STUDY ON THE TECHNO-ECONOMIC POTENTIAL OF THE DEVELOPMENT OF QUÉBEC’S HYDROGEN SECTOR AND ITS POTENTIAL FOR THE ENERGY TRANSITION

EXECUTIVE SUMMARY

POLYTECHNIQUE
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STUDY ON THE TECHNO-ECONOMIC POTENTIAL OF THE DEVELOPMENT OF QUÉBEC'S HYDROGEN SECTOR AND ITS POTENTIAL FOR THE ENERGY TRANSITION

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SUMMARY

The terms of reference of this study, which was carried out on behalf of Transition Énergétique Québec and Ministère de l'Énergie et des Ressources Naturelles, were to describe and analyze the current landscape and the challenges facing the development of the hydrogen sector.

The main aim of the study was to establish a basis for a techno-economic reflection to guide the development of future government initiatives, identify the most promising growth sectors for green hydrogen in the context of Québec's energy transition, and develop potential pilot projects to encourage the adoption of hydrogen by Québec society.

In this context, a bibliographic study mainly targeting economic, technical, and political developments in the hydrogen sector worldwide was conducted with a focus on the three last years. In addition, the main actors in Québec's hydrogen ecosystems were consulted, which improved the bibliographic study and highlighted potential business opportunities and deployment strategies in a number of economic sectors.

LIST OF ABREVIATIONS AND ACRONYMS

LCA	Life cycle analysis
ASME	American Society of Mechanical Engineers
BNQ	Bureau de normalisation du Québec
CAPEX	Capital expenditure
CCTT	College Centres for the Transfer of Technology
CO_2	Carbon dioxide
GHG	Greenhouse gas
H_2	Hydrogen
HRI	Hydrogen Research Institute
Kg	Kilograms
KWH	Kilowatt-hour
MEI	Ministère de l’Économie et de l’Innovation
MERN	Ministère de l’Énergie et des Ressources naturelles
MW	Megawatt
O_2	Oxygen
OPEX	Operating expense
TEQ	Transition énergétique Québec
ULC	Underwriters Laboratories of Canada
UQTR	Université du Québec à Trois-Rivières
FCEV	Fuel cell electric vehicle

PART A :

CURRENT REGIONAL, CANADIAN, AND INTERNATIONAL LANDSCAPE OF THE HYDROGEN ECONOMY

The growing demand for energy (especially in developing countries), the pressure of climate change, and growing environmental awareness are causing a marked and profound change in the current energy system. This energy transition, which prioritizes the use of renewable energies that can be deployed on a large scale at an affordable cost, is a global phenomenon that covers a myriad of uses, including mobility (especially in urban settings), heating, and tertiary sector activities. In the industrial sector, decarbonizing the energy system by direct electrification is more complex given the currently available technologies, especially in heavy industry processes that require high temperatures.

The ability to store energy is essential for any energy system in order to ensure a secure supply and a balance between supply and demand. Management of the electric network is another aspect to take into consideration as production must adapt instantaneously to demand—and even anticipate it. Hydrogen is regarded as a solution for all of these issues, both as an energy vector that acts as a substitute for hydrocarbons and as a means to store energy.

There is virtually no free hydrogen on the planet, which means that it must be produced by processing natural resources containing hydrogen molecules. It is not, therefore, an energy in the literal sense, but rather an energy vector just like electricity. Its chemical nature makes it very attractive because it can be stored in massive amounts for several months if needed and can be transported in liquid or gas form much like natural gas. Its molecular nature also means it can react with other elements such as carbon and nitrogen (or their derivatives) to manufacture value-added products, synthetic fuels (electrofuels), synthetic natural gas, and industrial chemical intermediates.

POWER-TO-X

The *Power-to-X* concept describes the principle of converting electricity produced from renewable sources into an energy vector or a chemical product. Depending on the pathway used, X can be:

- **A GAS**
  (***Power-to-Gas***)
  like pure hydrogen or methane
- **A LIQUID SYNTHETIC FUEL**
  (***Power-to-Liquid*** or ***Power-to-Fuels***)
  like diesel, kerosene, or methanol
- **AMMONIA**
  (***Power-to-Ammonia***)
- **INTERMEDIATES**
  (***Power-to-Chemicals***)
  like chemical products for industry

Power-to-Gas makes it technically possible to couple an electricity distribution network to a natural gas distribution network, making these networks interoperable (sector coupling).

Except where limited to the production of pure hydrogen, *Power-to-X* requires a carbon source that reacts with hydrogen to synthesize *X* (ammonia, for example, requires nitrogen). This approach is all the more valuable as it makes it possible to recycle and recover useful products from CO_2 generated by industrial activities that would otherwise have been released into the atmosphere.

THE HYDROGEN MARKET

Québec has set ambitious objectives to decarbonize its economy, meaning green hydrogen could play a major role in achieving energy transition targets. Given Québec's greenhouse gas balance, the following sectors should be prioritized:

- **HEAVY TRANSPORT AND INTENSIVE MOBILITY**
- **PRODUCTION OF ELECTROFUELS AND SYNTHESIS GAS**
- **DECARBONIZATION OF INDUSTRIAL PROCESSSES**
- **ENERGY STORAGE**
- **ENERGY SUPPLY FOR REMOTE SITES NOT CONNECTED TO THE POWER GRID**

There are a wide range of energy resources that can be used to produce hydrogen:

- **FOSSIL FUELS** (hydrocarbons, coal) using steam reforming or pyrolysis
- **RENEWABLE FUELS** (biomass, non-food crops, organic waste) using thermochemical processes (gasification or pyrolysis)
- **INTERMITTENT** (wind or solar) or CONTINUOUS (geothermal, hydraulic) **RENEWABLE ENERGIES** in association with electrolysis

Steam reforming, gasification of biomass and urban and agricultural organic waste, and water electrolysis are the only industrial technologies that are ready now or are very close to their commercialization phase that can be used to produce hydrogen on a large scale. In industrial chemistry, certain processes (e.g., chlorine soda and chlorates) also produce hydrogen that can be recovered.

In 2019, world production of hydrogen stood at 119 MT/year, of which Canada produced 3 MT. Part of this production, i.e., 45 MT/year, is not made up of pure hydrogen, rather it consists of gas mixtures containing hydrogen that are used exclusively in petroleum refining units. The remaining 74 MT/year of hydrogen is used in its pure form in refineries (24%) to recover heavy crude oil and meet the demand for cleaner fuels, in the chemical industry (65%) for the production of ammonia and methanol, and in various other industrial sectors (10%) such as steel production. Hydrogen demand has experienced growth in the order of 40% over the past ten years.

The petroleum and chemical sectors (methanol and ammonia) that will underpin the anticipated growth in demand for hydrogen are thus good targets for the development of green hydrogen. In the chemical sector, new markets are also possible, especially the manufacture of synthetic carbon-neutral liquid fuels, dimethylether (DME), which is a propane substitute, and ethanol from methanol.

In these three cases, a source of CO_2 is required, which points to a possible massive capture of industrial CO_2 with a view to closing the carbon cycle (circular economy).

The draw of *Power-to-Gas* is the potential for decarbonizing the methane used for the production of heat and electricity. However, the manufacture of synthetic natural gas by the Sabatier reaction is not yet competitive versus the price of gas. It is a long-term option. It is, however, possible to inject pure hydrogen into natural gas networks provided the technical constraints related to the pipelines are respected.

Green hydrogen-based electric mobility has received the most media attention because of its potential impact on the decarbonization of transport, a rapidly emerging sector. According to a study by the Hydrogen Council, hydrogen mobility is particularly interesting in the following situations:

- **LONG-DISTANCE ROAD TRANSPORT**
- **HEAVY TRANSPORT** (vehicles/machinery in the mining and forestry sectors)
- **HIGH INTENSITY TRANSPORT** (city buses, taxi fleets, warehouse forklifts, ports, and airports)
- **RAIL TRANSPORT**
- **MARITIME TRANSPORT**

Battery-operated electric vehicles are, for now, the best suited for individual transport over short distances (e.g., for commuting). However, in Québec, it is well known that the range of battery-powered vehicles is lower in winter, which could justify the electrification of light vehicles using hydrogen, at least in the case of intensive mobility (taxi fleets, delivery vans).

HYDROGEN PRODUCTION TECHNOLOGIES

To meet the obligations of the 2015 Paris Agreement, the growth of the hydrogen market will depend on decarbonizing production. In Canada, four options are under consideration:

- **HYDROGEN PRODUCTION BY STEAM REFORMING OF NATURAL GAS** with the capture and geological sequestration of carbon (blue hydrogen)
- **PRODUCTION OF SYNTHESIS GASES BY ONSITE COMBUSTION OF OIL SANDS** with the capture and geological sequestration of carbon (blue hydrogen)
- **USE OF ELECTRONUCLEAR ELECTRICITY SURPLUSES** (yellow hydrogen)
- **PRODUCTION OF HYDROGEN FROM HYDROELECTRICITY AND FROM WIND TURBINES** (green hydrogen)

In Québec, the potential for value creation of our hydroelectric and wind power in the form of hydrogen is incontestable. We only have to look at a production site such as Hydro-Québec's Romaine hydroelectric complex, which generates 8 TWh/year. One kilogram of hydrogen requires 55 to 60 kWh of electricity and 10 litres of water, i.e., approximately 140 kT of green hydrogen can be produced with 8 TWh, or approximately 25% more than Québec's current hydrogen production. In terms of wind power, Boralex's wind farm at the Seigneurie de Beaupré Park generates 365 MW, which corresponds to a total production of the order of 1 TWh, taking a utilization factor of 0.35 into consideration. The 8 TWh generated at the Romaine complex thus corresponds to eight wind farms of this type.

The production announced by Air Liquide at Bécancour for its project to install a 20 MW electroyzer will provide 8 T/day, i.e., 2.8 kT/year with an estimated utilization factor of 97%. It would take 50 projects of a similar size to produce 140 kT/year of green hydrogen.

If we take the example of hydrogen mobility, 140 kT/year of hydrogen corresponds to the annual requirement of 4,666 heavy trucks (approx. half of Québec's fleet). For industrial chemical applications, the use of 140 kT/year of hydrogen would correspond to a world-class plant that can produce more than 700 kT/year of ammonia.

There are currently three electrolysis technologies in use: alkaline electrolysis, proton exchange membrane electrolysis and solid oxide electrolysis.

Alkaline electrolysis is a commercial technology that has been used since the 1920s, especially for the production of hydrogen by the fertilizer and chlorine industries. Non-pressurized alkaline electrolyzers can produce over 200 T/day.

Proton exchange membrane systems were introduced by General Electric some 60 years ago to address the drawbacks of alkaline electrolyzers. They are compact and can produce hydrogen at a few dozen bars without a compressor. The current capacity of these electrolyzers is 5 MW.

Solid oxide electrolyzers, which have not yet reached the pre-industrialization phase, use ceramics as electrolytes and are composed of low-cost materials. They operate at high temperatures with an elevated level of electric efficiency.

FUEL CELLS

The fuel cell industry consists of 3 markets:

- **PORTABLE APPLICATIONS**
- **STATIONARY APPLICATIONS**
- **MOBILE APPLICATIONS**

The global fuel cell market totalled U.S. $4.5 billion in 2018. It is expected to grow by 20.9% and reach U.S. $11.54 billion by 2026. Stationary applications have so far dominated the market, but future growth will likely be driven by mobile applications.

Fuel cell technologies can be classified based on the electrolyte used and the energy source:

- **MOLTEN CARBONATE FUEL CELLS**
  use molten carbonates such as mixtures of lithium and potassium salts at high temperatures up to 650°C. MCFCs typically generate several MW.
- **PHOSPHORIC ACID FUEL CELLS**
  use phosphoric acid as an electrolyte. They operate at lower temperatures than MCFCs (in the order of 200°C). PAFCs typically generate several hundred kW.
- **PROTON EXCHANGE MEMBRANE FUEL CELLS**
  work on a principle similar to PAFCs. The phosphoric acid electrolyte is replaced by a membrane that allows protons to travel from one electrode to another. PEMFCs are fuelled by pure hydrogen.
- **SOLID OXIDE FUEL CELLS**
  use ceramics as an electrolyte just like solid oxide electrolyzers (the system can, in principle, be used both as an electrolyzer and as a fuel cell). As they operate at a very high temperatures (800°C), they require a heat source to work. They typically generate several hundred kW.

HYDROGEN DEPLOYMENT

Like the raw material market, the energy market went global several decades ago. Given the role that merchant hydrogen will be called on to play in the future and the fact that most actors in the hydrogen ecosystem are international industrial gas companies, the merchant hydrogen market is also likely to globalize.

At present, the first industrial deployments of green hydrogen in the new markets described above have been supported by investment policies and government assistance. Many developed countries already have action plans or roadmaps, including Japan, Germany, the United States, South Korea, China, and the European Union.

Canada does not have a hydrogen roadmap. The challenges facing Canada in the development of the hydrogen economy in the future include:

- **ESTABLISHING A SUPPLY CHAIN**
  that can simultaneously meet the needs of stationary and mobile applications and reduce costs
- **BUILDING A DISTRIBUTION INFRASTRUCTURE**
  (especially pipelines) to reduce transportation costs
- **ESTABLISHING A POLITICAL,**
  legal and regulatory framework that is coherent and that encourages the engagement of investors
- **RAISING PUBLIC AWARENESS OF THE BENEFITS OF HYDROGEN**
  as part of the energy transition and implementing measures to promote its adoption

In the context of the energy transition, the federal government plans to establish a legislative framework for clean fuels (taxation and carbon market) starting in 2021.

Québec is currently assessing its position in the hydrogen market. It intends to draw on proven industrial expertise (Hydro-Québec, Energir), economic actors ready to invest (Air Liquide, Hydrogenics, Harnois Énergies), and an active, high-level research ecosystem in the green hydrogen sector.

To conclude, a certain number of lessons can be learned from this economic analysis of the hydrogen market.

1.

IN THE CONTEXT OF THE ENERGY TRANSITION,

the deployment of hydrogen should take place first in countries with a competitive edge in terms of the production of renewable electric energy as well as a receptive domestic market that can absorb the production of green hydrogen for mobility and industrial purposes.

2.

INDUSTRIAL ROLLOUT SHOULD MIRROR THAT OF INDUSTRIAL GAS PRODUCERS,

that is, concentrate on the installation of significant capacity for captive applications that meet an existing demand. This kind of approach focuses either on major industrial users (petrochemical, steel production) or on intensive mobility applications (trucks, city buses, and taxi fleets), or both, provided production is sufficiently large.

3.

THE SPEED WITH WHICH ROLLOUT WILL TAKE PLACE

is linked to the anticipated decrease in production costs and the development of cost-effective and efficient supply chains. The uncertainty surrounding a realistic timetable for rollout must be taken into account in the formulation of a strategy, which needs to be flexible and neutral with respect to the technology plan and in keeping with the international landscape and the hydrogen strategies of other countries.

4.

INTERNATIONAL COLLABORATION TO FORMULATE TECHNOLOGICAL STANDARDS AND THE CERTIFICATION OF THE GREEN NATURE OF HYDROGEN

is certainly useful for countries that have a competitive edge in terms of hydrogen development as well as for potential users of technologies that have been or will be developed. For Québec and Canada, it is particularly important to develop regulations that are harmonized with those of the United States to ensure the successful rollout of green hydrogen on the North American market.

5.

THE ESTABLISHMENT OF FINANCIAL ASSISTANCE PROGRAMS

for innovation, commercialization, and the deployment of joint public/private technological platforms is the preferred option for many countries to fast-forward the penetration of decarbonized hydrogen in the market.

6.

SUPPORT FOR ALL THESE POLICIES

depends on the availability of experts and a highly qualified workforce. This is a major challenge that needs to be prioritized.

PART B:

TECHNO-ECONOMIC LITERATURE REVIEW OF HYDROGEN: FROM PRODUCTION TO USE

PRODUCTION BY ELECTROLYSIS

The electrolysis of water is an electrochemical process that decomposes water into hydrogen and oxygen through the passage of a direct electric current that induces and maintains redox reactions. The electrolyzer is composed of two electrodes covered with metal that are separated by an ionic conductor (electrolyte) and a source of direct current. Electrolysis is currently used to produce approximately 4% of the global demand for hydrogen.

Electrolyzers are composed of individual cells and peripheral units called BOPs (Balance of Plant). By assembling the electrolytic cells in stacks of varying size, hydrogen production can be tailored to demand. As electrolyzers are commercially available in modular form (up to several MW), they can be combined to provide the capacity required by large plants.

The efficiency of the electrolytic process is defined as the relationship between the gross calorific value (GCV) of hydrogen and the electricity used by the electrolyzer per kg of hydrogen produced. According to this criterion, the efficiency of electrolyzers ranges from 43 to 53 kWh/kg or 50% to 82%.

Electrolyzer technologies differ in the electrolyte used and the operating temperature. Low temperature electrolyzers include alkaline electrolysis cells (AEC) and proton exchange membrane electrolysis cells (PEMEC). High-temperature electrolyzers are mainly solid oxide electrolysis cells (SOEC).

Alkaline electrolysis technology is commercially mature and dominates the market. It has been used since the 1920s, especially for the production of hydrogen by the fertilizer and chlorine industries. The capacity of AEC electrolyzers is limited to 10%. They use two categories of electrolytic solutions, the most common being potassium hydroxide (KOH) at a mass concentration of 20% to 40%. The asbestos-based diaphragm separating the two electrodes limits the operating temperature to a maximum of 80°C. Zirconium oxide-based separators in a polysulfone matrix are also available to avoid health problems associated with the use of asbestos.

In alkaline electrolyzers, the cathode (negative electrode) releases electrons into the aqueous solution. The water decomposes, leading to the formation of hydrogen and hydroxide ions (OH^-). The charge carriers move through the electrolyte toward the anode (positive electrode) When they reach the anode, the electrons are absorbed by the negative anions, which are oxidized to form water and oxygen (O_2). The O_2 moves up the electrode. A membrane prevents the H_2 et O_2 from remixing but is permeable to OH^- ions. The hydrogen produced enters a gas-liquid separation unit (scrubber) that eliminates residual traces of electrolyte and cools down the hydrogen.

AECs can produce 99.9% (in volume) pure hydrogen. The purity can be improved even more using catalytic converters and adsorption dryers. The efficiency of AEC electrolyzers is approximately 80% but, in practice, hydrogen production performances range from 63 to 70% with respect to the net calorific value (NCV) of hydrogen gas. Corrosion is the main downside of this technology due to the use of an alkaline solution. In addition, the limited operating pressure and the low current densities of AECs caused by the formation of gas bubbles limit the real active surface area of the electrode. The development of catalyzers with higher current exchange densities and new cell concepts such as zero spacing electrode configurations are required to address this problem. Over the years, AEC electrolyzers have improved in terms of dynamic responses (frequent start-ups and variable power absorbed). However, compared with other types of electrolyzers, they offer a lower operational range and dynamic function, typically 10 to 110% of the nominal load. Right now, AEC electrolyzers can produce hydrogen at 10 bars, although the effect of increasing the operating pressure is being studied.

PEMECs (proton exchange membrane electrolysis cells) were first introduced in the 1960s by General Electric to address certain operational disadvantages of alkaline electrolyzers. PEMECs use pure water as an electrolytic solution, avoiding the recovery and recycling of the potassium hydroxide solution required by AEC electrolyzers. They generally need water that is much purer than the water used for AEC electrolyzers (minimum resistivity of 1 MΩ.cm).

The oxidation reaction of water occurs on the anode and generates oxygen, electrons, and protons. The electrons and protons are shifted to the cathode by the PEMEC electrolyzer. The hydrogen is generated at the cathode once the protons have been reduced.

The use of a solid membrane in PEMCs results in much more compact designs. PEMC electrolyzers can produce highly pure (>99.995%) and highly compressed hydrogen for decentralized production and for storage in fueling stations (30-60 bars without an addition compressor and up to 100-200 bars in certain systems compared with 1-30 bars for alkaline electrolyzers). However, pressures exceeding 30 bars are detrimental to economic performance. Their service life is currently shorter than that of alkaline electrolyzers. Because of the high cost of the polymer membrane, noble metal-based catalyzers, and bipolar plate materials, PEMECs cost more than AECs, which also impedes their commercial deployment. SOEC (solid oxide) electrolyzers operate at temperatures as high as 1000°C, which makes the electrolyzers much more efficient. However, this technology is not sufficiently mature for large-scale deployment.

In SOEC systems, hydrogen is generated at the cathodes and oxide anions move to the anode where oxygen forms in the solid electrolyte. This technology is also used in solid oxide fuel cells (SOFC).

The electric energy required to maintain the electrolytic process at such a high temperature is much less than that required for low temperature electrolysis and, overall, the energy demand only increases slightly. Consequently, such a system has a higher yield, especially if low cost thermal, renewable, nuclear, or residual energy is used. However, the high operating temperature affects the stability of the materials, which tend to deteriorate during cycling. The delamination of the oxygen electrode of the electrolyte in SOEC leads to deterioration and physical damage to the electrode at the anode-electrolyte interface, which reduces the service life of the anode.

The cost of producing hydrogen largely depends on the cost of the various energy sources (thermal and electric energy conversion systems must be used) and the production installations. As for the cost of hydrogen produced by electrolysis, the CAPEX of the electrolyzer, the equivalent operating hours at full charge, and the average cost of electricity are all key factors that have an impact on the price of hydrogen.

The evolution of the cost of electrolyzers is uncertain for the moment and will be a major challenge for hydrogen-based energy systems. Based on available data, the uninstalled cost is of the order of U.S. $500-1400/kW for AECs and U.S. $800-1800/kW for PEMECs. According to the most recent cost estimates by Bloomberg New Energy Finance, Chinese companies have been able to manufacture AEC electrolyzers at a very low CAPEX of U.S. $200/kW. As SOECs are still at the precommercial stage, there is a high level of uncertainly with respect to their CAPEX. The literature mentions costs of U.S. $1500/kW by 2030 and U.S. $330/kW over the longer term.

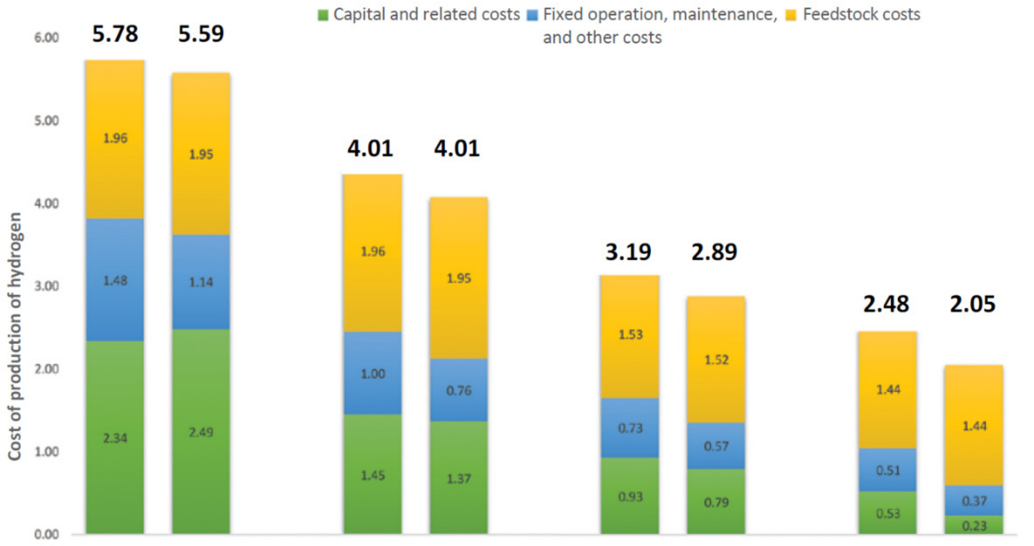
On average, the cell stack part of electrolyzers accounts for approximately 50% of the CAPEX of AECs and 60% of the CAPEX of PEMECs. The power electronics, gas conditioning, and other installation aspects account for most of the remaining costs. According to data provided by DOE, the cost of the BOP for a 1 MW electrolyzer accounts for approximately two thirds of the cost of the system, the power electronics account for half the cost of the BOPs, while the water circulation and hydrogen processing subsystems each account for one-fifth of the cost of the BOPs.

We anticipate that the production experience acquired will have a larger effect on the reduction of costs of SOECs, which are still in the development phase, compared to that for AECs and PEMECs, which have already been deployed commercially. In fact, efficiency gains resulting from the industrial scale production of AEC and PEMEC systems have already been realized. For SOEC technology, cost reductions could be achieved by using less costly and more robust construction materials and by upscaling operations.

According to the Hydrogen Council, the main criteria that will make it possible to reduce the cost of hydrogen in the future include producing electrolyzers on an industrial scale, improving the efficiency, operation and maintenance of electrolyzers, and using low cost electricity.

As for CAPEXes, a 60 to 80% reduction in the cost of large-scale production is anticipated by 2030. The major factors that would explain such a reduction include the shift from essentially manual production to increased reliance on automation and roll-to-roll production processes. Other favourable factors include new technological improvements (such as the optimization of the quantity of catalyzer and a reduction in the cost of catalyzers as well as an increase in the size of system with the resulting economy of scale. Moving from 1 to 2 MW systems that are typically deployed now to 80 to 100 MW systems, for example, will make it possible to considerably reduce the contribution of auxiliary systems to the costs. Overall, these improvements should reduce current CAPEXes of U.S. $2/kg H_2 to U.S. $0.50/kg H_2 by 2030. It is the decrease in the cost of electricity produced from renewable energy sources that will contribute the most to reducing the OPEX of electrolyzers. For example, offshore wind energy could reduce the costs by 40% from approximately U.S. $70/MWh to U.S. $40/MWh, which represents a reduction in costs of approximately U.S. $1.30/kg of H_2. The evaluation also shows that, in the case of a hypothetical CAPEX for the electrolyzer of U.S. $500/kW (regardless of the type of electrolyzer), access to renewable energies at a price of U.S. $20/MWh would allow the production of renewable hydrogen at approximately U.S. $2/kg.

A model house has been developed to determine the cost of hydrogen (excluding storage and distribution) produced by PEMEC and AEC technologies based on the current and future costs of the technologies, the price of electricity, utilization factors of 90% and 97%, and an internal rate of return (IRR) of 10% with 100% equity. The revenues from oxygen were not included in the evaluation.



	CASE 1 (PEMEC/AEC)	CASE 2 (PEMEC/AEC)	CASE 3 (PEMEC/AEC)	CASE 4 (PEMEC/AEC)
CAPEX ($/kW)	**1,800 / 1,400**	**1,100 / 800**	**700 / 500**	**385 / 200**
Electricity (¢/kW)	**3.4**	**3.4**	**2.65**	**2.5**

Study of the sensitivity of the cost of producing green hydrogen using PEMEC and AEC technologies (U.S. $)
– Cases 1 and 2 correspond to Hydro-Québec's Rate L, i.e., 4.55 c/kWh, case 3 is an electricity rate of 3.5 c/kWh, and case 4 is a rate of 3.3 c/kWh.

The results of the economic model shown in the figure above indicate that the most sensitive input parameter is the CAPEX of the system, i.e., the cost of the electrolyzer and of the BOPs. The second most sensitive factor is the electricity that powers the electrolyzer.

THERMOCHEMICAL AND BIOLOGICAL PRODUCTION

Thermochemical methods are mainly based on the gasification or pyrolysis of solid or liquid biomass to form a mixture of synthesis gas, H_2, and CO, followed by an additional treatment to produce H_2. The "solid biomass" category mainly includes woody and stalk biomass, i.e., wood biomass, wood waste, and straw as well as miscanthus. Solid municipal waste is another source of biomass that can be used in thermochemical conversion processes.

Biomass gasification can be achieved with atmospheric pressure (~1.6 bars) or high pressure (~34 bars) gasifiers. Air, pure oxygen, steam, or supercritical water can be used in the gasification process. Gasification is generally realized at ambient pressure, which has a negative impact on efficiency. Synthesis gas produced by gasification is purified and then undergoes a water-gas shift reaction that produces hydrogen.

During the pyrolysis process, the biomass is rapidly heated in the absence of air. It vaporizes and the organic vapours are quickly cooled down so that they condense into a viscous liquid called bio-oil. The bio-oil is then steam gasified (reforming of the bio-oil) to produce a synthesis gas that goes through a steam reforming and purification step to produce hydrogen.

Biogas is the result of an anaerobic digestion process of residual biomass from a variety of sources (animal waste, wastewater plants or industrial wastewater plants, landfills, etc.). This process is carried out by micro-organisms that decompose organic matter in nature or in biodigesters. Crude biogas is mainly composed of methane (CH_4) and carbon dioxide (CO_2) and is saturated in water (H_2O). However, it also contains corrosive contaminants that present a challenge when it comes to integrating it into the natural gas infrastructure. Crude biogas must first undergo a cleaning process to remove the contaminants. After this step, the gas can be treated and purified to obtain 100% methane that can then be used in various ways, including for the production of hydrogen using classic steam reforming technology. One of the most critical challenges with respect to the use of biogas as a source for hydrogen production is biogas quality and steady-state production, which are highly dependent on the origin and type of raw materials used as feedstock.

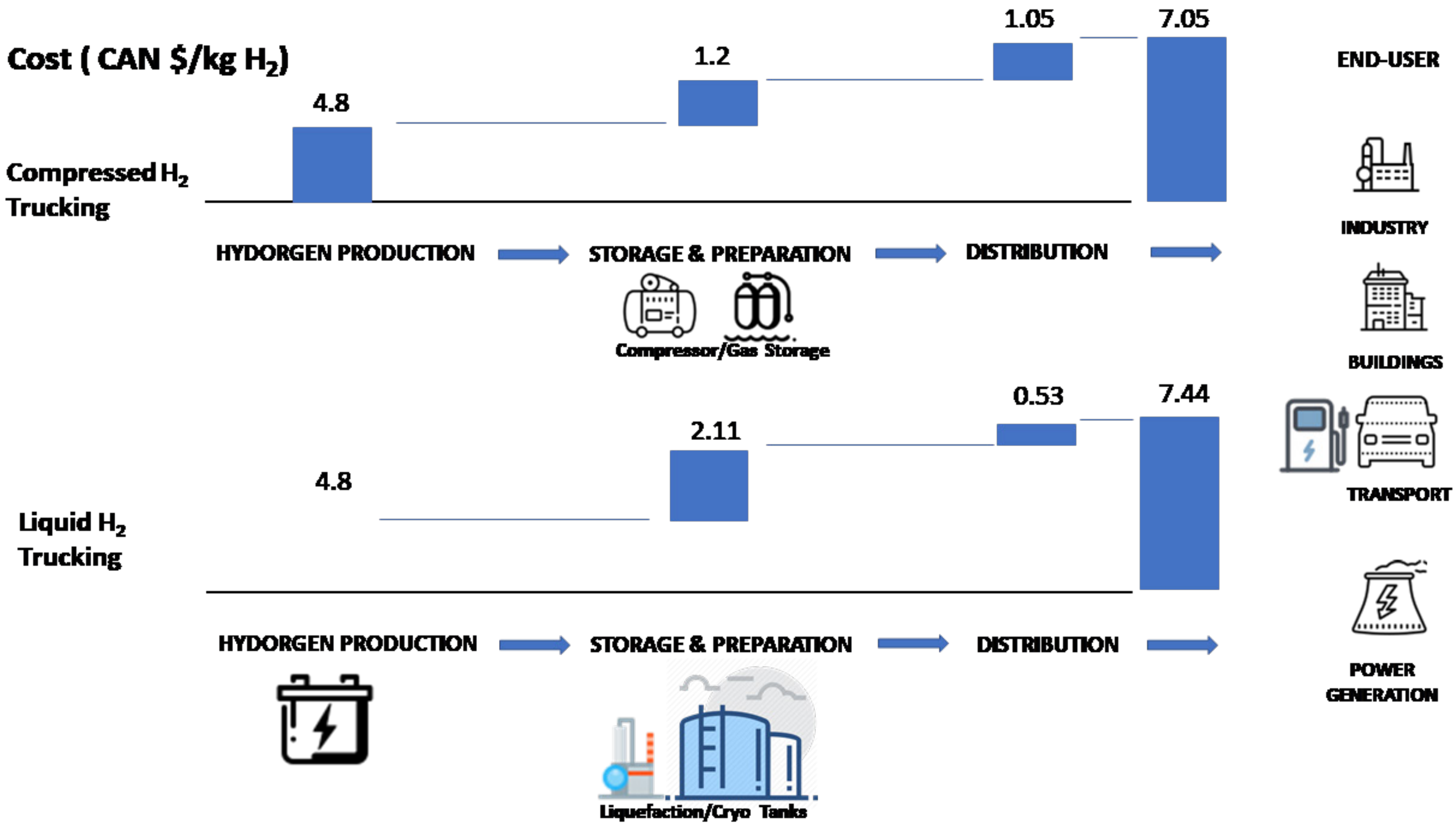
STORAGE AND TRANSPORT OF HYDROGEN

In order for hydrogen to play a key role in the global energy transition toward a clean and flexible energy system, it is crucial that it can be stored in large quantities over long periods of time and transported over long distances in a cost-effective way.

The storage of hydrogen is essential for hydrogen energy applications, especially when hydrogen is used on a large scale. To meet future potential demand for hydrogen on the energy market, a robust, reliable storage solution must be found for every application. The energy content (energy density) of an energy vector influences the way it is stored, and it is essential that the storage capacity be scalable. Hydrogen storage technologies can be divided into two main groups: physical storage and storage in the form of materials (also called chemical storage). The most commonly used storage method, which has long been tried and tested, is the physical storage method based on cooling or compression or a combination of the two. Storage in the form of materials is a more recent technology and has been the subject of numerous studies. Storage media include liquids, solids, and surfaces. Certain methods use chemical vectors where the hydrogen is charged and/or converted, stored on-site, or transported to the end user, then reconverted into pure hydrogen or used as is. The cost of hydrogen storage systems includes the CAPEX of the required infrastructure (equipment, catalyzers, etc.), the OPEX of continuous storage methods, the reconversion of the hydrogen, the cost of the energy supply (electricity for the compressor, cooling, heats of hydrogenation and dehydrogenation), and the loss of hydrogen over time (for instance by evaporation).

Hydrogen is currently transported by pipeline (hydrogen gas) where the infrastructure exists or by truck (gas or liquid hydrogen). The Hydrogen Council, which examined these three options, notes that the best option varies from case to case depending on the demand profile and the distance from the supply point. For short distances, compressed hydrogen gas offers the lowest cost. The transport of liquid hydrogen by road is more cost-effective for distances greater than 300 or 400 km. If hydrogen is already available in liquid form at the production or delivery site transportation over even shorter distances will be economical.

The Figure below shows the lowest cost estimates for the production, storage, and distribution of 1 kg of pure hydrogen in compressed or liquid form in Canadian dollars based on a production of 50 T/d and a distance of 600 km.



FUEL CELLS

There are different types of fuel cells depending on the nature of the electrolyte, the charge carrier, and their operating temperature. The principle of fuel cells is based on two electrochemical half reactions, each half reaction occurring either at the anode or at the cathode. In the case of the hydrogen/oxygen fuel cells, these reactions are, respectively, the oxidation of hydrogen at the anode and the reduction of oxygen at the cathode. They are separated by the electrolyte, an ionic material that allows ions to circulate but that blocks the passage of electrons. The transfer of the electrons produced by the oxidation of the fuel (production of electricity) takes place via an external circuit to the oxygen reduction cathode. The protons produced during hydrogen oxidation flow through the proton-conducting electrolyte to the superficial layer of the cathode electrocatalyst. When the protons arrive at this electrode, they combine with electrons and gaseous oxygen at the superficial layer of the electrocatalyst to produce water. As a result, the operation of a fuel cell involves the transfer of electrons from the anode to the cathode through an external circuit, producing an electric current. As a source of electrical energy, fuel cells will produce electricity continuously as long as they are supplied with fuel. This is the key difference between a fuel cell and a battery, both of which are electrochemical devices that produce electrical energy. However, fuel cell components are not consumed during electrochemical processes to produce electricity.

Fuel cells are classified according to the type of electrolyte and ionic charge carriers. The type of electrolyte determines the chemical reactions that take place in the cell, the catalyst required, the operating temperature range, and the type of fuel. Several fuel cell technologies are currently under development, each with its own advantages and limitations and level of maturity. The different types of fuel cells are:

- **PROTON EXCHANGE MEMBRANE FUEL CELLS (PEMFCs)**
  that use a solid polymer membrane as an ionic electrolyte, protons (H^+) as charge carriers, a Pt catalyst, and a hydrogen-based fuel. They can be used for backup power, portable power, and distributed generation.
- **DIRECT ALCOHOL FUEL CELLS (DAFCs)**
  that use a solid polymer membrane as an ionic electrolyte, protons (H^+) as charge carriers, a Pt catalyst, and hydrogen as fuel. They can be used for applications in immature markets (launch phase).
- **PHOSPHORIC ACID FUEL CELLS (PAFCs)**
  that are based on a H_3PO_4 gel as an electrolyte, protons as charge carriers, a Pt catalyst, and a hydrogen-based fuel. They can be used for distributed generation.
- **ALKALINE FUEL CELLS (AFCs)**
  that use a liquid potassium electrolyte, hydroxide ions (OH^-) as charge carriers, nickel-based catalysts, and hydrogen as fuel. They are used in military and space, emergency power, and transportation applications.
- **MOLTEN CARBONATE FUEL CELLS (MCFCs)**
  that use a molten carbonate salt electrolyte, CO_3^{2-} as charge carrier, a nickel alloy catalyst, and H_2, CH_4, and CO-based fuels. They can be used for electrical services and decentralized generation.
- **SOLID OXIDE FUEL CELLS (SOFCs)**
  that are based on a ceramic oxide electrolyte, O^{2-} ions as charge carriers, a perovskite catalyzer, and H_2, CH_4, and CO-based fuels or hydrocarbons. They can be used for distributed generation.
- **REVERSIBLE FUEL CELLS (RFCs)**
  that use a solid polymer membrane as an ionic electrolyte, protons (H^+) as charge carriers, Pt and ruthenium oxide catalysts, and hydrogen as fuel. They are found in emergency power supplies and for distributed power generation. These systems can also operate in reverse mode for the production of hydrogen by the electrolysis of water.

Advantages of fuel cells can be summarized as follows:

- **EFFECTIVENESS**
  Fuel cells are generally more efficient than combustion engines, whether piston or turbine.
- **SIMPLICITY**
  The essential elements of a fuel cell are very simple, with few or no moving parts. This results in very reliable and durable systems.
- **LOW EMISSIONS**
  With hydrogen as a fuel, the by-product of the main reaction of a fuel cell is pure water, which means that a fuel cell can be essentially “zero-emission.” However, it should be noted that, at present, CO_2 is almost always emitted during the production of fuels, whether hydrogen or others.
- **NOISELESS**
  Fuels cells operate with virtually no noise, even those that are equipped with large fuel processing equipment.

The biggest drawback of fuel cells today is their manufacturing cost, particularly the cost of catalysts (platinum for instance). The lack of infrastructure for the distribution of hydrogen also presents challenges for fuel cell deployment. The rapid technical advances underway for fuel cell and hydrogen applications will facilitate their large-scale deployment in the near future.

PART C :

PROPOSALS FOR THE DEPLOYMENT OF GREEN HYDROGEN IN QUÉBEC

Green hydrogen value chains are still poorly understood and immature. They are complex due to their multi-sectoral nature and risky in economic terms because they are very capital intensive. Like a number of countries that have developed roadmaps that include introducing a hydrogen component into their energy mix, we propose that Québec develop a target-based roadmap for green hydrogen, targets that would be jointly set by the government and supported by academic and industry experts.

The development of a roadmap is, in our view, an indispensable step to be taken in the coming months as it would provide a guide for investors with respect to future actions and lay a foundation that would inspire confidence in order to initiate structuring initiatives. The objective of this roadmap would be to steer and harmonize the development of green hydrogen over time. Without making any assumptions about the content of the roadmap, we believe that four priorities should drive government policy, namely:

PRIORITY 1

ESTABLISH A COHERENT AND SUPPORTIVE POLITICAL, LEGAL, AND REGULATORY FRAMEWORK
to help de-risk private investments.

PRIORITY 2

SET UP FINANCIAL INCENTIVES
(grants, tax cuts, regulations, showcase projects) to encourage investments.

PRIORITY 3

RAISE PUBLIC AWARENESS
of the benefits of hydrogen as part of the energy transition and implement measures to promote its adoption.

PRIORITY 4

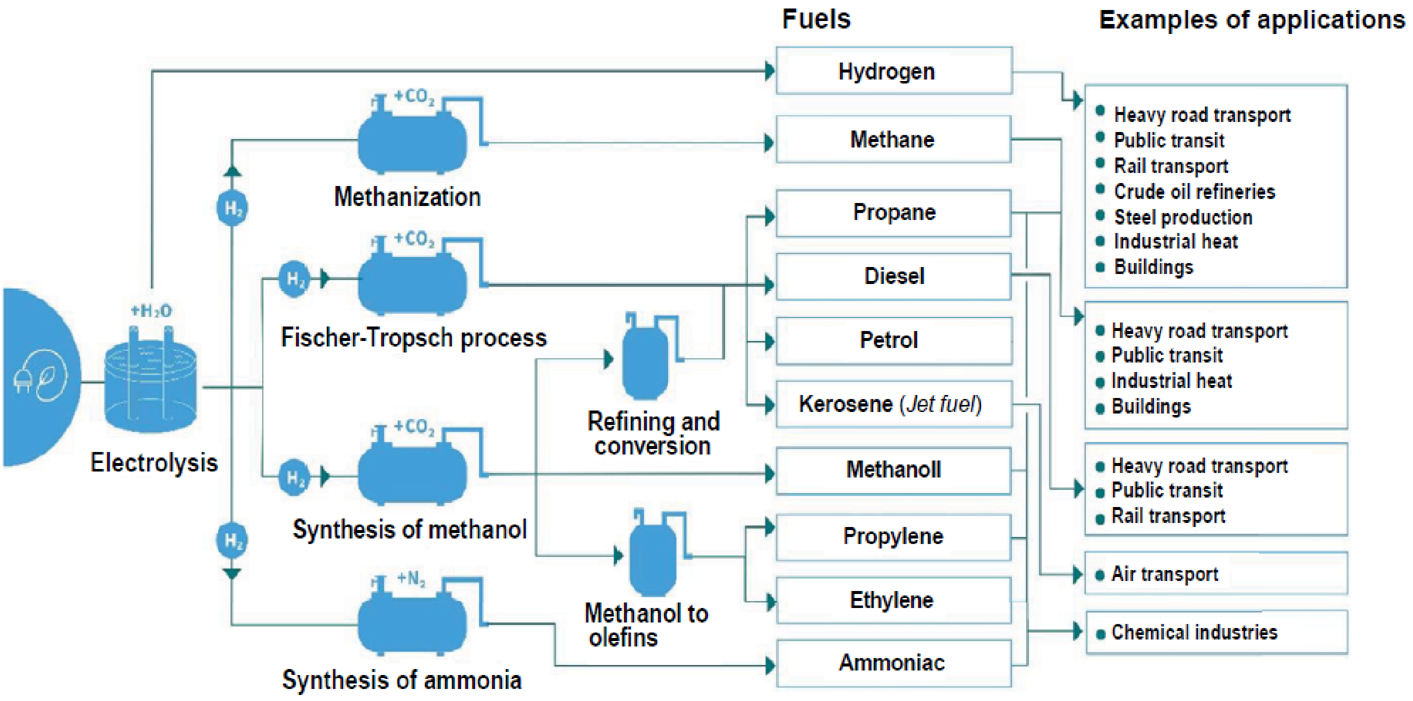
DEVELOP SKILLS
(university studies, research programs, innovation platforms) in the most promising areas of application.

The creation of a qualified Québec workforce in the hydrogen sector is a top priority. Even if Québec already boasts industrial and academic expertise in the hydrogen mobility and industrial hydrogen sectors, the virtual absence of qualified engineers and technicians in these areas is a limiting factor for its development.

A major government initiative is therefore needed in terms of training, in both CEGEPs and universities. We also believe that two initiatives could be implemented immediately, i.e., the creation of university teaching and research chairs in the field of green hydrogen and the funding of a Québec hydrogen cluster.

NEW HYDROGEN MARKETS

A recent study by DENA summarizes the new hydrogen markets well **(see the figure below)**. In Québec, three applications stand out: heavy or intensive mobility, heavy industry, and green chemistry.



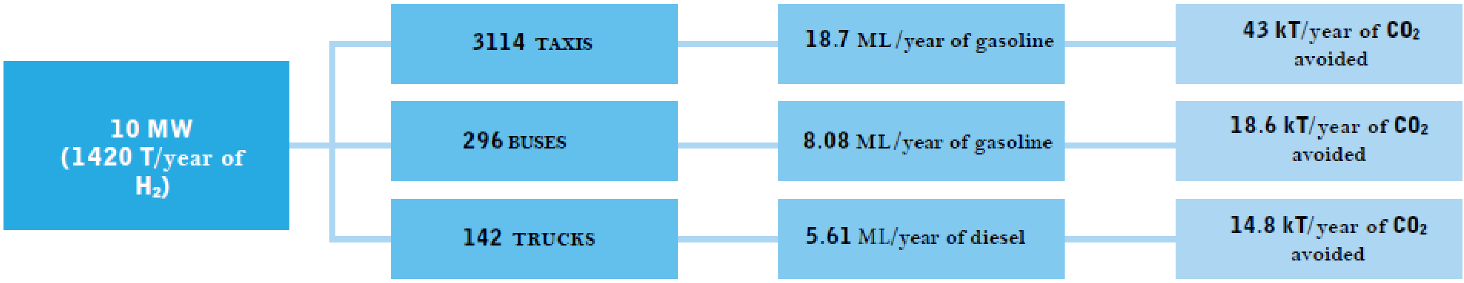
In Québec, the transportation sector emits 34 MT of CO_2 (43% of annual emissions), half of which come from the intensive freight and passenger sub-sectors. Three sub-sectors are particularly ill-suited for battery-powered electrification and would thus lend themselves well to hydrogen mobility:

- **ROAD TRANSPORT** **of freight over long distances due to the weight of the batteries that would be needed to ensure a good range for trucks**
- **INTENSIVE TRANSPORT BY BUS OR TAXI** **due to vehicle downtime for recharging**
- **EMERGENCY VEHICLES** **such as police cars and ambulances**

Considering average trips by type of transportation, the hydrogen consumption required to meet mobility needs is, in order of magnitude:

- **99 kg/year of hydrogen for a LIGHT VEHICLE and 456 kg/year for a TAXI (based on 0.76 kg/100 km**
- **4.8 T/year based on 8 kg/100 km for a HYBRID BUS**
- **10 T/year (actually between 6.6 T/year and 16 T/year) based on 80 kg of hydrogen per 500 to 1200 km for a CLASS 8 TRUCK**

Based on a 10 MW electrolyzer, the impact of hydrogen on the reduction of gasoline and diesel consumption and on CO_2 emissions is as follows:



If all the fuels consumed (and imported) in Québec, i.e., 369,000 barrels/d, were replaced with their equivalent in hydrogen (the conversion factor is 47.3 kg/barrel), 17.454 T/d of hydrogen would have to be produced, which represents an annual production of approximately 6.37 MT. In fact, given the comparative efficiencies of gasoline and diesel engines (35% and 42%, respectively) and a PEM fuel cell (~50%), approximately 20% less hydrogen would have to be manufactured, for a total of 5.1 MT. This would require an electrolysis capacity of about 34 GW and an energy consumption of close to 300 TWh, i.e., almost double the production capacity of Hydro-Québec. At CAD $1500/kW, the investment required would be CAD $47 billion.

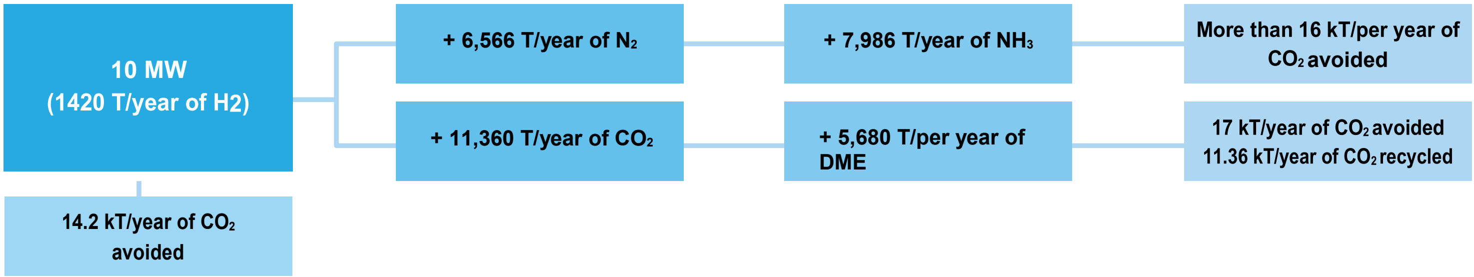
In Québec, eliminating greenhouse gas emissions in the chemical (including cement plants) and manufacturing industries, which account for nearly 20% of the total gases emitted, is more complex and time-consuming than the decarbonization of mobility. The petrochemical and steel industries, two important economic sectors for Montréal and Québec as a whole, are big CO_2 emitters that are concentrated on a few sites. Their complete decarbonization would be difficult but, on the other hand, the CO_2 could be captured at the source and recovered. This is the innovative approach undertaken by CO2 Solutions with Parachem in east-end Montréal as part of the Valorisation Carbone Québec program. A pilot capture unit developed by CO2 Solutions and sized for 10 T/d of CO_2 was successfully tested on the stack of one of the furnaces. This capture technology costs much less than competing technologies (CAD $28/T) and is therefore ideal for demonstrating the technical and economic feasibility of transforming CO_2 into everyday products, testing technologies, determining the criteria for industrial scale-up, and developing unique expertise in green chemistry. It could prove to be a key asset in the decarbonization of the entire industry. To this end, the establishment of a technology platform demonstration site involving both academic scientific expertise, industrial expertise, and government funding is an option that is worth seriously considering.

The Parachem site, and more generally the refinery sector in east-end Montréal, is a prime location to set up a green chemistry technology platform in Québec. A culture of industrial hydrogen, as well as an expertise in health, safety, and environmental concerns is already well established there. In addition, this sector is close to Varennes, where IREQ, Hydro-Québec's research centre, as well as other publicly announced developments are located.

Several projects with strong economic potential for decarbonizing our industry could see the day on this technological platform using a circular economy approach.

Green chemistry has great potential for using green hydrogen and recycling CO_2 to produce synthetic fuels (methane, propane), electrofuels, methanol, or DME. The manufacture of green ammonia is also interesting provided nitrogen can be obtained without a carbon footprint. The challenge is to find a technical, economic, or environmental use for the products in question. Each opportunity must thus be evaluated in its specific context and care must be taken not to generalize the results obtained in different contexts.

The figure below illustrates what could be produced in terms of DME and ammonia using green hydrogen, as well as the quantity of CO_2 that could be avoided using a 10 MW electrolyzer.



The availability of a 10 MW technical test platform would enable innovative technologies for the capture and recovery of CO_2 produced by industrial units to be tested in real conditions.

OFF-GRID SYSTEMS

Powering off-grid systems with stationary fuel cells is also potentially important for our economy. We propose that this approach be tested on a real case corresponding to a situation where the installation of high-voltage power lines cannot be justified.

On Îles-de-la-Madeleine, electricity is currently provided off-grid by a highly polluting 11 MW diesel power plant. A project to install 3 wind turbines is currently underway to decarbonize part of the electricity production. We propose to use this site to test intermittent renewable energy storage and stationary fuel cell technologies.

CONCLUSION

It is imperative to develop an in-depth understanding of the economic development of hydrogen based on the constraints specific to its manufacture (use of renewable energies that may be intermittent), storage, transport, and use in transportation and industry.

In this context as well, as hydrogen is increasingly emerging as a major component of the global energy transition, it is advisable that Québec position itself as a dynamic and credible player in the field. It is clear that the launch of a demonstration project in the mobility and industry decarbonization sectors of the industry will draw international attention to Québec, where hydrogen players are still few and far between and often unknown to one another. It would therefore be advisable to create a grouping or consortium to facilitate dialogue and liaise with governments when warranted. Professional associations and the various clusters working on clean technologies have a leading role to play in creating these synergies.

At the national level, it would be worth coordinating our efforts with other provinces and the federal government, especially with respect to regulations, standards, certification, and access to international markets.

Québec enjoys a unique position thanks to its massive, inexpensive, and reliable green electricity production. It also boasts a competent and diversified university system that covers all aspects of hydrogen production and usage technologies (steam reforming, electrolysis and gasification of biomass, green chemistry, fuel cells) and that is able to train the qualified workers who are needed. These are key assets that can enable us to develop a new green production economy and attract partners and investors to promising growth sectors.

The analysis of decarbonized hydrogen development projects worldwide shows that a partnership approach (often international) is the winning approach. It makes it possible to coordinate (with the help of governments) the different actors involved in new value chains (e.g., light vehicles, electricity production). The goal of this systemic approach is to collectively create, test, and de-risk the various technological building blocks and processes, which are essential milestones to ensure the long-term economic viability of this new industry. Given the importance of properly managing risks, we believe that an inclusive approach involving all stakeholders (government, industry, and the university network) is the right approach for Québec.

PART D:

PERCEPTION OF THE ECONOMIC ACTORS WITH RESPECT TO THE FUTURE OF GREEN HYDROGEN IN QUÉBEC

Part D is part of a larger study conducted by Polytechnique Montréal on behalf of Transition énergétique Québec (TEQ) and Ministère de l'Énergie et des Ressources naturelles (MERN) whose goal is to produce a realistic portrait as well as an objective analysis of the techno-economic landscape and the challenges facing the development of the hydrogen sector.

Overall, the main goals of the study conducted by Polytechnique Montréal were to identify the most promising niches with respect to the role of green hydrogen in Québec's energy transition, guide the future development of government initiatives to support the development of this sector, and identify avenues for the development of pilot projects aimed at increasing the use of green hydrogen in Québec.

In seeking to achieve the above-mentioned goals, CIRAIG carried out an information and consultation process involving the economic actors of the hydrogen sector in Québec as well as a series of interviews with various actors outside the economic sphere.

The goal of Part D, the last of a series of four, was to survey the perceptions, interests, and motivations of stakeholders across Québec to engage and invest in key economic development projects so as to provide a better understanding of the economic players most committed to green hydrogen and identify the strengths, weaknesses, opportunities, and threats (perceived and real) of the business environment.

CONSULTATIVE WORKSHOPS

Between April 9, 2020, and May 14, 2020, three consultative workshops were held with close to 50 internal stakeholders in the business environment of Québec's hydrogen sector. In order to bring together stakeholders with common interests, the workshops, each lasting 210 minutes, were broken down into three components:

1. **PRODUCTION COMPONENT**
2. **MOBILITY COMPONENT**
3. **INDUSTRIAL USAGES**

Following are the types of organizations represented in this series of consultative workshops:

PRODUCERS OR POTENTIAL PRODUCERS OF HYDROGEN (by various technical processes)

REPRESENTATIVES OF NETWORKS ASSOCIATED WITH ELECTRIFICATION AND RENEWABLE ENERGIES

ENERGY **DISTRIBUTORS**

RESEARCHERS WHOSE EXPERTISE IS RELATED TO HYDROGEN AND/OR RENEWABLE ENERGIES

MANUFACTURERS OF COMPONENTS RELATED TO HYDROGEN (fuel cells, electrolyzers, etc.)

REPRESENTATIVES OF ASSOCIATIONS OR NETWORKS RELATED TO ELECTRIFICATION AND MOBILITY

MANUFACTURERS OF AUTOMOBILES OR VEHICLE PARTS (heavy and light)

POTENTIAL **USERS** OF HYDROGEN IN THE MOBILITY SECTOR

INDUSTRIES INTERESTED IN INCORPORATING GREEN HYDROGEN INTO THEIR INDUSTRIAL PROCESSES

INDUSTRIES INTERESTED IN CREATING INDUSTRIAL SYNERGIES OR IN RECOVERING THEIR OUTPUTS (H2, CO2, etc.)

REPRESENTATIVES OF REGIONAL INDUSTRIAL AND ECONOMIC DEVELOPMENT ASSOCIATIONS

Representatives of TEQ, MERN, Ministère de l'Économie et de l'Innovation (MEI), Investissement Québec and Montréal International also participated in the workshops **as observers.**

H_2

MAIN THEMES

During these three workshops, the stakeholders chose to focus on the following main themes:

1. THE PRODUCTION OF HYDROGEN FROM BIOMASS

2. THE NEED TO OBTAIN CRITICAL INFORMATION

3. THE KEY ELEMENTS RELATED TO THE ECONOMIC RATIONALE

4. THEIR NEEDS IN TERMS OF SUPPORT MECHANISMS

5. THEIR NEEDS IN RELATION TO THE REGULATORY FRAMEWORK AND ITS DEFINITION

6. THEIR NEEDS IN TERMS OF RESEARCH AND SKILLS TO BE DEVELOPED

7. ELEMENTS RELATED TO THE SOCIAL ACCEPTABILITY OF HYDROGEN

A number of findings (summarized in the following table) emerged from these discussions:

SYNTHESIS OF THE MAIN SPECIFIC FINDINGS OF THE CONSULTATIVE WORKSHOPS

WORKSHOP – PRODUCTION ACTORS

- **The electrolysis of water is the technology most producers have opted for.**
- **The production of decarbonized hydrogen from biomass is an avenue worth exploring.** However, the economic and technical feasibility of this approach needs to be investigated further.
- **Government authorities must clarify the avenues that will be prioritized—**and potentially be supported by fiscal measures—in terms of opportunities for decarbonized hydrogen.
- **Producers must work together to develop a clear and transparent method to explain the associated business costs of projects.**
- **The main hurdle to overcome in adopting hydrogen is related to the high deployment costs of projects** (in the short term, encourage consumption close to the production site).
- **Identify potential non-regulatory support mechanisms:**
  - Publish a public list of grey hydrogen consumers.
  - Recognize efforts to reduce emissions in the carbon market by hydrogen initiatives.
- **Identify potential regulatory mechanisms:**
  - Rapidly establish a favourable, clear, and sustainable regulatory framework over time to enable the development of viable business plans.
  - Impose on industrial consumers of grey hydrogen a minimum progressive percentage of decarbonized hydrogen use.

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1 Québec Cap and Trade System

SYNTHESIS OF THE MAIN SPECIFIC FINDINGS OF THE CONSULTATIVE WORKSHOPS

WORKSHOP – MOBILITY ACTORS

- **Current costs** (fuels, vehicles, and charging stations) **are a major obstacle to the use of green hydrogen.**
- More communication is needed **to defuse the opposition of some to hydrogen mobility versus battery electric** (or conventional) **vehicles, and instead promote their complementarity with FCEVs.**
- **Encourage the right use of hydrogen in the right places, i.e., for the following applications:**
  - Long distance heavy transport
  - Captive fleets
  - Rail industry
  - Maritime industry
  - Aeronautics industry (e.g., syngas and long-range drones)
- **The current structure of Québec's taxi industry is not conducive to the introduction of hydrogen** given that it does not use captive fleets per se.
- **Introduce potential non-regulatory support mechanisms:**
  - Set ambitious government targets
  - Extend subsidies to all zero-emission vehicles
- **Introduce potential regulatory support mechanisms:**
  - Consider granting exemptions from gross vehicle weight load legislation and regulations to heavy haulers that choose to migrate to low-emission technologies
  - Require public transit authorities to acquire zero-emission vehicles
- **Conduct R&D in the following sectors:**
  - Develop systems designed to be flexible and modular based on the specific integration requirements of each project
  - Storage of high-density hydrogen
  - Performance in winter conditions (for Québec)

SYNTHESIS OF THE MAIN SPECIFIC FINDINGS OF THE CONSULTATIVE WORKSHOPS

WORKSHOP – INDUSTRIAL ACTORS

- **The cost differential for this transition is too great.** In the current context, some favour the adoption of natural gas and/or biofuels over hydrogen.
- **Depending on the applications and the fuel being replaced, some feel that we should not close the door to less expensive grey** hydrogen in order to assist in the transition to the new, required infrastructures.
- **Among the disincentives identified, some argue that the economic rationale for decarbonized hydrogen cannot hold** as long as the price per tonne of carbon remains low (i.e., below $60/tonne).
- **Mechanisms are lacking to promote the premium that would be associated with products with a low carbon footprint** (production powered by decarbonized hydrogen).
- **Governments should step up and demand international laws** and the global application of cap and trade rules.
- **There is an openness to regulatory mechanisms such as:**
  - Progressive taxation on the replacement of fossil fuels and grey hydrogen by decarbonized fuels
  - Progressive taxation of the capture and recovery of CO_2 emissions
- **Research, development, and partnerships:**
  - Foster industry/research consortia
  - Map needs in terms of inputs and outputs of Québec’s major industrial zones (potential synergies)
  - Conduct life cycle assessments of the various types of hydrogen (environmental LCA and life cycle costs)

The table below summarizes the main findings common to all types of stakeholders:

SUMMARY OF THE MAIN SPECIFIC FINDINGS OF THE CONSULTATIVE WORKSHOPS

MAIN COMMON FINDINGS

- **In the longer term, there needs to be an economic rationale. In the meantime, a government initiative could provide financial support for the deployment of this promising sector (in terms of both production and use).**
- **In the short term, use of hydrogen close to production sites, injection into the natural gas network, production of value-added products, and valorization of electrolysis outputs** (oxygen for example) should be encouraged.
- **Ensure sufficient availability for local use before turning to exports.**
- **Reserve exports for value-added products that provide sufficient local spinoffs.**
- **Implement potential non-regulatory support mechanisms:**
  - Subsidize OPEX (under certain conditions[1]) and CAPEX costs
  - Make low-interest loans available to producers (rather than CAPEX grants)
  - Set up ambitious test beds
- **Implement potential regulatory support mechanisms:**
  - Set up a stable and predictable regulatory framework for the long term
  - Establish progressive quotas for the use of decarbonized hydrogen
  - Adjust the rules to allow the injection of hydrogen into the natural gas network
- **Research, development and partnerships:**
  - Storage
  - Transport
  - Encourage consortia between industry, universities, and governments here and elsewhere
- **Do not overlook the importance of fostering social acceptability**[2]
- **Educate and inform stakeholders outside the business environment** (e.g., safety issues, economic benefits, etc.)

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[2] For details of the conditions, see Section 3.5.2 of the report.

[3] Our vision of the concept of social acceptability was inspired by the definition of Gendron (2014), i.e., “the consent of the public to a project or decision resulting from the collective judgment that the project or decisions is superior to known alternatives, including the status quo.”

The implementation of each of the proposals put forward in Part C must be assessed in terms of the strengths and weaknesses, opportunities, and threats to (SWOTs) the business environment in which the potential deployment of this sector is to take place. The table below summarizes the main SWOTs identified.

STRENGTHS, WEAKNESSES, OPPORTUNITIES, AND THREATS OF QUÉBEC'S BUSINESS ENVIRONMENT

STRENGTHS

- **Dynamism** of the actors in the ecosystem
- Relatively low **electricity rates**
- **Engagement of Hydro-Québec:** significant presence and availability of renewable electricity
- **Direct access** to the seaway and deep water ports

WEAKNESSES

- **High cost** for the construction of infrastructures and production, storage and distribution infrastructures and technologies
- **Immaturity** of certain storage and distribution technologies and lack of consensus on the preferred technological choices
- **Slow transformation** of the regulatory framework
- **Process for obtaining operating permits** by producers
- **Substantial investment of resources needed** to enable the required infrastructure to be put in place
- **Lack of a market mechanism** to enhance the value of the premiums attached to low carbon footprint products
- **Lack of a roadmap and a plan** for government investment and support
- **Immaturity** of the green hydrogen value chain
- **Low cost** per ton of carbon

OPPORTUNITIES

- **Anticipated growth** in demand worldwide
- **Potential for decreasing** the trade balance by reducing hydrocarbon imports
- **Potential for filing** commercial patents
- **Improved environmental performance and potential contribution** to the attainment of Québec's GHG reduction targets
- **Increased** independence in terms of access to chemical products (reduction in imports)

THREATS

- **Uncertainty** perceived by stakeholders with respect to the business environment
- **Low cost** of fossil fuels
- **Absence** of a globalized carbon exchange market
- **Rigidity** of certain laws and regulations
- **Incompatibility** between foreign and local standards
- **Social acceptability:** strong association of hydrogen with light vehicles (only) and controversial nature of this use
- **Difficulties** associated with the required scale-up and the reduction in costs
- **Generally poor knowledge** of high potential techno-economic uses of decarbonized hydrogen in Québec

For the benefit of readers, we have recapped the main proposals for each of the priority areas set out in Part C of this study. The table below illustrates the match between the initial proposals and the perceptions of the economic stakeholders who attended the consultative workshops.

The legend for the matches is given below the table. The matches were determined by taking into account the overall support of participants and the frequency with which participants voiced opposition or suggested improvements based on the discourse of the stakeholders involved.

LEVEL OF MATCH OF THE INITIAL PROPOSALS WITH THE PERCEPTIONS OF ECONOMIC STAKEHOLDERS

PRIORTY AREAS	INITIAL PROPOSALS	MATCH
SKILLS DEVELOPMENT	**Develop and reinforce technical training (college) and engineering training (university: BSc, MSc, PhD) skills**	🟢
	Fund a Québec industrial cluster	🟩
TRANSPORT ELECTRIFICATION	**Replace gasoline or diesel vehicles by fuel cell electric vehicles (FCEVs) for freight transport over long distances and for heavy machinery (mining and forestry sectors)**	🟢
	Replace gasoline or diesel vehicles by fuel cell electric vehicles (FCEVs) for public transit and/or taxis	🟥
	Replace gasoline or diesel vehicles by fuel cell electric vehicles (FCEV) for emergency vehicles (police cars, ambulances, etc.), municipal heavy vehicles, forklifts, and the mining and rail sectors	🟢
	Develop a captive fleet strategy	🟩
	Use a hub approach based on the construction of geographically distributed high-capacity stations	🟩

🟩 **Strong match** 🟢 **Strong match, with improvements and/or reservations** 🟨 **Partial match, with improvements and/or reservations** 🟥 **Weak match or rejection of the proposal**

LEVEL OF MATCH OF THE INITIAL PROPOSALS WITH THE PERCEPTIONS OF THE ECONOMIC STAKEHOLDERS

PRIORITY AREAS	INITIAL PROPOSALS	MATCH
DECARBONIZATION OF STEEL MILLS AND REFINERIES	**Replace the fossil fuels used in industrial processes by synthesis gases**	🟨
	Replace the hydrogen produced by steam reforming by green hydrogen in the refining sector	🟨
	Capture and recover CO_2 emitted by industrial processes	🟢
DEVELOPMENT OF GREEN CHEMISTRY	**Combine decarbonized hydrogen molecules with other molecules (e.g., recycled CO_2) to create value-added products (e.g., synthetic fuels, ammonia, etc.)**	🟢
OTHER	**Store and power off-grid systems using stationary fuel cell technologies connected to intermittent renewable energy sources**	🟢
	Coordinate concerted efforts with other Canadian provinces to develop export markets	🟩
	Get involved in the development of international technical standards and regulations	🟩
	Promote opportunities for synergy and networking among Québec hydrogen ecosystem actors	🟩

🟩 **Strong match** 🟢 **Strong match, with improvements and/or reservations** 🟨 **Partial match, with improvements and/or reservations** 🟥 **Weak match or rejection of the proposal**

This section focuses solely on proposals that did not achieve a strong match improvements.

First, the participants stressed the importance of developing a technically qualified workforce. The participants acknowledged that some College Centres for the Transfer of Technology (CCTT) should be given a greater role to play, possibly by revisiting their mandates. However, with respect to universities and the creation of teaching and research chairs in green hydrogen, the participants pointed out that the university network is already well equipped and that Institut de recherche sur l'hydrogène (IRH) affiliated with Université du Québec à Trois-Rivières (UQTR) has been devoted to hydrogen research since the late 1980s. Next, from the point of view of long-distance freight transport and heavy machinery, the participants recognized that a number of improvements are required, especially in terms of the regulatory framework. For example, the load capacity of semi-trailers where load capacity exemptions could possibly be considered for zero-emission vehicles. The positions of the actors tended to diverge when it came to public transit buses and taxi fleets. They noted that, in the short term, public transit corporations have chosen to focus on technologies other than FCEVs. However, the door is not entirely closed to this promising application should support and guidance mechanisms become available. As for the taxi industry, it appears that its ultra-fragmented structure makes this application difficult to operationalize for the moment. The fact remains, nonetheless, that the advantages of FCEVs are such that the proposal cannot be totally ruled out despite the position of the stakeholders consulted.

The decarbonization of sectors classified as major GHG emitters, while essential, will undoubtedly be complex to implement. In this case, the economic rationale and logic imposed by global markets will dictate the actions of major industrial players. As the idea of replacing the fossil fuels used in industrial processes with synthesis gases appears difficult to conceive for some because of the costs associated with such a transition and the need to adapt equipment and processes, replacing fossil fuels with natural gas or biofuels will likely be the first alternative considered. In general, for this to occur, it will be essential to implement a "carrot and stick" approach, i.e., create incentives such as carbon credits linked to the use of green fuels coupled with subsidies and, at the same time, regulate the gradual replacement of fossil fuels. The proposal to capture and recover CO_2 emitted by industrial processes was well received as it would be accompanied by an attractive profit potential for manufacturers. For example, manufacturers that already produce hydrogen and CO_2—as is the case for refineries—are open to such a proposal as it would allow them to convert the production of grey hydrogen into blue hydrogen, reduce their CO_2 emissions, and diversify their product offering with value-added products that could be sold locally or even exported. However the following key issues have yet to be resolved:

- **THE REAL CAPACITY TO TRANSFORM AND IDENTIFY OPPORTUNITIES** for such large volumes of CO_2
- **THE NEED FOR COACHING FROM THE CHEMICAL INDUSTRY TO MANAGE SAFETY ISSUES,** as the manufacture of value-added products is often not the core business of many large GHG emitters.

In light of the findings of our analysis, it appears crucial to draw up a Québec roadmap that clearly fits into the broader framework of an energy transition trajectory consistent with Québec's environmental and socio-economic goals and the results of any future studies. This roadmap should also be co-constructed with internal and external stakeholders in a democratic fashion to ensure its legitimacy with economic actors and all Quebecers alike. With respect more specifically to the success of an eventual Québec decarbonized hydrogen sector, it will also be crucial that the roadmap be able to spark (or even create) a strong and stable match between the quantities of hydrogen produced, on the one hand, and its use in the "right places," on the other. The workshop participants made it clear that this would help mitigate the magnitude of the financial risk that currently prevails and that appears to be hindering the growth of the sector in Québec despite the widely perceived economic opportunity and the enthusiasm that economic stakeholders express for it.

Lastly, in view of a subsequent analysis phase, we recommend that government departments and organizations responsible for the preparation of Québec's hydrogen roadmap to :

1.

INITIATE RESEARCH THAT WOULD ALLOW AVAILABLE TECHNOLOGIES TO BE PUT IN CONTEXT
together with their envisaged uses based on their environmental and social impacts as well as their costs from a life cycle standpoint (environmental LCA, life cycle cost analysis).

2.

EVALUATE AND FOSTER THE SOCIAL ACCEPTABILITY OF ENVISAGED USE SCENARIOS, without presuming a match between the stakes (or points of view) of one sector that uses hydrogen versus another.