# Hydrogen on the path to net-zero emissions

## Costs and climate benefits

Photo: Roberta Franchuk, Pembina Institute

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Hydrogen is increasingly being discussed as a promising fuel that could reduce the amount of fossil fuels burned in several sectors, such as transportation and heavy industry, and help move Canada toward its goal of net-zero carbon emissions by 2050. However, the climate advantage of hydrogen is highly dependent on how it is produced.

Before determining the role for hydrogen in decarbonizing Canada's economy, it is important to understand the different types of hydrogen that can be utilized. This primer examines basic properties of hydrogen, how it is produced, and the characteristics, costs (including current production costs in Canada), and carbon intensity of grey, blue and green hydrogen.

Any discussion of hydrogen must also be informed by an understanding of transportation and storage needs, including infrastructure, mode of transportation, and the state (i.e. gas or liquid) of the hydrogen being transported. Also key to the public conversation about hydrogen is knowledge about possible uses across Canada's economy, in both its pure form (utilizing fuel cells or through combustion) and blended with liquid fuels and natural gas. End uses covered in this primer include buildings, electricity generation and storage, industrial processes, and passenger and freight vehicles.

Finally, we articulate key facts to consider when identifying the role of hydrogen in Canada's energy transition.

## Key takeaways

- Hydrogen can play a role in decarbonizing Canada's energy systems.
- In terms of climate benefits, not all hydrogen is created equal:
  - **Grey hydrogen** is made by extracting hydrogen from natural gas using thermal processes such as steam methane reformation. It offers little to no climate benefit.
  - **Blue hydrogen** is made by extracting hydrogen from natural gas, and then using carbon capture and sequestration technology to store the remaining carbon. It has a low to moderate carbon intensity.
  - **Green hydrogen** is made by extracting hydrogen from water using electrolysis powered by renewable energy. With the lowest carbon intensity, it offers the greatest climate benefit.
- Low-carbon hydrogen can be used to reduce emissions in hard-to-decarbonize sectors, but currently only a small fraction of hydrogen produced worldwide is low-carbon.

# What is hydrogen?

Hydrogen is a colourless, odourless gas at room temperature that is usually found with other elements, such as oxygen, to form compounds (e.g. water [$H_2O$]). Once extracted, pure hydrogen can act as an energy carrier (akin to electricity) characterized by a high energy density, containing nearly three times as much energy by weight as natural gas, gasoline and diesel (Figure 1).[1]

Hydrogen is flammable, but is just as safe as natural gas, gasoline and diesel when protocols and materials for its correct use, storage and transportation are employed.

Currently, hydrogen is predominantly used for making other types of energy (i.e. as a feedstock) in industrial applications, such as oil refining and fertilizer manufacturing.[2,3]

Hydrogen can produce energy in two ways: either by being combusted (e.g. in an engine or a turbine) or by being fed into a fuel cell to produce electricity. In both cases, a notable characteristic of hydrogen is that it produces no carbon emissions at the point of use (only water vapour and heat when consumed in fuel cells).

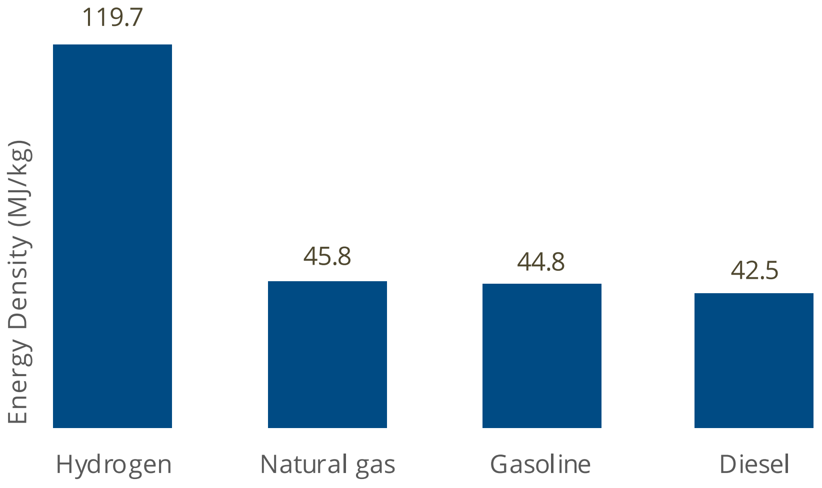

Figure 1. Energy density of hydrogen compared to other fuels

Data source: Yip et al.[4]

# How is hydrogen produced?

Hydrogen can be produced in a variety of different processes that are commonly distinguished by their feedstock (e.g. water or natural gas) and associated carbon intensity. There are three main types of hydrogen, which are commonly referred to as grey, blue and green hydrogen (see Figure 2 and Table 1).[5] A fourth type of hydrogen can be produced from the gasification of coal and is referred to as brown or black hydrogen depending on the grade of coal being used. This type of hydrogen will not be the focus of this primer due to the fact it has limited to no climate benefits and coal is being phased out as a fuel for electricity generation in Canada. In 2018, grey and brown hydrogen represented 99% of global hydrogen production, while production of green and blue was nascent.[6] When using natural gas as a feedstock (i.e. to make grey and blue hydrogen), methane and carbon dioxide ($CO_2$) emissions from extraction and processing will affect the total carbon intensity of the product.

Figure 2. The three main types of hydrogen

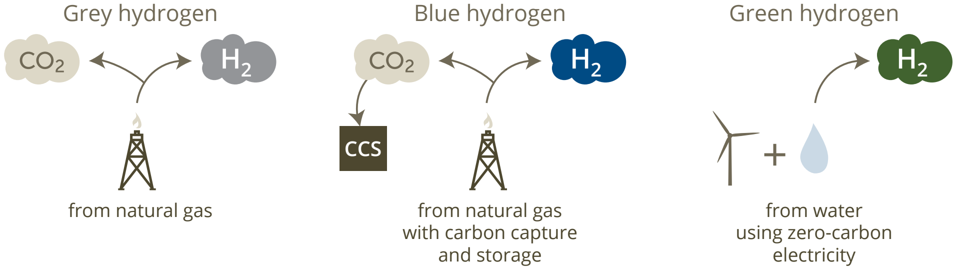

Table 1. Characteristics of the three main types of hydrogen[7]

| | Grey hydrogen | Blue hydrogen | Green hydrogen |
|---|---|---|---|
| Description | Produced from natural gas through steam methane reforming (SMR), wherein methane reacts with high-temperature steam, resulting in hydrogen and carbon dioxide | Produced in the same way as grey hydrogen, but also incorporates the use of carbon capture and storage to reduce the GHG emissions from production, typically by 80 or 90%[8] | Produced by running an electric current through water (electrolysis) using zero-carbon sources of electricity (e.g. solar or wind) |
| Feedstock | Natural gas | Natural gas | Water, zero-carbon (e.g. renewable) electricity |
| Carbon intensity[9,10] (includes upstream emissions) | 11.3 to 12.1 kg $CO_2$e/kg $H_2$[11]<br>(94.8 to 101.4 g $CO_2$e/MJ)<br>Highest | 2.3 to 4.1 kg $CO_2$e/kg $H_2$[12]<br>(19.6 to 34.5 g $CO_2$e/MJ)<br>Low to moderate | 0 to 0.6 kg $CO_2$e/kg $H_2$[13]<br>(0 to 5.3 g $CO_2$e/MJ)<br>Lowest |
| Production cost in Canada[14,15] (\$/kg $H_2$) [Relative production cost] | \$0.91 to \$1.42 | \$1.34 to \$1.85[16] | \$3.10 to \$5.01 |
| | \$ | \$\$ | \$\$\$ |
| Advantages | Improved air quality at the point of use<br>Abundant feedstock and mature natural gas industry<br>Inexpensive to produce | Improved air quality at the point of use<br>Abundant feedstock and mature natural gas industry | Improved air quality at the point of use<br>Decentralized production of hydrogen<br>Allows for the storage of excess renewable electricity |
| Disadvantages | Limited to no climate benefits | Relies on the use of carbon capture and storage technologies, which can be costly<br>Rate of carbon capture (i.e. the proportion of emissions that are captured and stored) directly influences carbon intensity<br>Is limited to production in areas with large geological storage potential for carbon | Higher production costs due to low scale<br>Requires high levels of renewable electricity generation |

# How is hydrogen transported and stored?

Hydrogen as a gas has low energy content by volume under atmospheric conditions, so it must be compressed or liquefied in order to be stored and transported. Cooling and liquefying hydrogen is more energy intensive than compression, and as a result liquefied hydrogen may have a higher carbon intensity, depending on the source of electricity used for the process.[17]

The transportation and distribution of hydrogen can occur using existing or new infrastructure. Hydrogen can be blended in natural gas and separated after transportation, thereby facilitating the use of existing natural gas transmission and distribution infrastructure to transport hydrogen over long distances. While most pipelines can accommodate small percentages of hydrogen blending (e.g. in the 5-15% range), the blending of higher percentages (or the transportation of pure hydrogen) may require specially purposed pipelines. Transportation of higher blends may be possible in newer natural gas pipelines or through the use of technologies to convert hydrogen to synthetic methane for distribution by pipeline.

Hydrogen can also be transported by rail or truck in compressed and liquefied form, similar to industrial gases. While liquefied hydrogen tends to be less expensive to distribute than compressed hydrogen, the liquefaction cost may act as a barrier.

Ultimately, the hydrogen demand and the transportation distance will influence the state of hydrogen and mode of transport used. The estimated cost of delivery and dispensing by truck is provided in Table 2. Distribution of blended hydrogen (in the 5-15% range) by pipeline is expected to be less expensive when an existing pipeline is used, or where large hydrogen demand justifies the capital cost of building specially purposed pipelines.[18]

Table 2. Cost of distributing and dispensing one kg of hydrogen by truck in Canada

| | 100 km | 500 km |
|---|---|---|
| Truck, gaseous $H_2$ | $6.00 | $9.90 |
| Truck, liquid $H_2$ | $2.80 | $3.00 |

Source: Zen Clean Energy Solutions[19]

Storage of hydrogen depends on the fuel's end use. Hydrogen is typically stored as a compressed gas in a high-pressure tank or as a liquid fuel in a cryogenic (low-temperature) container. The cost to store hydrogen varies widely, depending on the method of storage.

# How can hydrogen be used?

The use of hydrogen fuel is currently quite limited in Canada. Although Canada has a dynamic hydrogen industry, the sector is largely engaged in producing hydrogen for use as a chemical in industrial applications and exporting hydrogen-based technologies (e.g. fuel cells) to regions such as China, Europe and California.[20,21]

Hydrogen can replace fossil fuels for various applications, including in buildings, electricity, industry and transportation. But hydrogen's value-add lies in its potential to reduce emissions from hard-to-decarbonize sectors. Hydrogen can also be used in the production of fuels made by synthesizing (or combining) different types of gases (such as hydrogen, carbon monoxide and carbon dioxide). Examples include synthetic methane, methanol and ammonia. As hydrogen produces no harmful emissions at the point of use in a fuel cell, it contributes to improved air quality in regions where it replaces more polluting fossil fuels, such as natural gas, gasoline or diesel, that emit various levels of air contaminants that have adverse effects on health and the environment (e.g. smog, acid rain). Green and blue hydrogen can also be blended with fossil fuels (e.g. natural gas) to reduce the carbon intensity of the fuel. Table 3 outlines the main end uses of hydrogen that are currently in development or are commercially available, across four primary sectors.

Table 3. Possible end uses of hydrogen across various sectors

| Sector | Hydrogen<br>**In fuel cells: Hydrogen is directly converted into electricity**<br>**Through combustion: This typically requires switching to different engines or turbines.** | Blended hydrogen<br>**Blended with existing gas and liquid fuels to lower their carbon intensity.** |
|---|---|---|
| Buildings | Can be used to:<br>• power household appliances, such as hydrogen fuel cell heat pumps<br>• generate home electricity using a fuel cell<br>• produce combined heat and power (e.g. district heating systems) | Blended with natural gas used to heat, cool and power buildings (including combined heat and power)<br>Can be used in existing appliances (like furnaces and stoves) if blended into the natural gas grid. |
| Electricity | Can be used for:<br>• electricity generation (in some turbines)<br>• electricity storage: using electrolysis to convert excess electricity generation (e.g. from renewable sources) to hydrogen, in a process called "power-to-gas" | Blended with natural gas for electricity generation (in some turbines) |
| Industry | Theoretically feasible for use in high-temperature heat processes but technical challenges remain[22] | Blended with fossil fuels used to generate high-temperature heat in industry |
| Transport:<br>Light-duty passenger vehicles | Can be used in fuel cell vehicles | Not being pursued commercially |
| Transport:<br>Heavy-duty freight and mass transit | Can be used in fuel cell vehicles that carry heavy loads over long routes (i.e. heavy-duty vehicles (trucks, buses, rail, marine))<br>Fuel cell vehicles have higher energy storage density and shorter refuelling times, and are lower in weight than battery electric vehicles | Blended with diesel for use in retrofitted diesel engines[23] |

## Does hydrogen have a role in Canada's energy transition?

How hydrogen is made matters. Green hydrogen offers the greatest climate benefit. Blue hydrogen's carbon intensity — and climate benefit — depends on the rate of carbon capture and the level of emissions from natural gas extraction and processing. Hydrogen created with renewable energy (i.e. green hydrogen) or from natural gas with carbon capture and storage (i.e. blue hydrogen) can play a key role in decarbonizing Canada's energy systems. However, only a small fraction of hydrogen produced today is low carbon (i.e. green or blue).

Blending low-carbon hydrogen with fossil fuels can deliver incremental reductions in carbon intensity. Technical barriers will ultimately limit the blending percentage and, therefore, the climate benefits of this approach.

Hydrogen is not a one-size-fits-all solution for reducing carbon emissions. Realizing hydrogen's full potential will require robust national and provincial strategies that identify the sectors that will most benefit, fund research on new and cost-effective technologies, account for regional contexts, and introduce policies to encourage production and use. It's time for a national dialogue on the role of hydrogen as a contributing pathway to net-zero emissions and as a potentially important driver in a new clean economy for Canada.

# Endnotes

1 U.S. Department of Energy, *Increase Your $H_2$IQ!*, 5. https://www.energy.gov/sites/prod/files/2019/09/f67/fcto-increase-your-h2iq-training-resource-2019-update.pdf

2 Government of Canada, "Canadian Hydrogen and Fuel Cells Industry: Frequently Asked Questions," (2016). https://www.ic.gc.ca/eic/site/hfc-hpc.nsf/eng/h_mc00138.html

3 Jacques Roy and Marie Demers, *The hydrogen option for energy: a strategic advantage for Quebec,* 17 (2019). https://hydrogene.quebec/pdf/The%20Hydrogen%20Option%20for%20Energy_A%20Strategic%20Advantage%20for%20Quebec.pdf

4 Ho Lung Yip et al., "A Review of Hydrogen Direct Injection for Internal Combustion Engines: Towards Carbon-Free Combustion," *Applied Sciences* 9 no. 4842 (2019). doi:10.3390/app9224842

5 Although there are no official definitions for grey, blue and green hydrogen, Table 1 presents commonly accepted characterizations for each type.

6 International Energy Agency, *The Future of Hydrogen: Seizing Today's Opportunities – Technology Report*, 38 (2019). https://www.iea.org/reports/the-future-of-hydrogen

7 Other options for hydrogen production include industrial byproduct hydrogen and pyrolysis of biomass; those are not included in the table because they are expected to produce marginal volumes of hydrogen.

8 Although there is no official definition, blue hydrogen is usually deemed to capture 80 to 90% of carbon emissions produced by the SMR. Emissions from producing natural gas (e.g. methane, energy combustion to run operations), commonly referred to as "upstream emissions" are generally also accounted for.

9 Carbon intensity figures account for indirect emissions from electricity production as well as natural gas production (including methane emissions). Carbon intensity figures for grey and blue hydrogen assume natural gas as a feedstock. For reference, the approximate carbon intensity of compressed natural gas and liquefied natural gas are 64 and 113 g $CO_2$e/MJ, respectively; diesel is 95 g $CO_2$e/MJ; and gasoline is 88 g $CO_2$e/MJ.

10 Zen Clean Energy Solutions, *BC Hydrogen Study,* Appendix C, 183 (2019). https://news.gov.bc.ca/files/ZEN-BCBN-Hydrogen-Study-Appendices.pdf

11 The range in carbon intensity illustrates the variation in upstream emissions, with the lower limit representing natural gas produced in B.C. and the upper limit natural gas produced across Canada.

12 The range in carbon intensity for blue hydrogen illustrates the variation in carbon capture rate as well as upstream emissions. The lower value represents blue hydrogen produced with a 90% carbon capture rate at the SMR stage combined with upstream emissions observed in B.C. The upper value uses a 80% carbon capture rate combined with the average upstream emissions in Canada.

13 The range in carbon intensity for green hydrogen reflects the indirect emissions associated with electricity production, with the lower value representing off-grid wind and the higher value corresponding to hydro (e.g. methane emissions from reservoirs).

14 Jessica Lof et al, *Future of Freight Part B: Assessing Zero Emission Diesel Fuel Alternatives for Freight Transportation in Alberta* (CESAR, 2019), 25-29. https://www.cesarnet.ca/sites/default/files/pdf/cesar-scenarios/CESAR-Scenarios-Future_of_Freight_B.pdf

15 Cost estimates are in 2016 C$ for wholesale hydrogen production only and do not include costs associated with distribution and dispensing. The ranges solely reflect the variation in feedstock price, as explained in the source. The apparent overlap between grey and blue hydrogen costs depicts different natural gas market conditions.

16 Blue hydrogen costs include the cost of carbon capture and storage, estimated at about C$0.43/kg $H_2$. Source: *Future of Freight Part B.*

17 United States Department of Energy, "Fuel Cell Electric Vehicle Emissions," *Alternative Fuels Data Center.* https://afdc.energy.gov/vehicles/emissions_hydrogen.html

18 *The Future of Hydrogen*, 80.

19 Zen Clean Energy Solutions, *BC Hydrogen Study*, 54 (2019). https://www2.gov.bc.ca/assets/gov/government/ministries-organizations/zen-bcbn-hydrogen-study-final-v6.pdf

20 Government of Canada, "Canadian Hydrogen and Fuel Cell Industry," (2018). http://www.ic.gc.ca/eic/site/hfc-hpc.nsf/eng/Home

21 *BC Hydrogen Study,* 29. https://www2.gov.bc.ca/assets/gov/government/ministries-organizations/zen-bcbn-hydrogen-study-final-v6.pdf

22 *The Future of Hydrogen*, 119.

23 Hydra, "Hydrogen-As-A-Service For Commercial Fleets." https://hydraenergy.com/

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