TRANSITION ACCELERATOR REPORTS
Volume 4 • Issue 5 • July 2022

TECHNO-ECONOMICS OF A NEW HYDROGEN VALUE CHAIN SUPPORTING HEAVY DUTY TRANSPORT

Executive Summary

Mohd Adnan Khan, PhD
Catherine MacKinnon, MSc, P. Eng.
Cameron Young, MSc, P.Eng.
David B. Layzell, PhD, FRSC

The Transition Accelerator
L'Accélérateur de transition

TECHNO-ECONOMICS OF A NEW HYDROGEN VALUE CHAIN SUPPORTING HEAVY DUTY TRANSPORT

Mohd Adnan Khan, PhD
Energy Systems Analyst
TRANSITION ACCELERATOR

Catherine MacKinnon, P.Eng., MSc
Energy Systems Analyst
CESAR, UNIVERSITY OF CALGARY

Cameron Young, P.Eng., MSc
Energy Systems Analyst
CESAR, UNIVERSITY OF CALGARY

David B. Layzell, PhD, FRSC
Energy Systems Architect
TRANSITION ACCELERATOR

Cite as:
Khan M.A., MacKinnon C., Young C., and Layzell D. B. (2022) Techno-economics of a New Hydrogen Value Chain Supporting Heavy Duty Transport. Transition Accelerator Reports: Volume 4, Issue 5. Pg. 1-52. ISSN 2562-6264. Ver. 2
This document is available at https://transitionaccelerator.ca/techno-economics-of-a-new-hydrogen-value-chain-supporting-heavy-duty-transport/

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

Mohd Adnan Khan PhD

TRANSITION ACCELERATOR

Mohd Adnan Khan, PhD, is as an Energy Systems Analyst who joined the Transition Accelerator to help design pathways towards the establishment of a sustainable energy future. Adnan has a PhD in Material Science and Engineering and is passionate about working on renewable energy systems and contributing to the development of a future H_2 economy. He has over 8 years of industrial and academic experience leading research teams across the value chain of technology development and commercialization, driving innovation, and fostering collaboration among industry, government, and academia. He has published over 35 articles in top scientific journals, has 7 granted patents and now hopes his work will lead to the spin-out of consortia led projects, get change moving on the ground and help drive Canada towards a net-zero future.

Catherine MacKinnon P.Eng., MSc

CESAR, UNIVERSITY OF CALGARY

Catherine MacKinnon, P.Eng., MSc is an Energy Systems Analyst at the CESAR Initiative at the University of Calgary. She has a Master of Science degree in Sustainable Energy Development (SEDV) and a Bachelor of Science degree in Chemical Engineering from the University of Calgary. She is a Professional Engineer in good standing with The Association of Professional Engineers and Geoscientists of Alberta and has more than nine years of professional experience in the upstream energy industry in various technical, corporate, and financial roles. She recently completed her capstone project, exploring the carbon footprint and carbon management strategies of direct and indirect GHG emissions associated with operations of a remote, off-grid research station in the Yukon.

Cameron Young P.Eng., MSc

CESAR, UNIVERSITY OF CALGARY

Cameron Young, P.Eng., MSc is an Energy Systems Analyst at CESAR. He joined CESAR to help create a hydrogen economy in Canada. His work will include research on different pathways for hydrogen production, transmission, and distribution to provide pragmatic information for industry and policy makers. He hopes his work will help develop projects that convert Alberta's resources into a sustainable source of hydrogen fuel. Cameron has a Chemical Engineering & Management double-major bachelor's degree from McMaster University, a Masters in Sustainable Energy Development from the University of Calgary and is registered as a Professional Engineer with APEGA. He has 10 years of process engineering and project development experience in Alberta's energy sector.

David B. Layzell PhD, FRSC

TRANSITION ACCELERATOR

David B. Layzell, PhD, FRSC is an Energy Systems Architect with the Transition Accelerator, a Faculty Professor at the University of Calgary, and 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.

ACKNOWLEDGEMENTS

This work began in the Canadian Energy Systems Analysis Research (CESAR) Initiative at the University of Calgary, where it was funded by the Transition Accelerator and Natural Resources Canada.

With the launch of the Edmonton Region Hydrogen HUB in early 2021, the project was moved to the Transition Accelerator where it was completed with the support of the HUB's sponsors. The authors thank all sponsors for their support.

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

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

COPYRIGHT: Copyright ©2022 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: https://www.shutterstock.com/image-illustration/hydrogen-logo-on-gas-stations-fuel-1742689784

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

EXECUTIVE SUMMARY

Concerns about the adverse impacts of climate change have led Canada and other nations around the world to commit to net-zero greenhouse gas (GHG) emissions by 2050. The distributed, end use combustion of fossil-carbon based energy carriers (gasoline, diesel, jet fuel, natural gas) accounts for almost half of Canada's GHG emissions and another 24% can be attributed to their recovery and upgrading [1]. Clearly, the transition pathway to net-zero requires new energy systems where traditional fossil-carbon based fuels are replaced with zero-emission energy carriers that are produced with minimal or no GHG emissions.

While low carbon electricity will play a major role in replacing carbon-based fuels, there are certain sectors that require a zero-emission chemical energy carrier like hydrogen gas (H_2). Hydrogen is seen as the zero-emission fuel of choice for sectors such as heavy-duty transport, space heating in cold climates, many industrial sectors and as a backup for intermittent renewables in power generation.

The use of low GHG hydrogen to decarbonize our energy systems is of particular relevance in Alberta. The province is strategically positioned to be a global H_2 leader, blessed with excellent wind and solar resources to support electrolytic low GHG 'green' hydrogen production, as well as abundant natural gas and the geology for permanent CO_2 storage to make low GHG 'blue' hydrogen from fossil fuels.

Alberta currently produces more than 5000 tons of low-cost H_2 (about 0.9 to 1.4 C\$/kg$_{H2}$) per day, but most is coupled to significant emissions of GHGs, and virtually all is used as industrial feedstocks for the production of crude oil, fertilizers, fuels, and chemicals. Decarbonization of the province's hydrogen has the potential to reduce the carbon intensity of these industrial processes, generate zero emission fuels for export to other nations, and provide low GHG fuel hydrogen to decarbonize domestic transportation, space heating and power generation.

Based on Alberta's energy system in 2018 [2], the potential domestic fuel hydrogen market is about 13,000 t_{H2}/day, with transportation accounting for 21%, building space and water heating for 37%, and industrial heat and power generation for 42%. However, the successful buildout of a fuel hydrogen economy will require the creation of new value chains that will connect hydrogen supply to new demand sectors and make hydrogen available at a reasonable cost at widely distributed locations.

Since Canadians pay 5 to 10 times more per unit of energy for transportation fuels than for heating fuels, the transportation fuel market for hydrogen, especially for heavy-duty vehicles, holds the greatest promise for early adoption. In the transportation fuel market, target retail prices for hydrogen should be in the range of 5 to 8 \$C/kg$_{H2}$ to be competitive with the current prices for diesel. For heating markets in a net-zero future, retail hydrogen prices of 2-3 \$C/kg$_{H2}$ is a reasonable target.

This report presents the design and techno-economic analyses of new value chains for delivering hydrogen from centralized production sites to fueling stations supporting heavy duty vehicles, including trucks, buses, and trains. It builds on earlier studies from CESAR [3-5] and the Transition Accelerator [6-8], that show hydrogen to be the net-zero fuel of choice for heavy duty vehicles, and analysis on the techno-economics of compressing and pipelining hydrogen [9,10].

While the findings presented here should have relevance to any region of Canada interested in centralized, low GHG hydrogen production, the model parameters were chosen for their relevance to the Edmonton Region Hydrogen HUB (https://erh2.ca/), where different sized (0.4, 2 or 8 t_{H2}/day) hydrogen fueling stations (HFS) were assessed at distances of 5, 40 or 300 km from a centralized production facility.

Three hydrogen transportation modes were considered including: (A) compressed hydrogen in tube trailers (TT) trucked to stations, (B) liquid hydrogen (LH_2) in cryogenic tanks trucked to stations, and (C) compressed hydrogen in pipelines to the station. Detailed techno-economic analyses of the various processing units across the different value chains revealed the pre-tax, refueling costs of hydrogen which were then compared with what is needed to be competitive with diesel fuel without public subsidies.

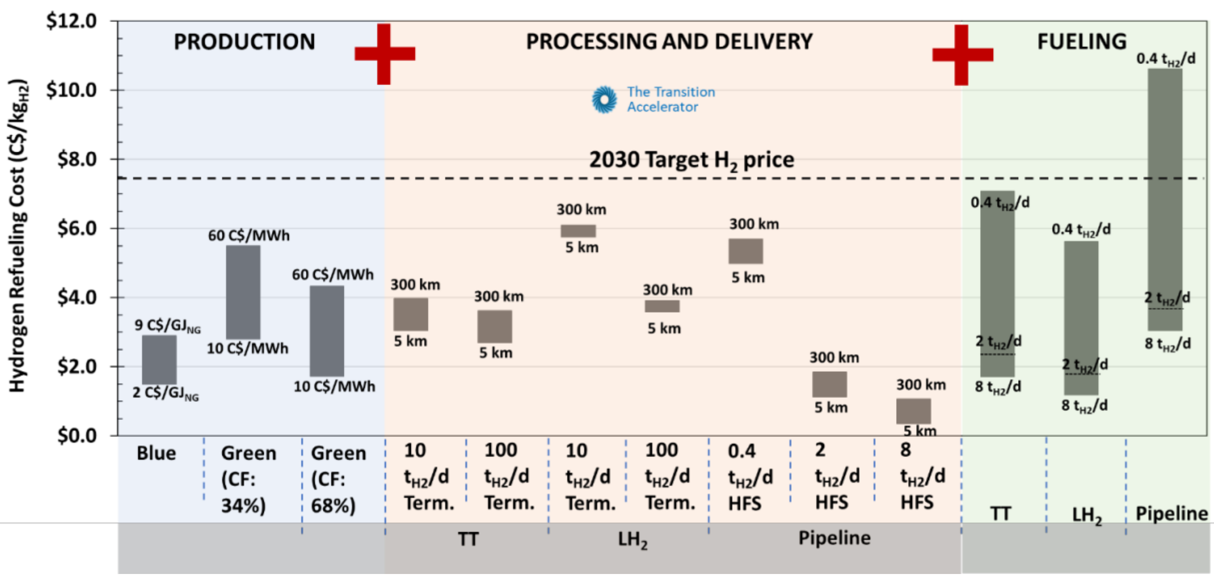

Figure ES. 1. Refueling cost of hydrogen (C$/$kg_{H2}$) for the different Supply Chains (A, B and C) and divided into production plus processing & delivery plus fueling cost.

Note: The black dash line represents the target hydrogen retail price based on a diesel cost of 1.25 C$/$L_{diesel}$, drive train efficiency of 0.86 PJ_{H2}/PJ_{diesel} plus a 2030 carbon price of 170 C$/$t_{CO2}$, without any fuel taxes on hydrogen. The analysis assumes use of large transmission pipelines capable of transporting 300 t_{H2}/day over 295 km and 100 t_{H2}/day over 35 km.

The techno-economic results revealed that processing, delivery and fueling of hydrogen is complex with several factors impacting the refueling cost of hydrogen. However, in a mature hydrogen economy, by employing economies of scale the total estimated refueling cost of hydrogen (**Figure ES. 1**) should be competitive with diesel for heavy duty transport at 5 to 8 C$/$kg_{H2}$ or 35 to 56 C$/$GJ_{H2}$. The **hydrogen costs can be summarized** as follows:

1. **Production costs**: The analysis reveals that to target a hydrogen refueling cost that is competitive with diesel in 2030, centralized production costs will have to be <3 C$/$kg_{H2}$. Green hydrogen production costs depend on the cost and near continuous availability of low-carbon electricity

supply. With the current cost of electrolyzers, if low-carbon electricity is available ≥68% of the time at low costs (< 30 C$/MWh), green hydrogen can be made for <3 C$/$kg_{H2}$. On the other hand, centralized blue hydrogen production via methane reforming represents the lowest cost (<1.8 C$/$kg_{H2}$) option in a province like Alberta with availability of low-cost natural gas and geology for CCS. Additionally, blue hydrogen offers the possibility of quickly getting to scale which will drive down costs.

2. **Processing and delivery costs**: As a low-density gas, the processing and delivery costs for hydrogen are high. In the early stages of market development with low demand (<1 t_{H2}/station/d), compressed hydrogen delivery via tube trailers makes the most sense for short distances, while liquid hydrogen delivery is more attractive for distances over 300 km. However, the processing and delivery costs with these supply chains (3-6 C$/$kg_{H2}$) are too high to be used in heating applications. In a mature market, dedicated pipeline delivery to large (≥2 t_{H2}/day) fueling stations will have lowest delivery costs (<1 C$/$kg_{H2}$) if there is large, aggregated demand (~1 t_{H2}/day per km of pipeline) to amortize the cost of the transmission pipelines.

3. **Fueling (HFS) costs**: The fueling station costs are impacted by delivery method (via TTs, liquid hydrogen tanks or pipelines), but in all cases, the larger the fueling station, the better the economics. This is also tied to the demand; with high utilization of the station's dispensing capacity critical to lowering fueling cost. The deployment of large fueling stations (≥2 t_{H2}/day) in combination with high utilization can lead to fueling station costs of 1.5-3 C$/$kg_{H2}$ depending on delivery method.

The techno-economic analyses identified a few key **observations**:

1. **Scale is critical**: The capital cost of many components in the value chain (e.g., liquefaction units, pipelines, compressors) have a much greater impact on the levelized cost of hydrogen at smaller scales than at large scales.

2. **Demand will drive down costs**: While employing economies of scale is important, it will only reap benefit if there is high utilization of the capacity of various process units. In other words, scale and demand must work together. Creating substantial demand (e.g., >2 t_{H2}/fueling station/day) in concentrated hydrogen hubs and corridors would be essential to economic viability. In transportation, this requires 100+ transit fuel cell buses, or 40+ Class 8 fuel cell trucks refueling daily at each station.

3. **Dedicated pure hydrogen pipelines are essential to enable use in multiple sectors**: With centralized hydrogen production, pipelines are the only practical option that enables opportunities in multiple sectors (transport, heat, power) and realize a cost and scale of supply that justifies the necessary infrastructure investments. Such a synergy among multiple demand sectors delivers benefits to all and should be integrated into strategic planning for the buildout of the hydrogen economy.

4. **Hydrogen value chain is capital intensive**: Hydrogen delivery and fueling costs are dominated by the capital expenditure that contributes 45-65% of the total cost per kg H_2 (assumes 8% return on investment).

5. **Technology development is necessary**: As a low-density gas, the compression and/or liquefaction are the costliest processing steps of the value chain. Technological improvements that increase

efficiency, reliability and lifetime of currently available compressors and liquefaction units will be critical to drive down cost of hydrogen.

To conclude, hydrogen not only offers a great opportunity to advance towards a clean future, but it is also an economic driver that opens up diverse opportunities. Yet as this study reveals, the challenges are substantial as fuel hydrogen value chains are complex, and the risks faced by investors are significant. Based on the techno-economic results, the report provides a few **recommendations** that can accelerate the adoption of hydrogen as a clean fuel.

1. **Strategic planning is needed** to fully utilize the potential of hydrogen and unlock significant economic value for Alberta and Canada. The government needs to work together with different stakeholders to develop strategic transition plans that coordinate and leverage current resources, infrastructure, know-how and expertise. A key part of the strategic planning would be to analyze the interdependencies among different demand sectors and plan infrastructure development, policies, and incentive programs accordingly. The results presented in the report indicate that pipelines are the only delivery option that would enable market opportunities in multiple sectors (transport, heat, power). Therefore, they should be integrated into planning the transition to a sustainable hydrogen economy.

2. **Creation of Regional Hydrogen Hubs and Economic Corridors** would be key to improve coordination and connect supply to demand. The work done in establishment of regional hubs such as the ERH2 could be used as a template to create similar hubs across the country. The energy transition is a complex challenge, and these hubs will be key to bring together various stakeholders from government, industry, and demand sectors to work together to minimize barriers.

3. **Mitigate investment risks**. The results indicate that the buildout of a new hydrogen value chain will be capital intensive. Therefore, there needs to be risk mitigation for that capital until demand increases. Policy makers and financial institutions need to employ various policies and financial tools to remove market barriers, ease regulatory burdens and mitigate investment risk which will attract private investment. Technical assistance, grants and interest free loans can play a critical role early in the project. Other tools could be in the form of guaranteed off-take agreements to meet utilization targets, or conditional capital to reduce utilization targets. Public finance institutions can make key contributions by providing investors with risk guarantees and other insurance tools.

4. **Support demand creation**. As mentioned earlier, while employing economies of scale is key, it fails without securing the demand for hydrogen fuel. Traditionally, most government policies and incentives programs have focused on low-carbon hydrogen production. Boosting the role of low carbon hydrogen in clean energy transitions requires a step change in demand creation. The results presented in this study indicate that for heavy-duty transport, significant demand will not materialize without a range of available vehicles at acceptable prices, together with predictable and affordable fuel prices. Therefore, incentive programs need to be developed to purchase heavy-duty fuel cell electric vehicles in parallel with programs to build a network of large size fueling stations.

5. **Promote innovation and pilot projects**. In an early market with many uncertainties, it will be important to provide support to shovel ready pilot projects and promote innovation. These projects will provide real world data and insights that must be made public, with transparent discussions, to identify bottlenecks to address.

REFERENCES

1. National inventory report 1990-2019 : Greenhouse gas sources and sinks in Canada. *Environment and Climate Change Canada* **2021**.
2. Natural Resources Canada, "Comprehensive Energy Use Database." *http://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/menus/trends/comprehensive_tables/list.cfm*.
3. Lof, J.; Layzell, D. The Future of Freight A: Trends and Disruptive Forces Impacting Goods Movement in Alberta and Canada. *Canadian Energy Systems Analysis Research ; http://www.cesarnet.ca/publications/cesar-scenarios*.
4. Lof, J.e.a. The Future of Freight B: Assessing Zero Emission Diesel Fuel Alternatives for Freight Transportation in Canada. *Canadian Energy Systems Analysis Research, Sep- . Available: http://www. cesarnet. ca/publications/cesar-scenarios* **2019**.
5. Layzell, D.B.; Lof, F.J.; McElheran, K.; Narendran, E.M.; Belanger, N.; Straatman, B.; Sit, S. The future of freight- Part C: Implications for Alberta of Alternatives to diesel. *Canadian Energy Systems Analysis Research ; http://www.cesarnet.ca/publications/cesar-scenarios* **2020**.
6. Lof, J.; MacKinnon, C.; Martin, G.; Layzell, D. Survey of Heavy-Duty Hydrogen Fuel Cell Electric Vehicles and Their Fit for Service in Canada. *The Transition Accelerator, Canadian Energy Systems Analysis Research*, **2020**.
7. Layzell, D.B.; Young, C.; Lof, J.; Leary, J.; Sit, S. Towards Net-Zero Energy Systems in Canada: A Key Role for Hydrogen. *Transition Accelerator Reports* **2020**.
8. Layzell, D.B.; Lof, F.J.; Young, C.; Leary, P.J. Building a transition pathway to a vibrant hydrogen economy in the Alberta Industrial Heartland *Transition Accelerator Reports* **2020**.
9. Khan, M.A.; Young, C.; Mackinnon, C.; Layzell, D.B. The Techno-Economics of Hydrogen Compression. *Transition Accelerator Technical Briefs* **2021**, *1*, 1-36.
10. Khan, M.A.; Young, C.; Layzell, D.B. The Techno-economics of hydrogen pipelines. *Transition Accelerator Technical Briefs* **2021**, *1*, 1-40.