Development and Deployment:

- ☐ How to repurpose existing infrastructure to H₂
- ☐ New technologies using H₂

Pilot, Demo projects for new H₂ uses:

- ☐ Blending to decarbonize NG for heat and power generation
- ☐ Pure H₂ for building building or industrial heat or power generation
- ☐ Pure H₂ for biofuel production or other industrial uses

New companies/jobs in Calgary Region:

- ☐ H₂ production technologies
- ☐ Vehicle assembly
- ☐ Fuel cell manufacturing
- ☐ Vehicle retrofit
- ☐ Vehicle maintenance
- ☐ H₂ using technologies

Year	t H ₂ /d	Possible Targets for Fleets
2023	0.5	1 train, 4 trucks
2024	1	3 trains, 8 trucks, 1 bus
2025	3	5 trains, 40 trucks, 10 buses, 100 taxis, 20 off road
2026	8	...
2027	16	...
2028	32	...
2029	64	...
2030	128	...

Rapidly Growing Fuel H₂ Demand:

- ☐ H₂ Corridors (Hwy 2, Hwy 1)
- ☐ Return to base operations (Calgary Transit, CP, Airport)

Figure 11.1 Overview of what a Calgary Region Hydrogen Hub would work to deploy in Phase 1 of an effort to establish a fuel hydrogen economy in the region.

From the analyses described here, we encourage the Calgary Region to take advantage of this opportunity by:

- A. **Funding and empowering a hydrogen hub** to build a consortium around a shared vision for a fuel hydrogen future. At their core, hydrogen hubs are about economic development, but in a sustainable way to meet regional, provincial, national, and global objectives to mitigate climate change. The consortia should include all levels of government (including First Nations), companies representing the entire value chain, non-profit organizations (universities, environmental groups, industry associations), and others willing to invest both time and resources to build and deploy a strategy that will attract both public and private sector funding. The hydrogen hub requires full-time, dedicated staff resources for a minimum of a three-year commitment (ideally 5+ years) to build on the information provided in this report, connect with the coalition of the willing, identify the most promising industry or municipal government-led initiatives, help them attract resources and then deploy, monitor, communicate and grow. The initial funding for this Hub will need to come from the government (municipal, provincial and federal), but with the successful project launches, there may be opportunities to attract other sources of funding.
- B. **Partnering with the Edmonton Regional Hydrogen Hub.** The [Edmonton Regional Hydrogen Hub](#) was set up almost two years ago, so they now have valuable experience in what should be done or not be done in deploying a fuel hydrogen economy. Rather than competition, they should be seen as a partner, especially in the creation of a Highway 2 corridor for heavy-duty hydrogen truck transport. Also, insights could be used to develop other corridors along Highway 1 or into Southern Alberta and the USA.
- C. **Connecting with Canadian Pacific, Calgary Transit, YYC and the AMTA to support regional hydrogen vehicle trials.** CP is already building fuel cell hydrogen locomotives and a fuel cell-grade hydrogen production and fueling facility in the region. Explore opportunities to support their efforts and benefit from their initiative. Calgary Transit is already linked to the Alberta Zero Emission Hydrogen Transit (AZEHT) project in Edmonton, and there is a possibility of moving one of those buses for trials in Calgary in 2024. The Alberta Motor Transport Association (AMTA) will be making H₂ trucks available for carriers to trial in 2023 and early 2024, and their focus is on the Edmonton Region. An active hydrogen hub in the Calgary Region could help them expand their initiative to the Calgary Region. The Calgary Airport (YYC) has committed to reducing its GHG footprint dramatically, and they are strategically located to play a significant role as a provider and user of hydrogen in an emerging hydrogen economy. Rocky Mountain GTL has a ready supply of hydrogen in the region and is located less than 1 km from the CP mainline east of Calgary.
- C. **Focusing on smaller-scale, distributed hydrogen production to serve the fuel market.** Unlike Edmonton, the Calgary Region does not have a large (100's to 1000's t H₂/d) nearby source of industrial 'gray' and 'blue' hydrogen production, some of which could be diverted to fuel hydrogen use. Therefore, we propose that the Calgary Region focuses over the next ~5 years on the smaller scale (up to 20 t H₂/d, but mostly ~4 t H₂/d), distributed production of low or zero GHG hydrogen close to emerging demand centres. (Rocky Mountain GTL's Carseland plant fits this scale at about 14 t H₂/d). Local hydrogen production could be 'blue', 'green' or 'turquoise' hydrogen that may cost more to produce than in Edmonton, but there should be significant cost savings associated with processing (e.g., liquefaction) and distribution of the fuel. Ideally, the hydrogen would be produced on-site, but if it does need to be moved to a fueling station, it may be worth exploring the possibility of using rail since CP is a potential producer and user, and the existing rail network is close to major transportation corridors.
- D. **Developing a carbon capture utilization and storage (CCUS) strategy.** In the transition to net-zero emissions, many companies in the Calgary Region are interested in being connected to a CO₂ pipeline network, where the CO₂ is geologically sequestered. Such pipeline infrastructure is essential for the local production of blue hydrogen: especially as the demand for hydrogen grows and there is interest in deploying hydrogen pipelines that will serve vehicle refuelling, building heat and power generation. Therefore, the region should be

helping to build a case for investment in CO₂ pipelines and CCUS storage sites to enable the growth of the hydrogen economy.

- E. **Encouraging renewable generation and green hydrogen production.** Southern Alberta has some of Canada's best conditions for wind and solar generation, and with the declining cost of electrolyzers, green hydrogen production is a promising opportunity for making fuel hydrogen for the region. For example, smaller dedicated wind and solar installations could support individual fueling stations, or large wind and solar farms could feed the grid when electricity prices are high and make hydrogen when the prices are low. Alternatively, power purchase agreements could enable grid-reliant electrolytic hydrogen production at fueling stations.
- F. **Deploying hydrogen for heat and power generation.** Blending hydrogen into natural gas distribution networks can generate GHG benefits while creating a variable buffer in the market demand for hydrogen that is made to support transportation markets.
- G. **Engaging the academic community.** Local colleges and universities can provide valuable training, insights, and technologies to advance a hydrogen economy. Therefore, they should be engaged in the early stages of the launching of a hydrogen hub.

12 REFERENCES

- [1] C. Benson Wahlen, "73 Countries Commit to Net Zero CO2 Emissions by 2050," *IISD | SDG Knowledge Hub | News*, 17-Dec-2019. [Online]. Available: <https://sdg.iisd.org/news/73-countries-commit-to-net-zero-co2-emissions-by-2050/>
- [2] Natural Resources Canada, "Comprehensive Energy Use Database." 15-Dec-2004 [Online]. Available: http://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/menus/trends/comprehensive_tables/list.cfm [Accessed: 11-Sep-2018]
- [3] Government of Canada 2022. 2030 Emissions Reduction Plan: Clean Air, Strong Economy. [Online]. Available: <https://www.canada.ca/en/services/environment/weather/climatechange/climate-plan/climate-plan-overview/emissions-reduction-2030.html> [Accessed 28 Oct 2022]
- [4] S. J. Davis *et al.*, "Net-Zero Emissions Energy Systems," *Science*, vol. 360, no. 6396, p. eaas9793, Jun. 2018, doi: 10.1126/science.aas9793.
- [5] A. Saeedmanesh, M. A. MacKinnon, and J. Brouwer, "Hydrogen is Essential for Sustainability," *Curr. Opin. Electrochem.*, vol. 12, pp. 166–181, Dec. 2018, doi: 10.1016/j.coelec.2018.11.009.
- [6] J. A. Dowling *et al.*, "Role of Long-Duration Energy Storage in Variable Renewable Electricity Systems," *Joule*, vol. 4, no. 9, pp. 1907–1928, Sep. 2020, doi: 10.1016/j.joule.2020.07.007.
- [7] Council of Australian Governments Energy Council and Energy Council, "Australia's National Hydrogen Strategy," Commonwealth of Australia, 2019. Accessed (2020) from: <https://www.industry.gov.au/sites/default/files/2019-11/australias-national-hydrogen-strategy.pdf>
- [8] Federal Ministry for Economic Affairs and Energy, "Germany: The National Hydrogen Strategy," Berlin, Jun. 2020 [Online]. Accessed (2020) from: https://www.bmbf.de/files/bmwi_Nationale%20Wasserstoffstrategie_Eng_s01.pdf
- [9] Committee on Climate Change, "Hydrogen in a Low-Carbon Economy," London, Nov. 2018 [Online]. Available: <https://www.theccc.org.uk/publication/hydrogen-in-a-low-carbon-economy/>
- [10] Fuel Cell & Hydrogen Energy Association, "Road Map to a US Hydrogen Economy," Dec. 2019 [Online]. Available: https://cafcp.org/sites/default/files/Road-map-to-a-US-hydrogen-economy_Executive-Summary.pdf
- [11] S. Kan, "South Korea's Hydrogen Strategy and Industrial Perspectives." *Edito Energie*, Ifri, Mar-2018 [Online]. Available: https://www.ifri.org/sites/default/files/atoms/files/sichao_kan_hydrogen_korea_2020_1.pdf
- [12] IHS Markit, "Hydrogen as the Enabler: Meeting China's Energy Challenge?," Mar. 2019 [Online]. Available: <https://cdn.ihs.com/www/pdf/0319/IHS-Markit-Hydrogen-China-Prospectus-March2019.pdf>
- [13] D. B. Layzell *et al.*, "The Future of Freight Part C: Implications for Alberta of Alternatives to Diesel." *Canadian Energy Systems Analysis Research*, Jan-2020 [Online]. Available: <http://www.cesarnet.ca/publications/cesar-scenarios>
- [14] Government of Alberta, 2021. Alberta Hydrogen Roadmap. [Online]. Available: <https://www.alberta.ca/hydrogen-roadmap.aspx>
- [15] Government of Canada. 2020. Hydrogen Strategy for Canada. [Online]. Available: https://www.nrcan.gc.ca/sites/nrcan/files/environment/hydrogen/NRCan_Hydrogen-Strategy-Canada-na-en-v3.pdf
- [16] Government of Alberta Regional Dashboard, <https://regionaldashboard.alberta.ca/region/calgary/#/>
- [17] City of Calgary, "Our City", <https://www.calgary.ca/structure/our-city.html>
- [18] Calgary Economic Development, "Why Calgary? Our Economy in Depth", PowerPoint Presentation, February 2022, <https://origin.calgaryeconomicdevelopment.com/assets/Reports/Research/Why-Calgary-Our-Economy-in-Depth.pdf>
- [19] The Conference Board of Canada, January 2022; Statistics Canada, 2022
- [20] Calgary International Airport Facts & Figures, Fact Sheet, <https://www.yyc.com/en-us/media/factsfigures/factsheet.aspx>
- [21] IEA, The Future of Hydrogen Technology Report (2019), <https://www.iea.org/reports/the-future-of-hydrogen>

- [22] Asia Pacific Energy Research Centre, "Perspectives on Hydrogen in the APEC Region," Institute of Energy Economics, Japan, Tokyo, Jun. 2018 [Online]. Available: <https://aperc.ieej.or.jp/file/2018/9/12/Perspectives+on+Hydrogen+in+the+APEC+Region.pdf>
- [23] Benziger et al. "The power performance curve for engineering analysis of fuel cells," *Journal of Power Sources*, 2006. [Online]. Available: <https://www.sciencedirect.com/science/article/abs/pii/S0378775305007196>
- [24] Ramsden et al. "Hydrogen Pathways - Updated Cost, Well-to-Wheels Energy Use, and Emissions for the Current Technology Status of Ten Hydrogen Production, Delivery, and Distribution Scenarios," *National Renewable Energy Laboratory*, Technical Report NREL/TP-6A10-60528, March 2013. [Online]. Available: <https://www.nrel.gov/docs/fy14osti/60528.pdf>
- [25] L. Collins, "Producing green hydrogen for \$1/kg is achievable in some countries by 2030", *Energy Transition*, December 2021. [Online]. Available: <https://www.rechargenews.com/energy-transition/producing-green-hydrogen-for-1-kg-is-achievable-in-some-countries-by-2030-woodmac/2-1-1118580>
- [26] Khan MA, MacKinnon C, Young C and Layzell DB. 2022. Techno-economics of a new Hydrogen Value Chain supporting heavy duty Transport. *Transition Accelerator Reports: Volume 4, Issue 5*. Pp 1-52. ISSN 2562-6264. Available: <https://transitionaccelerator.ca/techno-economics-of-a-new-hydrogen-value-chain-supporting-heavy-duty-transport/>
- [27] <https://www.osti.gov/biblio/1860481>
- [28] Wang Q, Jianqiu L, Bu Y, Xu L Ding Y, Liu R, Xu Y, Qin Z 2020. Technical assessment and feasibility validation of liquid hydrogen storage and supply system for heavy-duty fuel cell truck. 2020 4th CAA International Conference on Vehicular Control and Intelligence. Available: <https://ieeexplore.ieee.org/abstract/document/9338639>
- [29] <https://www.airliquide.com/stories/hydrogen/air-liquide-and-faurecia-are-bringing-liquid-hydrogen-heavy-duty-vehicles>
- [30] Layzell DB, Young C, Lof J, Leary J and Sit S. 2020. Towards Net-Zero Energy Systems in Canada: A Key Role for Hydrogen. *Transition Accelerator Reports: Vol 2, Issue 3*. <https://transitionaccelerator.ca/towards-net-zero-energy-systems-in-canada-a-key-role-for-hydrogen>
- [31] Layzell DB, Lof J, Young C, and Leary J. 2020. Building a Transition Pathway to a Vibrant Hydrogen Economy in the Alberta Industrial Heartland. *Transition Accelerator Reports. Volume 2, Issue 4*. Pp 1-59. ISSN 2562-6264. <https://transitionaccelerator.ca/building-a-transition-pathway-to-a-vibrant-hydrogen-economy/>
- [32] Litun, R.O. (2022). Towards Hydrogen, A Hydrogen HUB Feasibility Study for Southeast Alberta. *Transition Accelerator Reports Vol. 4, Issue 3*, Pg. 1-213. ISSN 2562-6264 <https://transitionaccelerator.ca/towards-hydrogen-a-hydrogen-hub-feasibility-study-for-southeast-alberta>
- [33] Khan, M.A., Young, C., and MacKinnon, C. and Layzell, D. (2021). The Techno-Economics of Hydrogen Compression. *Transition Accelerator Technical Briefs Vol. 1, Issue 1*, Pg. 1-36. ISSN 2564-1379. Available: <https://transitionaccelerator.ca/techbrief-techno-economics-hydrogen-compression/>
- [34] Khan, M.A., Young, C. and Layzell, D.B. (2021). The Techno-Economics of Hydrogen Pipelines. *Transition Accelerator Technical Briefs Vol. 1, Issue 2*, Pg. 1-40. ISSN 2564-1379. Available: <https://transitionaccelerator.ca/techbrief-techno-economics-hydrogenpipelines/>
- [35] Hy4Heat Website, <https://www.hy4heat.info/>
- [36] Government of Canada, "A clean electricity standard in support of a net-zero electricity sector: discussion paper", [Online]. Available: <https://www.canada.ca/en/environment-climate-change/services/canadian-environmental-protection-act-registry/achieving-net-zero-emissions-electricity-generation-discussion-paper.html>
- [37] NET Power Technology Website, <https://netpower.com/technology/>
- [38] Allam Power Cycle, Wikipedia, https://en.wikipedia.org/wiki/Allam_power_cycle
- [39] Governments of Ontario, New Brunswick, Alberta and Saskatchewan, "A Strategic Plan for the Deployment of Small Modular Reactors", [Online]. Available: <https://open.alberta.ca/dataset/de9ebaba-81a7-456e-81a2-2c57cb11412e/resource/62319fa5-aa5a-4329-b980-5c85a924c7c7/download/energy-interprovincial-strategic-plan-deployment-of-smrs-2022.pdf>
- [40] World Nuclear News, "Alberta oil sands producers look to SMRs", June 2021. [Online]. Available: <https://world-nuclear-news.org/Articles/Alberta-oil-sands-producers-look-to-SMRs>
- [41] Nature Portfolio, "Turbines driven purely by hydrogen in the pipeline", [Online]. Available: <https://www.nature.com/articles/d42473-020-00545-7>

- [42] GE Gas Power, “Hydrogen fueled gas turbines”, [Online]. Available: <https://www.ge.com/gas-power/future-of-energy/hydrogen-fueled-gas-turbines>
- [43] NS Energy, “Gas turbines in the US are being prepped for a hydrogen-fuelled future”, January 2021. [Online]. Available: <https://www.nsenergybusiness.com/features/gas-turbines-hydrogen-us/>
- [44] S. Hughes, “Reducing Urban Greenhouse Gas Emissions: Effective Steering Strategies for City Governments”, *IMFG Perspectives*, No. 16, 2017. [Online]. Available: https://tspace.library.utoronto.ca/bitstream/1807/82861/1/imfg_perspectives_no16_reducingurbangreehousegas_hughes_2017.pdf
- [45] City of Calgary, “Climate Emergency Declaration”, *Calgary’s Climate Change Program*, [Online]. Available: <https://www.calgary.ca/environment/climate/climate-change.html#emergency>
- [46] H21 Project Website, <https://h21.green/>
- [47] United Nations Climate Change, “Canada. 2022 National Inventory Report (NIR)”, April 2022. [Online]. Available: <https://unfccc.int/documents/461919>
- [48] YYC Sustainability Strategy. Powerpoint deck made available to the Transition Accelerator
- [49] M. Piesing, “The epic attempts to power planes with hydrogen”, *BBC Future*, March 2022. [Online]. Available: <https://www.bbc.com/future/article/20220316-the-epic-attempts-to-power-planes-with-hydrogen>
- [50] Airbus ZEROe, “Towards the world’s first zero-emission commercial aircraft”, [Online]. Available: <https://www.airbus.com/en/innovation/zero-emission/hydrogen/zeroe>
- [51] M. Gallucci, “ZeroAvia’s hydrogen-powered test plane is nearly ready for takeoff”, *Canary Media*, June 2022. [Online]. Available: <https://www.canarymedia.com/articles/air-travel/zeroavias-hydrogen-powered-test-plane-is-nearly-ready-for-takeoff>
- [52] J. O’Callaghan, “Quiet and green: Why hydrogen planes could be the future of aviation”, *Horizon The EU Research & Innovation Magazine*, July 2020. [Online]. Available: <https://ec.europa.eu/research-and-innovation/en/horizon-magazine/quiet-and-green-why-hydrogen-planes-could-be-future-aviation>
- [53] D. Thomas, “Hydrogen Hinted for Calgary-Banff Passenger Scheme”, *Railway Age*, March 2022. [Online]. Available: <https://www.railwayage.com/passenger/hydrogen-hinted-for-calgary-banff-passenger-scheme/>
- [54] 2G Website, “Hydrogen CHP: Climate-neutral without compromise”, <https://2-g.com/en/solutions/h2-ready>
- [55] Association of American Railroads, “Freight Railroads & Climate Change”, <https://www.aar.org/climate-change>
- [56] Association of American Railroads, “Freight Rail Facts & Figures”, <https://www.aar.org/facts-figures>
- [57] Canadian Pacific, “Calgary Intermodal Facility”, https://www.cpr.ca/en/Documents/Intermodal_Map_Calgary.pdf
- [58] Canadian National, “Logistics Parks”, <https://www.cn.ca/en/our-services/supply-chain-services/logistics-parks/>
- [59] Canadian Pacific, “CP Network Map 2020”, <https://www.cpr.ca/en/choose-rail-site/Documents/cp-network-map-2020.pdf>
- [60] Canadian Pacific, “CP Announces Hydrogen-Powered Locomotive Pilot Project”, December 2020, <https://investor.cpr.ca/news/press-release-details/2020/CP-announces-hydrogen-powered-locomotive-pilot-project/default.aspx>
- [61] <https://erh2.ca/>
- [62] Canadian Pacific, “Canadian Pacific expands Hydrogen Locomotive Program to include additional locomotives, fueling stations with Emissions Reduction Alberta grant”, November 2021, <https://www.cpr.ca/en/media/canadian-pacific-expands-hydrogen-locomotive-program-to-include-additional-locomotives-fueling-stations-with-emissions-red>
- [63] Emissions Reduction Alberta, “CP Hydrogen Locomotive Program”, <https://www.eralberta.ca/projects/details/cp-hydrogen-rail-initiative/>
- [64] Global News, “ATCO to build fuelling stations in Edmonton, Calgary for CP Rail’s hydrogen locomotive program”, May 2022, <https://globalnews.ca/news/8808929/atco-edmonton-calgary-cp-rail-hydrogen-stations/>
- [65] J. Koselj, “Zero-emission vehicle registrations in Canada hit 8.3 per cent in first quarter of 2022”, *Electric Autonomy Canada*, May 2022, <https://electricautonomy.ca/2022/05/27/q1-2022-ihs-how-many-zev-registrations-canada/>
- [66] Vicinity Motor Corp. Website, “Vicinity Lighting EV”, <https://vicinitymotorcorp.com/>

- [67] Transport Canada, "Medium and heavy-duty zero-emission vehicles", [Online]. Available: <https://tc.canada.ca/en/road-transportation/innovative-technologies/zero-emission-vehicles/medium-heavy-duty-zero-emission-vehicles>
- [68] Natural Resources Canada, "Transportation Sector - Alberta", [Online]. Available: https://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/menus/trends/comprehensive/trends_tran_ab.cfm
- [69] Government of Alberta, "Traffic Data Mapping", <http://www.transportation.alberta.ca/mapping/>
- [70] Air Liquide, "Air Liquide's technology chosen for the world's largest hydrogen station in Beijing, China", July 2021, <https://www.airliquide.com/group/press-releases-news/2021-07-08/air-liquides-technology-chosen-worlds-largest-hydrogen-station-beijing-china>
- [71] D. Bain, "Ground broken on world's largest hydrogen refueling station", My PG Now, September 2022, <https://www.myprincegeorgenow.com/166506/news/ground-broken-on-worlds-largest-hydrogen-refueling-station/>
- [72] R. Martineau, "Fast Flow Future for Heavy-Duty Hydrogen Trucks - Expanded Capabilities at NREL Demonstrate High-Flow-Rate Hydrogen Fueling for Heavy-Duty Applications", National Renewable Energy Laboratory, June 2022, <https://www.nrel.gov/news/program/2022/fast-flow-future-heavy-duty-hydrogen-trucks.html>
- [73] IRU, "Driver shortages surge, expected to jump up to 40% in 2022: new IRU survey", June 2022, <https://www.iru.org/news-resources/newsroom/driver-shortages-surge-expected-jump-40-2022-new-iru-survey>
- [74] S. Banker, "The Autonomous Truck Revolution Is Right Around The Corner", *Forbes*, May 2021, <https://www.forbes.com/sites/stevebanker/2021/05/11/the-autonomous-truck-revolution-is-right-around-the-corner/?sh=15a1e2512c96>
- [75] T. Bove, "90% of long-haul trucking may soon be self-driving. Are you ready to share the road with an autonomous 18-wheeler?", *Fortune*, April 2022, <https://fortune.com/2022/04/07/autonomous-long-haul-trucking-to-transform-u-s-logistics/>
- [76] E. Garsten, "Pilot, Kodiak Partner To Build Service Centers For Autonomous Trucks", *Forbes*, August 2022, <https://www.forbes.com/sites/edgarsten/2022/08/23/pilot-kodiak-partner-to-build-service-centers-for-autonomous-trucks/?sh=13824fa41505>
- [77] Government of Canada, "Shell Canada Energy Quest Project", <https://www.nrcan.gc.ca/science-and-data/funding-partnerships/funding-opportunities/current-investments/shell-canada-energy-quest-project/18168>
- [78] North West Redwater Partnership, "Sturgeon Refinery - Carbon Capture and Storage", <https://nwrsturgeonrefinery.com/project/carbon-capture-and-storage/>
- [79] Nutrien, "Exciting project reduces emissions at Redwater", *Stories*, June 2020, <https://www.nutrien.com/what-we-do/stories/exciting-project-reduces-emissions-redwater>
- [80] Enhance Energy Website, "Producing low carbon energy", <https://enhanceenergy.com/>
- [81] Air Products, "Canada Net-zero Hydrogen Energy Complex", <https://www.airproducts.com/campaigns/alberta-net-zero-hydrogen-complex>
- [82] CISION, "Suncor and ATCO partner on a potential world-scale clean hydrogen project in Alberta", May 2021, <https://www.newswire.ca/news-releases/suncor-and-atco-partner-on-a-potential-world-scale-clean-hydrogen-project-in-alberta-810940277.html>
- [83] ScienceDirect Topics, "Autothermal Reforming - An Overview", <https://www.sciencedirect.com/topics/engineering/autothermal-reforming>
- [84] TC Energy, "Media Advisory: TC Energy eyes Crossfield site for low-carbon hydrogen production hub", April 2022, <https://www.tcenenergy.com/announcements/2022-04-26-media-advisory--tc-energy-eyes-crossfield-site-for-low-carbon-hydrogen-production-hub/>
- [85] TC Energy, "Hydrogen - Nikola Agreement", <https://www.tcenenergy.com/operations/energy-solutions/nikola-hydrogen-agreement/>
- [86] TC Energy, "Media Advisory: Hyzon Motors and TC Energy announce hydrogen modular production hub development agreement", November 2021, <https://www.tcenenergy.com/announcements/2021/2021-11-10--media-advisory--hizon-motors-and-tc-energy-announce-hydrogen-modular-production-hub-development-agreement/>
- [87] J.H. Holbrook et al., "5 - Control of hydrogen embrittlement of metals by chemical inhibitors and coatings", *Gaseous Hydrogen Embrittlement of Materials in Energy Technologies*, Volume 1 in Woodhead Publishing Series in Metals and Surface Engineering, Pages 129-153, 2012, <https://www.sciencedirect.com/science/article/pii/B9780857095367500052?via%3Dihub>

- [88] M. Ratoi, H. Tanaka, B.G. Mellor *et al.*, “Hydrocarbon Lubricants Can Control Hydrogen Embrittlement”, *Scientific Reports* 10, 1361, 2020, <https://www.nature.com/articles/s41598-020-58294-y#citeas>
- [89] H. Barthélémy, “The Effects of Purity and Pressure on Hydrogen Embrittlement of Metallic Materials (ID 149)”, Air Liquide PowerPoint Presentation, 3rd International Conference on Hydrogen Safety Ajaccio, September 16-18, 2009, https://h2tools.org/sites/default/files/2019-08/presentation_4.pdf
- [90] ACER European Union Agency for the Cooperation of Energy Regulators, “Repurposing existing gas infrastructure to pure hydrogen: ACER finds divergent visions of the future”, July 2021, <https://www.acer.europa.eu/news-and-events/news/repurposing-existing-gas-infrastructure-pure-hydrogen-acer-finds-divergent-visions-future>
- [91] C. Peace, “R&D helping to repurpose infrastructure to transport hydrogen”, *John Wood Group*, July 2021, <https://www.woodplc.com/insights/articles/r-and-d-helping-to-repurpose-infrastructure-to-transport-hydrogen>
- [92] J. Lof and D. B. Layzell, “The Future of Freight A: Trends and Disruptive Forces Impacting Goods Movement in Alberta and Canada.” Canadian Energy Systems Analysis Research, Sep-2019 [Online]. Available: <http://www.cesarnet.ca/publications/cesar-scenarios>
- [93] J. Lof *et al.*, “The Future of Freight B: Assessing Zero Emission Diesel Fuel Alternatives for Freight Transportation in Canada.” Canadian Energy Systems Analysis Research, Sep-2019 [Online]. Available: <http://www.cesarnet.ca/publications/cesar-scenarios>
- [94] Meadowcroft, D. B. Layzell, and N. Mousseau, “The Transition Accelerator: Building Pathways to a Sustainable Future,” The Transition Accelerator, Aug. 2019 [Online]. Available: <https://www.transitionaccelerator.ca/blueprint-for-change>