Hydrogen Factsheet - Canada

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Political and economic environment	
Main export partners for goods (by trade value in 2019)[1]	• USA (C$443 bn., €301 bn.)[2] • EU (C$50 bn., €34 bn.) • China (C$24 bn., €16 bn.)
Main export goods (by share of total trade in 2019)[3]	• Energy products (mostly crude oil and bitumen)[4] (19%) • Motor vehicles and parts (16%) • Consumer goods (12%)
Most relevant free trade agreements (year of entering into force)	• European Union (CETA) (2017) • USA & Mexico (CUSMA, before NAFTA) (2021) • United Kingdom (2021) • Australia, Brunei, Chile, Japan, Malaysia, Mexico, New Zealand, Peru, Singapore, Vietnam (CPTPP) (2018) • South Korea (CKFTA) (2015) • EFTA region (2009)
Hydrogen strategy and economy	
Current annual grey hydrogen production[5]	• 3 Mt (via Steam Methane Reforming, SMR)
Largest hydrogen consuming sectors	• Refining • Chemical production

Existing hydrogen strategy[5]	• Released in December 2020
	• Does not come with its own budget
	• Sets the following goals for Canada for 2050:
	  - Canada among the 3 largest producers of clean hydrogen globally
	  - End-use costs between 1,50-3,50 C$/kg
	  - Hydrogen makes up 31% of final energy demand (20,5 Mt/a)
	  - Hydrogen sector worth C$47 bn. (€32 bn.), with 358,000 jobs
	  - At least 5 mil. FCEVs on the road
	  - Canada exports significant amounts of hydrogen
	• Stresses the significance of partnerships with Indigenous communities, who could benefit from business opportunities and increased energy independence in a hydrogen economy

[1] Government of Canada (2020)

[2] Average exchange rate of 2019-2022: 1 EUR = 1.47 CAD

[3] Ibid.

[4] CEC (2020a)

[5] NRCan (2020a).

Projects in operation (renewable or low-carbon)[6]	• 6x electrolysis plants (>23 MW) • 2x SMR + CCS (>300 kt H_2/year) • 2x from oil (with CCS)
Existing hydrogen pipelines[7]	• Total length: 147km, 6th largest pipeline network globally
Planned major projects [up to 2030][6]	• 12x electrolysis plants in planning (>258 MW). Various other green hydrogen export projects in preliminary planning (>5 GW) • 6x SMR + CCS (>1,133 kt H_2/year)
Main support schemes for "clean hydrogen" at the federal level	• "Low-carbon and Zero-emissions Fuels Fund" (C$ 1,5 bn. or €1 bn. for low-carbon fuels including hydrogen) • From fall 2022: Federal investment tax credit of up to 30% on clean hydrogen
Main potential end-uses for domestic hydrogen demand[8]	• Injection in gas grids for space heating and heating for industry (oil and gas, steel, cement) • Feedstock for industry (synthetic fuels, ammonia, methanol, oil refining, metals and steel) • Transport (long distance, heavy duty, rail, sea, material transport) • Electricity storage (stationary plants, remote areas, back-up power)
Hydrogen export potential[9]	• Estimated at 25-35 Mt H_2/a in the long-term for green hydrogen.
Main hydrogen production technologies in focus[8]	• According to the federal strategy: Cheap, low-carbon forms of hydrogen in the short- and mid-term (emphasis on blue hydrogen); increased focus on emission-free hydrogen in the long-term (green, fossil-based and nuclear) • Certain Eastern provinces including Quebec focus on green hydrogen
Primary focus of export substance	• Both blue (mainly to Asia) and green hydrogen (mainly to Europe)

	Year	2020	2030	2040	2050
Estimated costs of Canadian hydrogen production [Levelised Cost of Hydrogen, LCOH in USD/kgH_2][10]	baseline	3.3 - 6.6	2.6 - 4.3	2.2 - 3.6	1.9 - 2.8
	optimistic	2.7 - 4.7	2.2 - 3.6	1.8 - 2.9	1.5 - 2.5

Transportation options to Europe	• Shipping via Atlantic provinces to the EU, through:
	  • Existing oil product & ammonia terminals (and ships) for NH_3/ LOHC exports
	  • Newly built H2-ready LNG terminal or dedicated ammonia terminals; newly built LH_2 terminals and ships (first ships available from 2025 onwards)

[6] IEA (2021a)

[7] PNNL (2016)

[8] NRCan (2020a)

[9] adelphi (2021)

[10] Own calculations based on Brändle et. al. 2020 (EWI H_2-Tool): low temperature electrolysis, only onshore wind and solar PV.

Main sustainability challenges		
Methane and CO_2 emissions associated with blue hydrogen	• Blue hydrogen production is associated with significant unaccounted upstream and downstream methane emissions as well as energy-related CO_2 emissions associated with CCS. • Without thorough emissions monitoring, fugitive CO_2 could escape unnoticed from the storage site during injection and over time. • Utilisation of captured CO_2 for enhanced oil recovery further raises questions regarding the carbon footprint.	
Water resources/ water stress level	• With 7% of the world's fresh water, Canada has little water risks. However, certain locations with very good RE potential in Alberta and Saskatchewan show high water risks.	
Fracking	• 65% of Canadian natural gas is produced from unconventional tight or shale resources[11], for which hydraulic fracturing (fracking) is used. • Fracking is associated with a host of environmental problems such as degradation of water availability and quality, chemical spills and induced seismicity.	
Oil sands production	• 63% of Canadian oil is produced from oil sands • Oil sands production is very energy- and emission-intensive, has a large freshwater usage and causes environmental damage to groundwater, habitats and biodiversity.	
Land use conflicts, conflicts of interests with environmental protection, etc.	• Less problematic than in many other countries, due to the availability of very large areas with very low population density and comparably low biodiversity.	
Existing and future energy system & decarbonization strategy	2019	2030 (forecast, reference case)
Total electricity generation (net imports) [TWh]	641 (-47)	700 (-52)[12]
RES share in electricity generation	66%	71%[12]
CO_2 intensity of electricity mix [gCO_2/kWh][13]	131.2	95.3
Dominant fossil fuel in electricity generation (share in total generation)	Natural gas (10%)	Natural gas (17%)
GHG emissions (incl. LULUCF) in kg per unit of GDP [14]	0.43	-
GHG emissions (incl. LULUCF) in tons per capita [15]	19.8	-
Decarbonization goals[16]	• -40 to 45% by 2030 (compared to 2005) • Net zero by 2050	

[11] NRCan (2020b)

[12] CER (2020b, Reference case)

[13] IEA (2020a)

[14] OECD.Stat (2021)

[15] Ibid.

[16] Government of Canada (19.05.2022)

Opportunities for hydrogen cooperation and trade between Canada and the EU

Strengths	Weaknesses
Existing federal hydrogen strategy, with goal to become a large producer and exporter of hydrogen	In certain provinces, independent renewables developers face challenges due to vertically integrated electricity companies in monopoly
Very good RE potential for low-cost green hydrogen production and export, especially in Eastern Canada	Sustainability issues associated with hydrogen production from fossil fuels (methane and CO_2 emissions, fracking, oil sands production)
Strong interest in Atlantic provinces in exporting green hydrogen to Europe	Delays in implementation of large-scale energy infrastructure projects (e.g. pipelines) in the past
Cheap electricity prices and extremely high shares of renewables in Eastern Canada (some provinces with >90% RE in the power mix)	Water risk[17] in areas with strong RE potentials in Alberta and Saskatchewan
Comparatively short shipping distance from Eastern Canada to Europe compared to the Arabian Peninsula, Persian Gulf, Southern Africa or South America	
Geopolitical advantages of energy trade relationship, with Canada being a long-standing democratic partner	
Existing collaboration on energy issues, partner in IPHE consortium	
Leading hydrogen technology sector, but also opportunities for EU technology providers	
Good governance, experienced energy workforce and great conditions for doing business	

Source: own

Convergence	Divergence
High ambitions for climate change mitigation at federal level, as well as in many provinces	Strong focus on fossil-fuel based hydrogen due to significance of oil and gas sector
Hydrogen is seen as vital to the future energy system (2050: 31% of Canadian energy demand)	Preference for focusing on emission-intensity of hydrogen instead of colour-codes (e.g. green or blue hydrogen)
Liberal and democratic partner with high human rights standards	

Source: own

[17] This includes all water-related risks, by aggregating indicators such as the physical quantity, quality and regulatory & reputational risk categories. For further details see WRI 2021.

Executive Summary

Canada is one of the ten largest hydrogen producers worldwide, producing three million tons of grey hydrogen per year (Mt/a). The country is leading in the development of hydrogen technology such as fuel cells and electrolysers.

In December 2020, Canada released its federal hydrogen strategy, which sees hydrogen as an opportunity to boost economic growth, reach climate neutrality and diversify the oil and gas sector. For 2050, it aims for Canada to be among the three largest clean hydrogen producers globally as well as a large exporter. The strategy focuses on both blue and green hydrogen but emphasises the favourable conditions in Canada for fossil fuel-based hydrogen.

In 2050, hydrogen is envisioned to make up 31% of final energy demand (21 Mt/a), predominantly in space and process heating, as industrial feedstock, in transport and for electricity storage. Funding of C$1.5 bn. (€1.1 bn.) is provided through the "Low-carbon and zero-emissions fuels fund" for low-carbon fuels, including hydrogen. A federal tax credit for clean hydrogen was announced in Budget 2022 and is expected to be made available from fall 2022. Several Canadian provinces have released their own hydrogen strategies. The federal hydrogen strategy emphasizes that the provinces should pursue their hydrogen pathways based on their own resources and assets.

With great potential for both onshore and offshore wind energy and a large hydropower capacity, Canada could become a green hydrogen exporter. Especially in the Atlantic provinces, which lie closest to Europe, there is great potential for green hydrogen production and export. Due to its large natural gas reserves and potential CO_2 storage sites, there is also great potential for blue hydrogen production in Western Canada.

For hydrogen shipping, it is estimated that ammonia- and LOHC-based seaborne transport will be the most cost-efficient options in the short- and medium-term, while liquid hydrogen could become the cheapest option in the long-term when pure hydrogen is needed. Shipping costs are estimated to be similar for hydrogen shipped from Canada, the US or the Arabian Peninsula.

The main sustainability challenges that could arise regarding hydrogen in Canada are the methane and CO_2 emissions associated with fossil fuel-based hydrogen production, water risks in Western Canadian locations with very good RE potentials and the environmental damage associated with fossil fuel extraction (especially fracking).

1. Political system, governance & economy

Canada is a constitutional monarchy with a parliamentary elected government. The current head of government is Prime Minister Justin Trudeau from the Liberal Party, who has been in office since 2015. Canada has a federal administrative structure, with ten provinces (Alberta, British Columbia, Manitoba, New Brunswick, Newfoundland & Labrador, Nova Scotia, Ontario, Prince Edward Island, Québec and Saskatchewan) and three federal territories (Northwest Territories, Nunavut and Yukon). The provinces and territories have extensive responsibilities over regional policy issues including energy and the use of natural resources.

Canada is the second-largest country by area and the ninth largest economy in the world. In 2019, GDP was C$1.74 trillion (€1.18 trillion) and GDP per capita was C$46,200 (€31,400)[18]. Energy and related industries made up 8.1% of GDP in 2020, with 4.7% of employed Canadians (845,500) working directly or indirectly in energy[19]. The main export partners are the US, EU and China, the main export products are crude oil and bitumen, vehicles and their parts, and consumer goods. Energy accounts for 23% of total exports.

2. Energy and Electricity

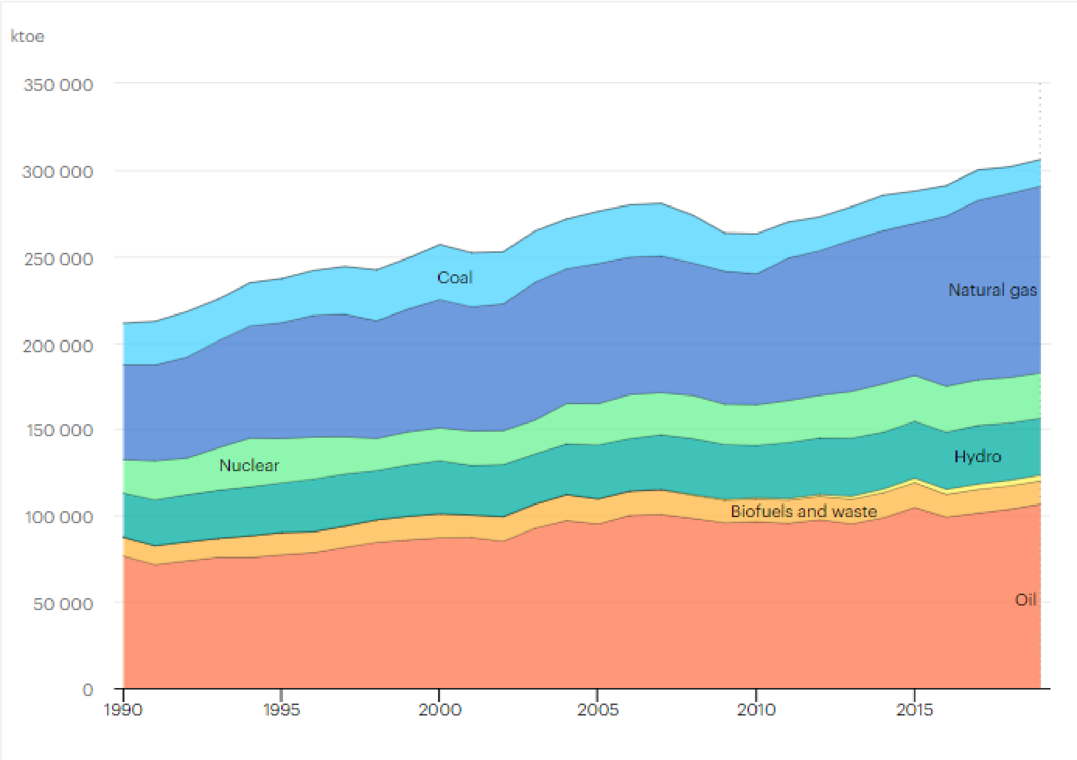
2.1. Production and demand

Canada is the sixth-largest producer of energy worldwide, the fourth-largest of oil and uranium, the fifth-largest of natural gas, and the third-largest of hydropower. The majority of oil and natural gas is produced in Alberta (2019: 81% of oil, 71% of gas)[20]. Canada has the sixth-largest primary energy consumption and fifth-largest primary energy consumption per capita in the world[21]. This can be explained by the country's large area size, rough climatic conditions as well as the energy-intensive production and processing of oil and gas[22].

As Figure 2 shows, oil and gas made up the largest share in primary energy consumption in 2019 (35% respectively), followed by hydropower (11%), nuclear (9%), coal (5%), biomass and waste (4%) and other renewables including wind and solar (1%). Thus, fossil fuels still account for 75% of primary energy consumption. Further, primary energy consumption has grown by 45% since 1990, mostly due to growth in the use of natural gas and oil. Coal is increasingly being displaced.

[18] World Bank (2020a)
[19] NRCan (2021)
[20] NRCan (2020b)
[21] BP (2020)
[22] OECD/IEA (2018)

Figure 1: Primary energy consumption of Canada, 1990-2019[23]



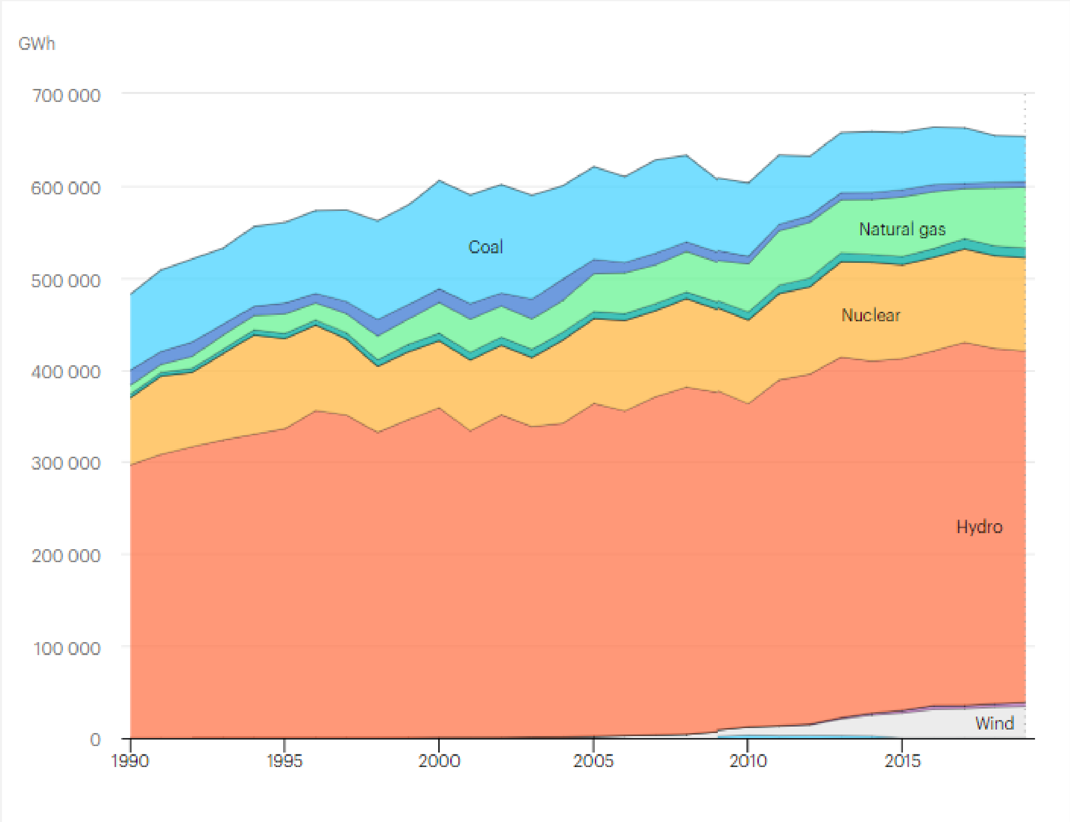
Source: IEA 2020b. All rights reserved. Total energy supply (TES) by source, Canada 1990-2020. Available at: https://www.iea.org/countries/canada

In 2018, industry and resource extraction accounted for the largest share of final energy consumption (39%). While most industries (pulp and paper, metals and steel, manufacturing, refineries, chemicals, construction, forestry and cement) have slightly decreased their energy use since 1990 (-3%), energy use of resource extraction (mostly oil and gas) has grown greatly (+317%). Transport makes up the second-largest share in final energy consumption (29%), followed by buildings (29%).[24]

Electricity generation in Canada totalled 635 TWh in 2019.[25] The power mix was made up by hydropower (59%), nuclear (15%), natural gas (10%), coal (7%), wind (5%), biomass (2%) and solar (1%) (average emission intensity: 131.2 g CO_2/kWh[26], EU: 255[27]). As Figure 3 shows, coal's share in the power mix has decreased significantly since 1990. In contrast, the share of natural gas has increased. Slight growth can be observed for nuclear energy, for which Canada is now the sixth-largest producer, as well as for renewables (from 62% to 66% since 1990). The fastest-growing electricity sources were wind (1995: 59 GWh, 2019: 34,000 GWh) and solar (1995: 4 GWh, 2019: 4,200 GWh).

[23] IEA (2020b)
[24] NRCan (2019a)
[25] NRCan (2021)
[26] IEA (2020a)
[27] EEA (2021)

Figure 2: Canada's power mix, 1990-2019[28]



Source: IEA 2020c. All rights reserved. Electricity generation by source, Canada 1990-2019. Available at: https://www.iea.org/countries/canada

The coal phase-out in electricity generation until 2030 was legally decided in 2018. The federal government expects that the share of natural gas in electricity supply will grow as a result[29]. Nuclear energy is also seen as an important element of a diversified energy mix. While 6 of 19 reactors will close until 2024, the majority shall be refurbished. There are no plans to construct new traditional reactors. However, the future deployment of small modular reactors is supported.

Canada has a large hydropower fleet (560 plants, 81 GW), which has grown by 10 GW in the past decade. Over the next few years, the large plants “Site C” in British Columbia, “Keeyask” in Manitoba, and “Muskrat Falls” in Newfoundland and Labrador are expected to be fully commissioned (total of 2.6 GW). Wind energy capacity totalled 14 GW in 2021 (8th largest fleet in the world), with most wind farms in Ontario, Quebec and Alberta. Wind deployment was very fast between 2008 and 2015, and fell subsequently. Total solar capacity was at 3.6 GW in 2021, with 99% of solar plants in Ontario. Solar deployment was very fast between 2009 and 2016 and fell afterwards. The stagnating growth of wind and solar can be explained by Canada’s already largely emission-free power mix, a missing federal renewable energy (RE) target, the recent push-back to RE expansion by conservative provincial governments, as well as the neglect of wind expansion in Quebec due to the province’s electricity surpluses in past years.[30]

[28] IEA (2020c)

[29] CER (2020b, Chapter 3. Reference and High/Low Price Case Results, Electricity Generation)

[30] National Observer (2017).

2.2. Import and export

Canada is a net energy exporter. In 2020, energy products, which accounted for 18% of total exports, were exported to 142 countries and worth C$95 bn (€65 bn.).[31] Canada is the third-largest exporter of both oil and electricity and the sixth-largest of uranium, natural gas and coal. 90% of energy exports go the US (C$86 bn., €59 bn.). The US imports 79% of oil, 56% of uranium, 42% of natural gas and 9% of electricity, that is produced in Canada. In 2020, Canadian electricity exports accounted for 67.2 TWh. Quebec is Canada's largest electricity exporter, followed by Ontario, Manitoba and British Columbia.

Canadian energy imports (mostly oil, gas and coal) account for 6% of total imports. 77% of imported energy comes from the US (C$24 bn., €16 bn.).[32] Provinces such as mainly Alberta, Manitoba and British Columbia import electricity from the US to meet peak demand or take advantage of cost benefits[33]. Electricity imports totalled 9.8 TWh in 2020.

3. Decarbonization and RES policies

In June 2021, the Canadian parliament passed the 'Bill C-12', which enshrined the net-zero target for 2050 as well as a more ambitious economy-wide target (and new Nationally Determined Contributions) for 2030 (40-45% instead of 30% reduction compared to 2005) in law. The bill also demands that the government sets interim five-year targets and develops implementation plans and progress reports, which are to be evaluated by an independent committee[34].

In 2016, under the leadership of Prime Minister Trudeau, the federal government, the provinces and territories agreed on a coordinated strategy for climate and energy policy with the establishment of the Pan-Canadian Framework on Clean Growth and Climate Change (PCF). Canadian climate mitigation policy now builds on three main pillars, the most important being the federal carbon tax. Since 2019, this federal 'backstop' carbon pricing system has been applicable in those provinces and territories, which do not have their own pricing system that meets the federal minimum standards[35]. In 2019, the federal tax levied on producers and traders of most fossil fuels started at C$20 per tonne of CO_2 (€14), rising to C$50 (€34) in 2022 and C$170 (€116) in 2030. In addition, there is an 'output-based pricing system' (OBPS) for large industrial emitters, which sets sector-specific emission caps[36]. Those companies that emit less than the cap receive tradable certificates in return, and those that emit more have to buy those certificates or make payments in accordance with the federal tax. After several provinces had sued against the federal carbon tax, Canada's Supreme Court confirmed its constitutionality in March 2021.

The second pillar of climate policy is the phase-out of coal-fired electricity generation, which was enshrined in law in 2018.[37] Affected are all coal-fired plants: Nova Scotia (7), Alberta (6), Saskatchewan (1) and New Brunswick (1). The third pillar is the introduction of the Clean Fuel Standard (CFS), which will require suppliers of liquid fuels (gasoline, diesel, kerosene, other fuel oils) to gradually reduce their fuel emission intensities from December 2022.[38] The standard will be accompanied by a trading system for suppliers.

[31] NRCan (2021)
[32] NRCan (2020b)
[33] CER (2021a)
[34] Pembina Institute (2021)
[35] ECCC (2021)
[36] IETA (2021)
[37] Government of Canada (2018)
[38] Pembina Institute (2020)

In December 2020, the federal government updated its climate plan, by increasing the federal carbon tax to C$170 by 2030 and setting up a budget of C$15 bn. (€10 bn.) for the retrofitting of buildings, production of low-carbon fuels (including hydrogen), grid modernisation, energy storage, RE expansion, low-emission vehicles and charging infrastructure[39]. These funds were added to the already committed C$60 bn. (€41 bn.) within the PCF and another C$6 bn. (€4 bn.) from the "Clean Infrastructure Fund". The new climate plan also considers the development of a carbon border adjustment mechanism (CBAM) after consulting with the EU. In February 2021, another C$15 bn. (€10 bn.) were committed over eight years for the expansion of public transport[40].

The 2021 budget provides for a further C$17.6 bn. (€12 bn.) for green recovery investments, including in energy technologies, retrofitting, carbon capture and storage (CCS), energy efficiency, battery production and ZEVs. In June 2021 it was announced, that from 2035, the sale of new internal combustion vehicles will be banned[41]. Already today, there are emission standards for road vehicles and support schemes for ZEVs in place. In March 2022, the Federal Government presented an updated emission reduction plan for 2030, with new investments worth C$9.1 bn. (€6,2 bn.) for measures supporting ZEVs, CCUS, low-carbon fuels and green electricity. In the plan, Canada also set a target to reduce methane emissions from oil and gas by 75% until 2030 (compared to 2012). With the release of Budget 2022 in April, the funds behind the updated climate plan were specified, among those are C$3.4 bn. for zero-emission vehicles and charging infrastructure, C$2.6 bn. for CCUS projects and C$2.2 bn. for emission-reduction projects through a low-carbon economy fund.

Canada does not have a federal RE target, but a target for 90% emission-free electricity (which includes nuclear) by 2030 (Government of Canada 2020). A substantial, long-term support scheme for RE does not exist. From 2007 to 2011, the federal government supported RE with a small feed-in tariff of C$0.01 for up to 10 years (IEA 2013). Between 2018 and 2023, the government's "Emerging Renewable Power" programme supports emerging energy technologies (including offshore wind, geothermal, solar farms) with C$200 mil. (€136 mil.). The "Clean Energy for Rural and Remote Communities" programme supports RE projects in rural areas with C$220 mil. (€150 mil.). The updated climate plan from December 2020 promised another C$964 mil. (€656 mil.) for RE and grid modernisation projects over four years. Another C$300 mil. (€204 mil.) Also, the public Infrastructure Canada Bank has announced C$2.5 bn. (€1.7 bn.) for green grid infrastructure projects and energy storage over 1.5 years in 2020.[42] The 2021 budget provides for a further C$1 bn. (€0.7 bn.) for large-scale clean technology projects, which also include RE.[43] The Budget 2022 made available C$900 mil. (€612 mil.) for clean electricity and grid modernisation.

While there is no federal RE target, targets differ at the provincial level. British Columbia, Newfoundland and Labrador, and Manitoba (all of which have RE shares in electricity generation of 95% or higher) have no RE targets or have already achieved them. Quebec also has more than 99% of RE in the power mix, but set the target to increase RE generation by 25% until 2030[44]. In Ontario (60% nuclear, 35% RE in the power mix), there is the target to expand RE capacity to 20 GW by 2025. However, the conservative government brought RE deployment to a standstill by repealing the provincial feed-in tariff, which had been in place since 2009.[45] In 2016, Alberta (mainly natural gas- and coal-fired electricity generation, with only 9% RE) set a 30% RE target for the power sector by 2030. After the conservatives took over government in June 2019, the successful auction system was discontinued after three

[39] SP Global (2020)

[40] Government of Canada (2021a)

[41] Reuters (2021)

[42] Canada Infrastructure Bank (2020)

[43] Government of Canada (2021a)

[44] Gouvernement du Québec (2016)

[45] National Observer (2020)

rounds[46]. The province's 2030 target is now out of reach. Saskatchewan has the target of increasing the RE share from currently 17% to 50% in 2030.[47] In 2021, Nova Scotia set an 80% RE target for 2030. New Brunswick achieved its 40% RE target for 2020. Prince Edward Island currently has no RE target.

4. Hydrogen sector in Canada

Canada produces 3 Mt per year of almost exclusively grey hydrogen and is thus one of the 10 largest producers worldwide[48]. 75% of production takes place in Western Canada. Hydrogen exports to the US amounted to no more than 22,400 t in 2019[49]. With a total length of 147 km, Canada has the sixth-largest hydrogen pipeline grid in the world (PNNL 2016). Hydrogen is primarily consumed in the chemical industry (ammonia and methanol production) and refineries[50]. Fuel cell vehicles are still very rare, there were less than 100 new registrations between 2019 and 2021.[51] There are no fuel cell buses nor trains operating in Canada.

There is an active hydrogen technology sector in Canada, with over 100 companies and 1,600 employees (80% located in British Columbia).[50] The country is leading in the development of fuel cell systems, electrolysers and components, hydrogen fuelling systems and industry applications. Other Canadian companies are active in research, testing and consulting relating to hydrogen. 80% of revenue in the technology sector comes from exports, mostly to China, the US and Germany. Canadian fuel cell technology is part of 80% of running fuel cell applications worldwide. There are several companies along the Canadian hydrogen value chain, in green hydrogen production (including Hy2Gen, Hydrogen Optimized, Hydrogenics/Cummins, Next Hydrogen, RH2C), fossil hydrogen production (including Proton Technologies, Ekona, Air Products, Air Liquide, Praxair, Messer), storage and distribution (including ATCO, Enbridge, Hydrogen in Motion), fuelling (HTEC, Power Tech) and fuel cell development (Ballard Power Systems, Daimler, Greenlight Innovation, Hydrogenics/Cummins, Hyundai, Loop, NFI Group, Toyota, Unilia).

In Canada, there are 6 operating hydrogen electrolysis plants, with a capacity of more than 23 MW. In Bécancour (Quebec), the gas supplier Air Liquide and electrolyser developer Hydrogenics/Cummins completed the construction of a 20 MW PEM electrolysis plant in early 2021. In Ontario, Enbridge Gas and Hydrogenics/Cummins began in 2018 the operation of the first major PtG energy storage project (2.5 MW), through the production of green hydrogen from excess renewable electricity. Another 12 hydrogen electrolysis plants with a capacity of more than 258 MW are planned. There are various other green hydrogen export projects in preliminary planning stages in Canada's Atlantic provinces, predominantly in Newfoundland and Labrador and Nova Scotia (accumulative capacity: > 5 GW). Most of these projects plan to begin production by 2026/27 and to use green ammonia as a hydrogen carrier.

There are two operating projects each for the production of hydrogen from natural gas + CCS and from oil + CCS, another two SMR+CCS plants are planned. In Alberta, Shell has been running a blue hydrogen project since 2015, storing emissions associated with SMR underground in the Quest CCS Facility (around 1 million tons of CO_2 per year). At the same location, the gas supplier ATCO is planning a large-scale blending project, feeding up to 5% of hydrogen into the gas grid. Lastly, in Saskatchewan, Proton Technologies is developing a pilot project for the production of low-emission hydrogen by

[46] Calgary Herald (2019)

[47] CER (2021b)

[48] Layzell et al. (2020), Clean Energy Canada (2020)

[49] World Bank (2020b)

[50] NRCan (2019b)

[51] Statistics Canada (2022)

injecting oxygen into existing oil reservoirs to break down hydrocarbons and water underground. The split off hydrogen is then extracted, while the CO_2 should remain trapped in the soil.

5. Hydrogen strategies & support schemes

In December 2020, Canada released its federal hydrogen strategy[52], which emphasises the opportunities of hydrogen for the country: It could grow the export economy, diversify the oil and gas sector, advance the domestic hydrogen technology sector and help with decarbonisation and energy security. The strategy sets the following goals for Canada for 2050:

- Canada among the 3 largest producers of clean hydrogen globally (both blue and green)
- End-use costs between 1,50-3,50 C$/kg (1.00-2.40 €/kg)
- Hydrogen makes up 31% of final energy demand (20,5 Mt/a)
- Hydrogen sector worth C$47 bn. (€32 bn.) with 358,000 jobs
- At least 5 mil. FCEVs on the road
- Canada exports significant amounts of hydrogen

While the strategy does not specify how much hydrogen shall be produced in the future, the export focus would require more than the expected demand of 20 Mt/a by 2050. No production routes are pre-excluded, the focus is instead on emission intensity. It is assumed that, depending on the region, the cheapest, low-emission type of production will prevail. The strategy emphasises the cost advantage of fossil fuel-based hydrogen production in Canada, due to large reserves and good conditions for CCS. According to the strategy, with Canada's conditions, domestically produced blue hydrogen would be able to cover demand for decades. The strategy does not get into the details of expanding renewable energy capacity for green hydrogen production. It is concluded that meeting long-term demand will require a diversified production mix including blue and green hydrogen.

According to the more ambitious scenario of the strategy, Canada's hydrogen demand is expected to be at 4 Mt/a by 2030 and 20 Mt/a by 2050 (currently at 3 Mt/a). It is claimed that, generally, direct electrification shall be preferred to hydrogen. Hydrogen is to be used primarily in energy-intensive applications, where it is superior to other low-emission alternatives. Still, in the estimated final energy mix for 2050, hydrogen plays a large role, even in sectors and applications that could be electrified (31% hydrogen, 30% electricity, 12% biofuels, 12% low-carbon fuels, 6% natural gas and 9% other). With 11 Mt/a, 52% of hydrogen is estimated to be used for blending into gas grids, from where it will be used predominantly for space heating (where electric heat pumps offer a more efficient alternative), but also for process heat in industrial processes. Blending rates could reach 86%, according to the strategy. With 7 Mt/a, 35% of hydrogen is used as feedstock in industry, primarily in the production of low-carbon fuels, refineries, production of ammonia and methanol and metals and steel production. With 3 Mt/a, 13% is used in transport, mostly in heavy duty and long-distance applications, rail and sea transport, and mining. FCEVs are expected to make up 25% of passenger cars. Lastly, although excluded in the demand models, hydrogen is seen as important in providing electricity storage for stationary, remote and back-up power.

In terms of implementation, the strategy recommends the development of "regional blueprints" that build on the respective geographic and economic conditions in the provinces and territories. Through "early deployment hubs", self-sufficient local hydrogen economies shall develop and expand, grow into a national hydrogen economy. The strategy identifies suitable locations in Alberta's industrial region; around ports in British Columbia, Ontario, Quebec and Atlantic Canada; in the region between Montreal and Detroit; and around electrolysis sites in Manitoba, Quebec and British Columbia.

[52] NRCan (2020a)

No explicit budget was announced with the strategy. Available funding of C$1.5 bn. (€1 bn.) is provided through the "Low-carbon and zero-emissions fuels fund" for low-carbon fuels, including hydrogen. A strategic steering committee has been established to promote and oversee implementation of the strategy. With Budget 2022, the Federal Government announced the introduction of an investment tax credit of up to 30% for clean hydrogen. Details on the proposed incentive will become available later this year.[53] With the new budget, the mandate of the state-owned Canada Infrastructure Bank has been expanded to also allow for investments in hydrogen production, transportation and distribution.

The hydrogen strategy stresses the importance of partnerships with Indigenous communities, for whom the energy sector represents one of the largest employers in Canada. Around 14,000 Indigenous people worked in the energy sector in 2019, with 10,000 people working in oil and gas. Also, Indigenous people play a significant role in renewable energy deployment, (co-)owning and operating many projects across the country. Indigenous communities could both benefit from business opportunities along the hydrogen value chain (e.g. renewable electricity production, build-out and operation of production and distribution infrastructure, etc.) as well as from increased energy independence as locally produced hydrogen replaces imported diesel as an energy resource in remote indigenous lands. Companies such as Fortescue Future Industries are already today cooperating with indigenous communities on green hydrogen projects.

In April 2022, the Commissioner of the Environment and Sustainable Development to the Parliament of Canada published a report criticising the Federal Hydrogen Strategy for making unrealistically high projections for hydrogen demand and for hydrogen's contribution to Canada's emission reductions.[54] The report criticised that the strategy's assumptions were not backed up by realistic cost estimates or provincial or federal policies. It also questioned the feasibility of large-scale hydrogen blending, as envisioned in the federal strategy, pointing to technical and economic challenges.

Due to the provinces' extensive responsibility over natural resources and energy policy, it is expected that they will follow their own hydrogen path based on resource assets, climate policy and economic priorities. Several provinces have announced own hydrogen strategies or have already released them. The federal hydrogen strategy emphasizes that the provinces should pursue their hydrogen pathways based on their own resources and assets.

Alberta has published its hydrogen roadmap in November 2021. As Canada's largest oil and gas producer, the province is particularly interested in blue hydrogen, recognising it as a strategic opportunity for expanding the value chain of natural gas and exporting to markets in the US, Asia and Europe[55]. British Columbia released its hydrogen strategy in July 2021. Due its large gas reserves and good conditions for wind and hydropower as well as an active hydrogen technology sector, the province is very interested in a hydrogen economy based on both blue and green hydrogen.[56] Ontario released its own hydrogen strategy in April 2022, aiming for low-carbon hydrogen produced from nuclear, renewable and fossil energy to become an emerging alternative energy carrier. It sees an advantage in the province's nearly emission-free electricity mix (mostly nuclear and hydro) as well as in existing storage and pipeline infrastructure for natural gas.[57] In May 2022, Quebec released its hydrogen strategy, with a focus on deploying green hydrogen produced from hydropower and wind energy for domestic decarbonisation. End-use is envisioned especially in energy-intensive industry (including steels and refining) and for synthetic fuel production. Hydrogen export is not a focus of the strategy. While the Atlantic provinces have not yet released their own hydrogen roadmaps, some – such as Newfoundland and Labrador – have signalled great interest to become international exporters of green hydrogen.

[53] Government of Canada (2022)

[54] Office of the Auditor General of Canada (2022)

[55] Alberta (2020, 2021)

[56] British Columbia (2021)

[57] Ontario (2022)

6. Potential for hydrogen production

6.1. Green hydrogen

As its hydrogen strategy emphasises, Canada, with a 66% renewable and 81% emission-free (including nuclear) electricity mix, has an advantage for green hydrogen production. Largely, this is due to Canada being the third-largest producer of hydroelectricity. For hydropower, there has been surplus capacity in provinces such as Manitoba, Quebec and Newfoundland and Labrador in the past.[57] In Quebec, however, no more surpluses are projected for the coming years, given domestic electricity demand growth and the province's export commitments to New York and Massachusetts.

However, there is also great potential for both onshore and offshore wind and solar energy. For wind power, very large areas of Canada have average wind speeds of over 8 m/s at heights of 120 m, mostly located on the Atlantic Coast (see Figure 4). For offshore wind, there are many areas with speeds of 10 m/s and more on the Atlantic Coast and at the Great Lakes (comparable to Northern Germany).[58] For solar power, Canada has very large areas with solar irradiation levels of more than 1,250 kWh/kWp across the country (comparable to Northern Italy) and extensive regions in Alberta and Saskatchewan with solar irradiation levels of more than 1400 kWh/kWp (comparable to Northern Spain) (see Figure 5).

As several studies show, Canada has the potential to produce enough RE to cover its own energy demand and additionally export significant RE amounts, which could be in the form of hydrogen[58]. According to one study[59], which looked at Canada's RE production potential in detail and could even be interpreted as a conservative estimate due to several restrictions and outdated assumptions[60], this potential amounts to 3,650 TWh/a, made up by mainly onshore wind (1,380 TWh/a), hydro (1,020 TWh/a), offshore wind (522 TWh/a) and solar (329 TWh/a).

When looking at individual provinces, Piria et al. (2021) show that for Newfoundland and Labrador and other Atlantic provinces, as well as for Quebec, the respective RE production potential exceeds today's final energy demand by a large margin. Assuming that final energy demand will decrease quite significantly due to energy efficiency improvements in most of these provinces, it is concluded that across Eastern Canada, there is great potential for future green hydrogen production and export.[61] Further, assuming that Canada realises its RE production potential, reaches climate neutrality in 2050 and uses only RE for electricity generation and hydrogen production, Piria et al. (2021) estimate the country's green hydrogen export potential at around 25 to 35 million tons per year (Mt/a). Depending on the extent to which fossil fuels and nuclear energy will be used, the export potential is estimated to be much higher.

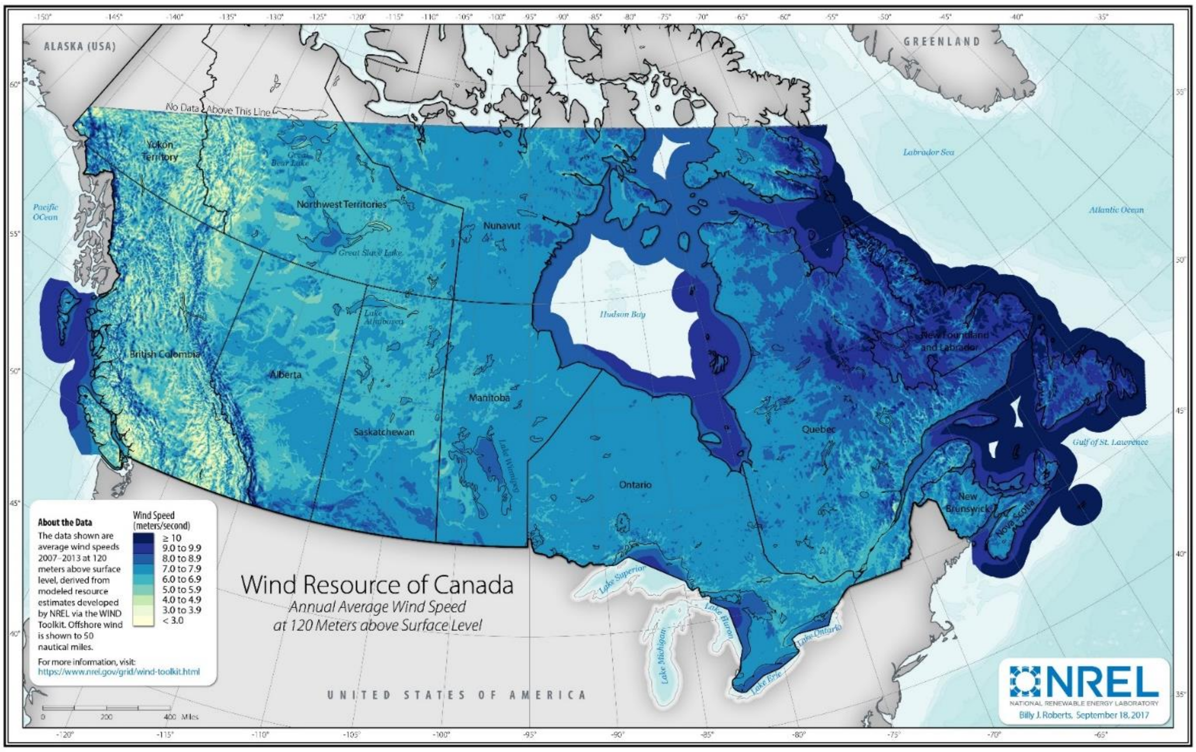
[58] Piria et al. (2021), Barrington-Leigh and Ouliaris (2016), Zozmann et al. (2021), Aghahosseini et al. (2019)

[59] Barrington-Leigh and Ouliaris (2016)

[60] Next to excluding conservation areas, indigenous lands, large water areas and assuming large minimum distances to roads and settlements, the source also uses partly outdated assumptions about productivity and costs of RE (e.g. for onshore wind, relatively low energy yield per area (23 GWh/km²/a) are assumed, for offshore wind, locations with a water depth of 30m are excluded, which is technically exceeded today.)

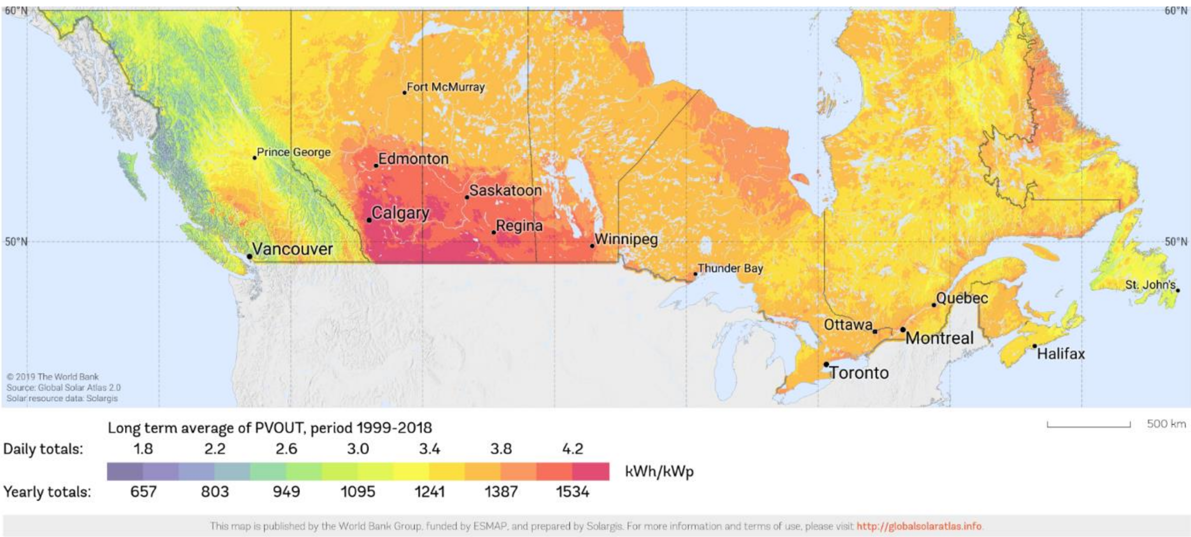
[61] Piria et al. (2021)

Figure 3: Wind speeds across Canada at 120 m heights[62]



Source: Roberts, Billy J., September 18, 2017. Canada Wind Speed at 120-Meter above Surface Level National Renewable Energy Laboratory. Available at: https://www.nrel.gov/gis/assets/images/wtk-120m-can-2017-01.jpg

Figure 4: Solar irradiation across Canada[63]



Source: Map obtained from the Global Solar Atlas 2.0, a free, web-based application is developed and operated by the company Solargis s.r.o. on behalf of the World Bank Group, utilizing Solargis data, with funding provided by the Energy Sector Management Assistance Program (ESMAP). For additional information: https://globalsolaratlas.info

[62] NREL (2017)

[63] Global Solar Atlas (2021)

6.2. Blue hydrogen

The Canadian hydrogen strategy identifies great domestic conditions for the production of blue hydrogen, due to the availability of large natural gas reserves, extensive potential storage sites for captured CO_2, existing fossil fuel infrastructure and the technical expertise in the Canadian oil and gas industry. The most important production method, steam methane reforming (SMR), is technically mature in Canada.[64] Methane pyrolysis is still in an early stage of development.

Today, Canada is the fourth-largest producer of natural gas. At the end of 2017, Canadian natural gas resources amounted to 34,500 bcm. With that amount, Canada could maintain its current level of production for another 300 years.[65] The largest reserves are located in the Western Canadian Sedimentary Basin, which includes parts of Manitoba, Saskatchewan, Alberta, British Columbia and the Northwest Territories. Alberta is the currently largest gas producer, followed by British Columbia and Saskatchewan.

Canada is leading in research and development of CCS, which is pursued as a key decarbonisation technology by the federal government and used for enhanced oil recovery by the oil and gas industry in pilot projects. Potential storage sites for captured CO_2 are large and well spread-out across the country, also in vicinity to large gas reserves in the Western Canadian Sedimentary Basin.[66]

To transport blue hydrogen from Western Canada to Europe, pipelines with a length of around 4,000 km would need to be built through Quebec to the Atlantic Coast. Such transcontinental pipelines are considered by the federal hydrogen strategy. However, no concrete plans exist as of today. Whether such projects will find public support in Quebec remains uncertain. Only recently, Quebec's government has cancelled a planned LNG export project, which would have transported natural gas from Western Canada across Quebec, due to environmental concerns[67].

6.3. Other forms of hydrogen production

The federal hydrogen strategy also considers nuclear power as a potential source of emission-free electricity for hydrogen production. However, Canada's federal energy agency, the Canada Energy Regulator, expects stagnating shares of nuclear energy in the future.[68] 6 of 19 reactors (18 of those are located in Ontario) will close by 2024. The others will have reached an average age of 40 years by then, but are planned to be refurbished.[69] While no new traditional reactors are planned, the deployment of small modular reactors (SMRs) is supported. Yet, all demonstration projects are still at an early stage. Given their uncertain future, the overall expected stagnation in the share of nuclear energy in the power mix and the great RE potential in Canada, it seems unlikely that SMRs will play a large role in Canada's energy system. Thus, future production of hydrogen from nuclear energy will likely be minor compared to green and blue hydrogen production.

Due to Canada's legislated phase-out of coal-fired electricity until 2030, the production of hydrogen from coal gasification is unlikely to develop at scale and will not be considered here. However, the strategy identifies in-situ gasification[70] for crude oil and bitumen as a potential production pathway in the future,

[64] Layzell et al. (2020)

[65] NRCan (2020a, b)

[66] Global CCS Institute (2019), NRCan (2015)

[67] CBC (2021)

[68] CER (2022)

[69] WNISR (2020)

[70] In this process, the gasification takes place deep underground, such as in an existing oil field, and the hydrogen is filtered using a selective membrane. This has the advantage of leaving the CO_2 underground.

which is being tested in demonstration projects in Alberta and Saskatchewan. Due to its early developmental stage, the prospects for this technology are uncertain.

6.4. Hydrogen production costs

According to one study[71], levelized cost of green hydrogen produced in Canada will be in the range of 2.20-3.60 (US$/kg) in 2030, 1.80-2.90 (US$/kg) in 2040 and 1.50-2.50 (US$/kg) in 2050 (see Appendix for assumptions). For 2030, the federal hydrogen strategy estimates costs for blue hydrogen to be in the range of 0.80-1.60 (US$/kg) and for green hydrogen to be around 2.60 (US$/kg). The strategy doubts that drastic costs reductions for green hydrogen, as expected by certain studies until 2030[72], are applicable to Canada and concludes that fossil-based production is likely to be cheaper in Canada.

But, even if Canada may not be able to compete with the world's cheapest solar locations, the country offers very favourable conditions for hydropower and onshore and offshore wind in global comparison.[70]. Wind power is already the cheapest form of electricity in Canada today, with past onshore wind auctions in Alberta having reached extremely low prices (€24.7-26.5/MWh) in global comparison.[73] Further, electricity prices are generally very low today in Canada, with the lowest retail prices for industrial consumers found in Manitoba and Quebec. In April 2020, industrial consumers paid $C5.66ct/kWh (€3.85ct/kWh) in Montreal, one of the lowest prices among OECD countries.[74]

Due to Canada's very low electricity prices for industry, good conditions for both onshore and offshore wind energy and large hydropower capacity, it is expected that production costs for green hydrogen in Eastern Canada will be relatively low compared to the rest of the world in the short- and mid-term.[75] In addition, Canada scores relatively well in international comparison on a range of other factors that influence green hydrogen production costs: low capital costs, good infrastructure, the availability of skilled workers and very good conditions in terms of ease of doing business and governance (see Figure 1). Indeed, a recent analysis focusing on green hydrogen imports for Germany has identified Canada among the highest-ranking countries with green hydrogen export potential – together with Algeria, Australia and Saudi Arabia.[76]

Also, in terms of blue hydrogen production, Canada can be expected to be among the cheapest future producers due to its large reserves and available CO_2 storage sites. Already today, in a comparison with hydrogen producers bordering the Pacific, Canada produces at lower prices than Australia and Chile.[77]

7. Hydrogen transport to the EU

Hydrogen from Canada would need to be transported to Europe via ships. The three most widely discussed long-distance shipping options for hydrogen are in form of liquid hydrogen (LH_2), ammonia (NH_3), or liquid organic hydrogen carriers (LOHCs), because these achieve higher volumetric energy densities than gaseous hydrogen and are thus overall less expensive. Since the associated conversion and reconversion processes are very energy-intensive, they increase supply costs significantly, making

[71] Brändle et. al. (2020)
[72] BloombergNEF (2020)
[73] Menzies and Marquardt (2019)
[74] NRCan (2020b)
[75] Piria et al. (2021)
[76] Guidehouse (2022)
[77] APERC (2018)

up 60-80% of the total long-distance transport costs.[78] The final choice for these hydrogen shipping options will depend significantly on the required end-use form of hydrogen in Europe.

Overall, studies show that ammonia- and LOHC-based seaborne transport will be the most cost-efficient options for all shipping distances in the short- and medium term.[79] Furthermore, if ammonia is used directly and not reconverted back to hydrogen, it could also be preferred for certain end-uses in the long-term.[80] However, when pure hydrogen is needed, some expect that liquid hydrogen could become the cheapest shipping option in the long-term, as substantial cost reductions are possible.[78] Additionally, the energy losses resulting from ammonia (re-)conversion increase with the purity of hydrogen needed. Since some applications such as fuel cells require high purity, this results in the entire ammonia transportation chain to be more expensive. Large-scale transatlantic hydrogen trade would require newly built h2-ready LNG terminals, dedicated ammonia terminals, or/and newly built LH_2 terminals and ships. Existing ammonia and oil product terminals may also be used for NH_3/LOHC exports. Storage and distribution infrastructure will be required on both sides of the Atlantic.[81]

Canada has several ports for handling oil shipments (including Port of Montreal, Port de Quebec, Newfoundland Offshore, Come by Chance, Port Saint John and Port Hawkesbury, Nova Scotia) on the East coast.[82] Although five LNG terminals were planned for the East coast, they have either been cancelled or planning has been stalled due to regulatory hurdles and uncertain financial prospects. In terms of ammonia, Canada has an established infrastructure with several ports on the East Coast[83]. There are currently no LPG export terminals on the East coast.

Shipping hydrogen across the sea raises its price significantly compared to hydrogen supplied by pipeline. Still, due to the much more expensive (re-)conversion processes, shipping costs may only make up 30% of transport costs for most international distances.[84] Thus, it is estimated that shipping costs will, in the mid- and long-term, be similar for hydrogen shipped from the Arabian Peninsula and North America (see Table 1). The modelling is based on the optimistic scenario[85] by Brändle et al. (2020), who calculated future green hydrogen supply costs from different countries. Transport costs for LH_2 are comparable to other estimates.[86] Due to converging transport costs (except for hydrogen shipped from more distant locations such as Argentina), the difference in levelized cost of hydrogen (LCOH) (excluding transport) will determine which supplier country will be able to supply hydrogen at cheapest total costs. As Figure 1 shows, Canada's LH_2 exports by ship could potentially compete with those of Morocco, the US and Saudi Arabia in the future.

[78] Guidehouse (2021)

[79] IEA (2019), Guidehouse (2021)

[80] Wijayanta et al. (2019)

[81] IEA (2019), Ammonia Energy (2021), Clyde & Co. (2021)

[82] CEC (2020)

[83] CN (2021), Fertilizer Canada (2021)

[84] Brändle et al. (2020), Guidehouse (2021)

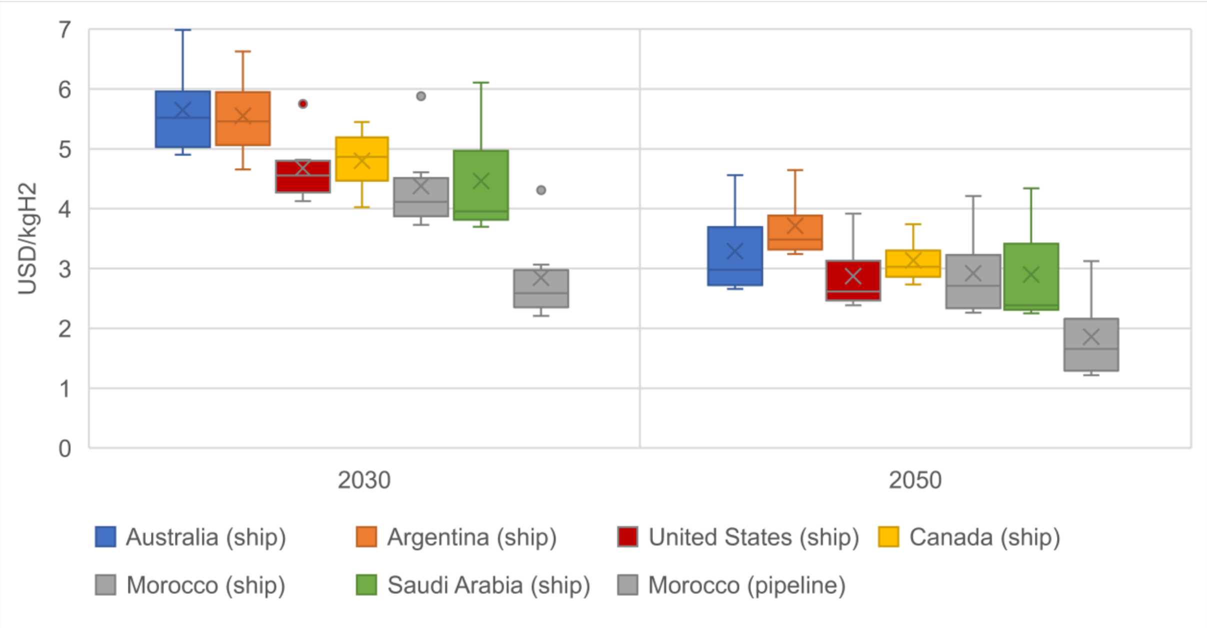
[85] Shipping costs are based on IEA (2019) and Wijayanta et al. (2019), which estimate a 20% cost reduction for liquefaction costs, a 50% reduction for shipping costs and a 45-55% cost reduction for import and export terminals until 2050.

[86] Guidehouse 2021, Fraunhofer IEE (2021)

Table 1: Estimated supply cost of green LH2 from different countries to the EU[87]

Origin – Destination, Distance, (Mode)	**Costs** (USD/kgH2)	**2030**	**2040**	**2050**
Morocco – Spain 750 km (low cost new pipeline)	Total supply:	2.2 – 4.3	1.7 – 3.6	1.2 – 3.1
	LCOH:	2.0 – 4.1	1.5 – 3.4	1.0 – 2.9
	Transport:	0.2	0.2	0.2
Morocco - Spain 39 km (ship)	Total supply:	3.7 – 5.8	3.0 – 5.0	2.2 – 4.2
	LCOH:	2.0 – 4.1	1.5 – 3.4	1.0 – 2.9
	Transport:	1.7	1.5 – 1.6	1.2 - 1.3
Saudi Arabia – Italy 3042 km (ship)	Total supply:	3.7 – 6.1	3.0 – 5.2	2.2 – 4.3
	LCOH:	1.9 – 4.2	1.4 – 3.5	1.0 – 3.0
	Transport:	1.8 – 1.9	1.6 – 1.7	1.3
USA – Netherlands 8050 km (ship)	Total supply:	4.1 – 5.8	3.2 – 4.8	2.4 – 3.9
	LCOH:	2.2 – 3.7	1.6 – 3.1	1.1 – 2.6
	Transport:	2.0	1.6 - 1.7	1.3
Canada – Netherlands 5148 km (ship)	**Total supply:**	**4.0 – 5.4**	**3.3 – 4.5**	**2.7 – 3.7**
	LCOH:	2.2 – 3.6	1.8 – 2.9	1.5 – 2.5
	Transport:	1.8 – 1.9	1.5 - 1.6	1.2 – 1.3
Argentina – Netherlands 13,751 km (ship)	Total supply:	4.7 – 6.6	4.0 – 5.6	3.2 – 4.6
	LCOH:	2.3 – 4.2	1.9 – 3.4	1.6 – 2.9
	Transport:	2.3 – 2.4	2.1	1.6 – 1.7

Figure 5: Estimated supply cost of green LH2 from different countries to the EU[87]



Note: X in the Boxplots marks the average supply cost value.

[87] Calculations based on Brändle et al. (2020), Optimistic scenario based on: onshore wind and solar PV resources; low temperature electrolysis; electrolyser CAPEX in USD/kw: 400 in 2030, 300 in 2040, 200 in 2050. For further assumptions, see Annex.

8. Sustainability issues

Canada's interest in producing and exporting grey and blue hydrogen could lead to significant GHG emissions. Grey hydrogen production already today accounts for 4% of Canada's GHG emissions.[88] Hydrogen production from natural gas is associated with significant unaccounted upstream and downstream methane emissions. Further, without thorough emission monitoring, fugitive CO_2 could escape unnoticed from the storage site during injection and over time[89]. Utilisation of captured CO_2 for enhanced oil recovery further raises questions regarding the carbon footprint of hydrogen. Recent assessments indicate that blue hydrogen can approximate the low emission intensity of green hydrogen only if very low rates of methane leakage of less than 1% and carbon capture rates of at least 93% are accomplished.[90]

There are further sustainability issues associated with Canada's hydrogen production from fossil fuels. With regard to natural gas, 65% is currently produced from unconventional tight or shale resources in Canada, for which hydraulic fracturing (fracking) is used.[91] Fracking is associated with a host of environmental problems such as degradation of water availability and quality, chemical spills and induced seismicity. With regard to oil, the majority (63%) is produced from oil sands in Canada. Compared to conventional extraction, oil sands production is very energy-intensive and around 81% more emission-intensive.[92] It accounts for 30% of Canada's natural gas consumption and 12% of the country's GHG emissions.[93] Oil sands production is also associated with large freshwater usage and environmental damage to groundwater, habitats and biodiversity.[94]

In terms of hydrogen electrolysis, emission intensity would be quite low for production from grid electricity in Canada in global comparison. This is due to the country's largely emission-free electricity mix, with high shares of RE (66%) and nuclear (16%). Still, the situation varies between the provinces: Quebec, British Columbia, Manitoba, Newfoundland and Labrador all have RE shares of 95%-99%[95]. Ontario (60% nuclear, 35% RE) and New Brunswick (39% nuclear, 31% RE) also have largely emission-free electricity mixes. Alberta (92% of fossil fuels), Saskatchewan (84%) and Nova Scotia (76%) still largely depend on fossil fuels.

Canada also seems to have a global advantage for the production of hydrogen using electrolysis in terms of water security, as the country possesses 7% of the world's fresh water.[96] However, medium to high water stress level can be identified for certain regions in Alberta and Saskatchewan, which also have the highest solar energy potential in Canada. For areas with strong wind energy potential in Eastern Canada, no water risks can be identified.[97]

Apart from that, the availability of very large surfaces with very low population density and comparably low biodiversity decreases the potential for conflicts with regard to land use and environmental protection in comparison to many other countries. RE expansion faces few acceptance problems in many parts of the Canada, due to the widespread support for these technologies and also thanks to the low population density.

[88] Layzell et al. (2020)
[89] IPCC (2018)
[90] Bauer et al. (2021)
[91] NRCan (2020b)
[92] NRDC (2019)
[93] CER (2020c), NRCan (2020b)
[94] National Geographic (2019)
[95] CER (2021c)
[96] NRCan (2020a)
[97] WRI (2021)

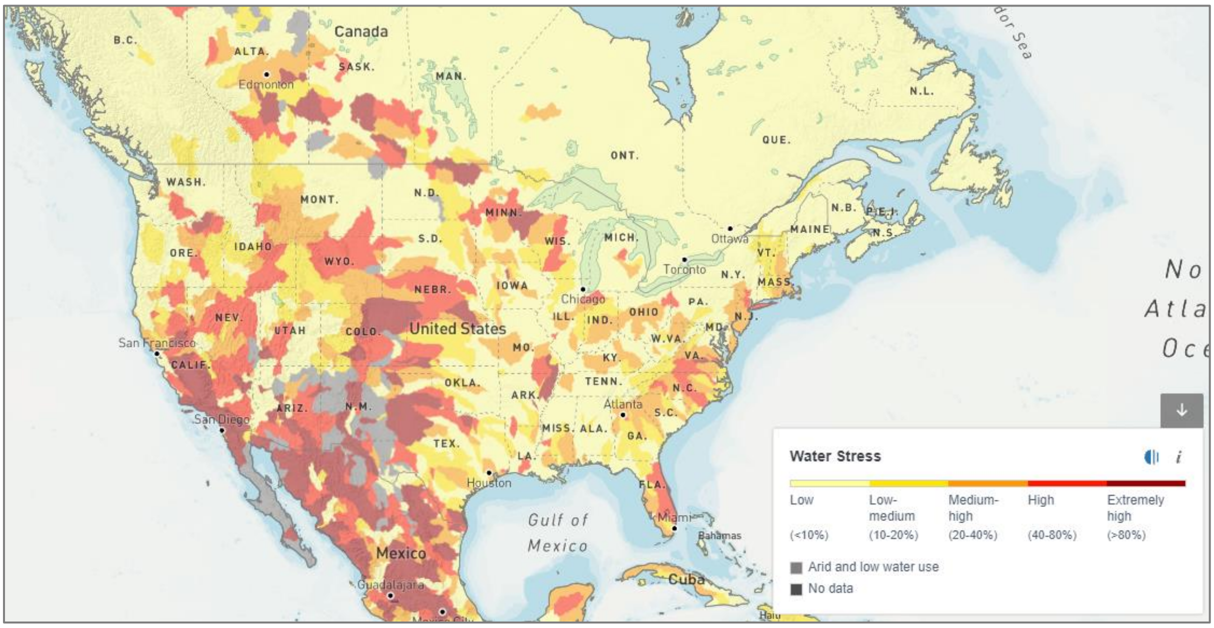
Appendix

Datasets by Brändle et. al. (2020) (Institute of Energy Economics at the University of Cologne, EWI) and Fraunhofer IEE (2021) as part of their PtX-Atlas project were used in this study to show and compare green hydrogen production and -supply potentials between different countries.

Brändle et. al. (2020) modelled the total green hydrogen supply costs from multiple countries based on solar and wind energy for electricity generation and liquid hydrogen transport by pipeline or ship to other countries, assuming it will be the cheapest in long-term. They estimated the theoretical hydrogen production potentials of the countries solely based on solar and wind resources, and suitable land areas. They did not consider other constraints like access to water and do not account for technological, socio-economic or ecological factors, as are partly considered in the PtX-Atlas analysis. Furthermore, the authors only considered hydrogen production sites either based on solar or wind energy, but not both together as hybrid systems, assuming that in most countries suitable wind and PV resource areas do not overlap. Also, only standalone systems without connection to the grid were considered, assuming that excess renewable electricity is thrown away, if it cannot be used for hydrogen production. These assumptions, amongst others, can lead to an overestimation of future hydrogen production costs.

Fraunhofer IEE (2021) as part of their PtX-Atlas modelled which countries have the potential to produce green hydrogen and -derivates beyond their own needs based on RES, and can therefore become a relevant hydrogen exporter for the global market by 2050. Their modelling is not only based on RES potentials (from PV, onshore wind, hybrid sites), suitable land areas, but also on socio-economic conditions for the development of a PtX infrastructure. Not considered for the hydrogen production are, inter alia, areas with a population density of > 50 inhabitants/km², nature reserves, and potentially critical habitats, areas with electricity generation costs of more than 4 ct/kWh for wind and 3 ct/kWh for PV (based on the Global Wind Atlas and Global Solar Atlas), and - most importantly - areas with more than low water stress levels (based on WRI's Water Risk Atlas) as shown, for example, in Figure 6. These restrictions lead to significantly lower hydrogen production potentials than in the modelling of Brändle et. al. (2020).

Figure 6: Extract from WRI's Water Risk Atlas, showing water restrictions in North America



Source: World Resources Institute. https://www.wri.org/aqueduct#aqueduct-tools

Following the more rigorous restrictions and conservative assumptions considered by Fraunhofer IEE (2020), their PtX-Atlas generally shows significantly higher green hydrogen production and supply costs to Europe than the modelling by Brändle et. al. (2020). An example of the differences in the results is shown in Table 2 based on the green hydrogen production in the USA with shipping to the Netherlands.

Table 2: Different modelling results for the costs of liquid hydrogen supply from USA to the Netherlands in 2050 (in USD/kg)

Source	Total supply costs	LCOH	Transport costs
Fraunhofer IEE (2021)	3.7 – 5.14	2.9 – 4.3	0.8
Brändle et. al. (2020), baseline scenario	3.2 – 4.6	1.9 – 3.3	1.3
Brändle et. al. (2020), optimistic scenario	2.4 – 3.9	1.1 – 2.6	1.3

Source: Own illustration and conversion of data from Fraunhofer IEE (2020) and Brändle et. al. (2020).

In this factsheet, we only showed the result of Brändle et. al. (2020)'s so-called "optimistic scenario" for green hydrogen supply costs to Europe because the assumptions under Brändle et. al. (2020)'s "baseline scenario" and Fraunhofer's PtX-Atlas regarding the future development of electrolyzer CAPEX and RE costs are further away from the findings of other recent studies than in Brändle et. al. (2020)'s optimistic scenario. Regarding the CAPEX for low-temperature electrolyser systems by 2050, Fraunhofer IEE (2021) expects only cost reductions to 470 – 550 EUR/kW and Brändle et. al. (2020) assume 450 USD/kW under their baseline scenario. However, other recent studies by the IEA (2019) and IRENA (2019) forecast the electrolyzer CAPEX to fall to approx. 200 $/kW in 2050, which is the same expectation as under Brändle et. al. (2020)'s optimistic scenario. Regarding the LCOE expectations, Table C.9 in the study by Brändle et. al. (2020) shows that also here the optimistic scenario estimations are closer to the findings of other studies than the baseline scenario assumption.

The conservative assumptions by Brändle et. al. (2020)'s baseline scenario and Fraunhofer's PtX-Atlas can lead to an overestimation of future green hydrogen production cost and -supply costs. However, on the other hand, both studies in all scenarios assume a uniform weighted average cost of capital (WACC) of r = 8%, which is likely too optimistic for many developing and emerging countries and can thus lead to an underestimation of hydrogen production costs in those countries.

Table 3 Selected techno-economic assumptions by Brändle et. al. (2020)

		2020	**2030**	**2040**	**2050**
LCOE	PV baseline ($ /MWh)	-	23 – 60	19 – 50	16 – 40
	PV optimistic ($ /MWh)	-	20 – 50	15 – 40	12 – 30
	Onshore baseline ($ /MWh)	-	28 – 90	26 – 80	24 – 76
	Onshore optimistic ($ /MWh)	-	26 – 80	23 – 73	22 – 68
	Offshore baseline ($ /MWh)	-	50 – 380	45 – 330	40 – 300
	Offshore optimistic ($ /MWh)	-	47 – 350	39 – 290	34 – 250
Electrolyser low temperature	CAPEX baseline ($/kW)	950	625	537.5	450
	CAPEX optimistic ($/kW)	500	400	300	200
	Efficiency (%)	66.5	68	71.5	75
	Lifetime	25	25	25	25
	CAPEX baseline ($/kW)	4000	1800	1275	750

Electrolyser high temperature	CAPEX optimistic ($/kW)	2400	800	650	500
	Efficiency (%)	77.5	80.5	82	83.5
SMR + CCS	CAPEX ($/kWH2)	1627	1360	-	1280
	OPEX (% of CAPEX/a)	3	3	-	3
	Efficiency (%)	69	69	69	69
	CO2 capture rate (%)	90	90	90	90
Pyrolysis	CAPEX ($/kW$H_2$)	-	-	-	457
	OPEX (% of CAPEX/a)	5	5	5	5
Pipeline	Lifetime (years)	40	40	40	40
	CAPEX ($/tpa/km)	4	4	4	4
	OPEX (%CAPEX/a)	5	5	5	5
	Utilization (%)	75	75	75	75
Ship	Lifetime (years)	30	30	30	30
	CAPEX($/t)	37,455	33,709	25,282	16,855
	OPEX (%CAPEX/a)	4	4	4	4
	Speed (km/h)	30	30	30	30
	Berthing time (h)	48	48	48	48
	Fuel use (MJ H_2/km)	1,487	1,487	1,487	1,487
	Boil off (%/day)	0.2	0.2	0.2	0.2
Export Terminal	Lifetime (years)	30	30	30	30
	CAPEX ($/tpa)	747	672	504	336
	OPEX (%CAPEX/a)	4	4	4	4
	Electricity use (kW/kg H_2)	0.61	0.61	0.61	0.61
	Boil-off (%/day)	0.1	0.1	0.1	0.1
Import Terminal	Lifetime (years)	30	30	30	30
	CAPEX ($/tpa)	4,939	4,445	3,334	2,223
	OPEX (%CAPEX/a)	4	4	4	4
	Electricity use (kW/kg H_2)	0.2	0.2	0.2	0.2
	Boil-off (%/day)	0.1	0.1	0.1	0.1
Liquefaction	Lifetime (years)	30	30	30	30
	CAPEX ($/tpa)	5,385	4,846	4,362	3,877
	OPEX (%CAPEX/a)	4	4	4	4
	Electricity use (kWh/kg H_2)	6.1	6.1	6.1	6.1
	Availability (%)	90	90	90	90

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