Water for the Hydrogen Economy

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November 2020

Preface

The purpose of this report is to highlight the importance of water in the development of the hydrogen economy. This topic is most applicable to water stressed regions that have visions for large scale hydrogen production. To date, limited research had been published on this topic. This paper reviews the water demands for three of the most likely methods for producing hydrogen on a large scale. This paper explores the case study of future hydrogen production in Alberta and discusses the projected water demands that will likely require tradeoffs with existing water consuming sectors in the province. In short, this study concludes that water resources should be carefully considered in Alberta and other water stressed regions when planning the transition to a hydrogen future. As mentioned, this is a first iteration in the exploration of this topic. Feedback and collaboration from industry, researchers, and stakeholders is strongly encouraged.

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Background

Hydrogen is the most abundant element on earth; however, it rarely exists on its own. Fresh water is one of the most abundant naturally existing substances on earth; however, its geographic distribution is highly variable, which makes many countries, states and cities water stressed. The purpose of this paper is to begin to explore the connection between hydrogen and water as hydrogen develops as a key energy source in the transition to a low carbon economy.

The concept of using hydrogen as a replacement fuel for transportation has been around for several decades. The increased attention that hydrogen energy has received in recent years is a result of the decreased cost of renewables, as well as the increased urgency to reduce global energy emissions [1]. Hydrogen is light and produces no direct emissions of pollutants or greenhouse gases. Although hydrogen is energy dense by mass, it has always posed logistical challenges as it requires large volumes for storage and transport. Practical use of hydrogen in today's energy economy in various sectors will require continued reduction in costs through the upscaling of carbon capture storage (CCS), production facilities, electrolysis technologies and transportation infrastructure, as well as the thoughtful consideration of how reliable water sources will fuel the industry. Furthermore, the adoption of a hydrogen economy will require a coordinated effort by government, industry, and society.

Water use in the hydrogen economy

1. What are the pathways for hydrogen production?

Hydrogen is an energy carrier, rather than a natural energy source. Producing hydrogen requires an initial source of energy to separate hydrogen from its natural occurring chemical compounds. Once separated, hydrogen can generate useable energy through combustion, or through use in a fuel cell.

Hydrogen can be produced through several pathways (refer to Figure 1); however, there are three processes which will be reviewed for the purposes of this paper:

- **Steam methane reforming (SMR)** is the most commonly used process for hydrogen production. Steam reforming is the high temperature reaction of methane with steam (water) to produce hydrogen and carbon dioxide [2]. SMR can be combined with carbon capture storage (CCS) to reduce the emissions released into the atmosphere.

- **Autothermal reforming (ATR)** is an alternative method of producing hydrogen through a combination of SMR and partial oxidation. ATR has been recognized in this paper for its ability to capture CO2 more easily and for its relatively lower water demand. It is also expected to be simpler, more compact and cheaper than SMR [3]. However, it should be noted that ATR is still considered a developmental process as it has not been widely commercialized [4].

- **Electrolysis** is a commercially available process which uses an electric current to split water into hydrogen and oxygen [5]. Electrolysis is considered a renewable method for producing hydrogen when combined with solar, wind, hydro, or geothermal as the source of electricity.

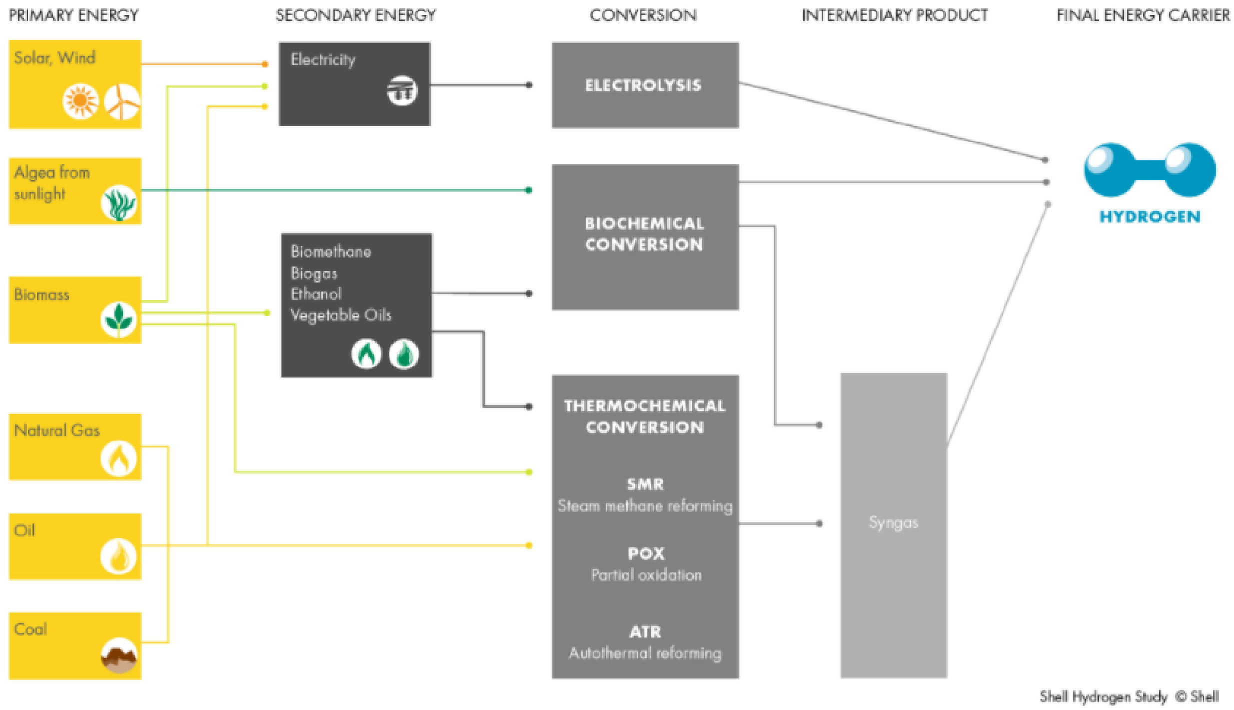

Figure 1 - Pathways to hydrogen production [6].

2. How much water is required for hydrogen production?

The quantity of water required for hydrogen production is dependent on the method used to produce hydrogen, as well as the way the production facility decides to manage the necessary water streams.

1) Steam methane reforming

Producing hydrogen through the process of steam reforming requires a theoretical stochiometric amount of *4.5 L of water per kg of hydrogen.

- Steam reforming: $CH_4 + H_2O \rightarrow CO + 3H_2$
- Water gas shift: $CO + H_2O \rightarrow CO_2 + H_2$
- Overall: $CH_4 + 2H_2O \rightarrow CO_2 + 4H_2$

***Steam generation and system cooling:** Please note that this is the theoretical stoichiometric mass consumed in the chemical reaction. The process of steam reforming will also require significant water for steam production and system cooling [7]. The steam reforming processes release a large amount of energy, and how this energy is managed impacts water consumption. Processes that generate steam for other uses can at least double the water consumption. There is a large amount of heat rejection, and the options for heat rejection include dry coolers, wet cooling towers, and once through cooling. The selection of the heat rejection process determines if there is water consumption, as in a wet cooling tower, or cooling water withdrawal and return for once through cooling. There will also be a wastewater stream that must be managed.

Case study: Linde Engineering is a large-scale hydrogen producer that uses the steam reforming method. Extracting operational data from their facility report allows us to infer different water demands based on assumptions of how they manage their water [8].

- **Stochiometric demand:** Although the stoichiometric ratio of water to hydrogen is 4.5, Linde reports that a ratio of 5.85 L H_2O / kg H_2 is required for their process.
- **Steam demand:** 7.35 L H_2O / kg H_2 is required for excess steam production. Depending on what percentage of this steam is allowed to return to the atmosphere versus what percentage can be condensed and recycled will greatly impact the overall water consumption of the facility.
- **System cooling demand:** 38.0 L H_2O / kg H_2 is required for system cooling. Although it is not expected that this water is "consumed," it is important to note that it is required for plant operation.

Conclusion: Based on the Linde facility data, we can infer that water consumed in hydrogen production ranges from 5.85-13.2 L H20 / kg H_2. Additional wastewater would also be expected to be generated in the process, but this is not described in the report by Linde.

2) Autothermal reforming

Autothermal reforming is a developmental process for producing hydrogen. The process uses the best features of partial oxidation and SMR [9]. The primary benefit of ATR is that it releases CO_2 in a concentrated stream, which allows for easier application of carbon sequestration.

Producing hydrogen through the process of ATR requires less heat and water than SMR to drive the reaction. Extrapolation from the Johnson Matthey process estimates 31,000 L/hr of demineralized water is required to produce 6,000 kg/hr of hydrogen [10]. Assuming a 70% efficiency coefficient for the use of water in the process, and production of demineralized water, the total water demand will be equivalent to ~7.4 L H_2O / kg H_2.

3) Electrolysis

Producing hydrogen through the process of electrolysis theoretically requires 9 L of water per kg of hydrogen based on the stoichiometric values. [11].

- $2H_2O \rightarrow O_2 + 4H^+ + 4e^-$
- $4H^+ + 4e^- \rightarrow 2H_2$
- Overall: $2H_2O \rightarrow O_2 + 2H_2$ [12]

However, most commercial electrolysis units on the market today advertise that they require between 10 and 11 L of deionized water per kg of hydrogen produced. Commercial electrolyzer units with published water demands are listed in Table 1. Other companies with commercial electrolyzer units who do not have publicly available water demands include PROTON, McPhy, and Nel. Note that additional water would be required depending on the process of converting surface/tap water to deionized (DI) water.

Additional water will also be required for system cooling. HYRDOGENICS' PEM electrolyzer requires **15.5 L of tap water per kg of H2** [13]. A schematic of the electrolysis process is included in Appendix A.

Table 1 - Water demands of commercially available electrolysers.

Commercial Unit	Water demand (DI water/kg H2)
SIEMENS SILZER 300	10 L
HYDROGENICS HYLZER	11.1 L
CHE Hydrogen Generation Plant	11.1 L

4) Emerging options for hydrogen production

Steam methane reforming, autothermal reforming and electrolysis were reviewed in this paper as these are the most likely options to be pursued to scale in Alberta. However, there are several processes for producing hydrogen that were not reviewed in detail in this paper. There are also processes that link together several technologies that may reduce water consumption. Each method will have its own associated water and feedstock demands. Likewise, each process will have its own associated challenges and costs. The authors will continue to monitor developments and update as information arises.

3. What is the current and projected cost of hydrogen production?

The cost of hydrogen production varies depending on a number of factors including production logistics (e.g. the scale of the production facility, storage and transportation costs, purpose of use, etc.), and the type of energy source used to convert electricity to hydrogen. Costs are also continuing to decrease as the efficiency of electrolyzers improves. The average low cost of hydrogen (LCOH) produced from various renewable and fossil fuel energy sources is shown below in Figure 2 [14]. The cost of sourcing water for a hydrogen facility may vary, and in some cases water shortages may make some projects logistically challenging, resulting in additional costs. Future projections predict decreasing costs of renewable hydrogen production using electrolysis, and stable costs of hydrogen production using fossil fuels and CCS through 2050 (Figure 3).

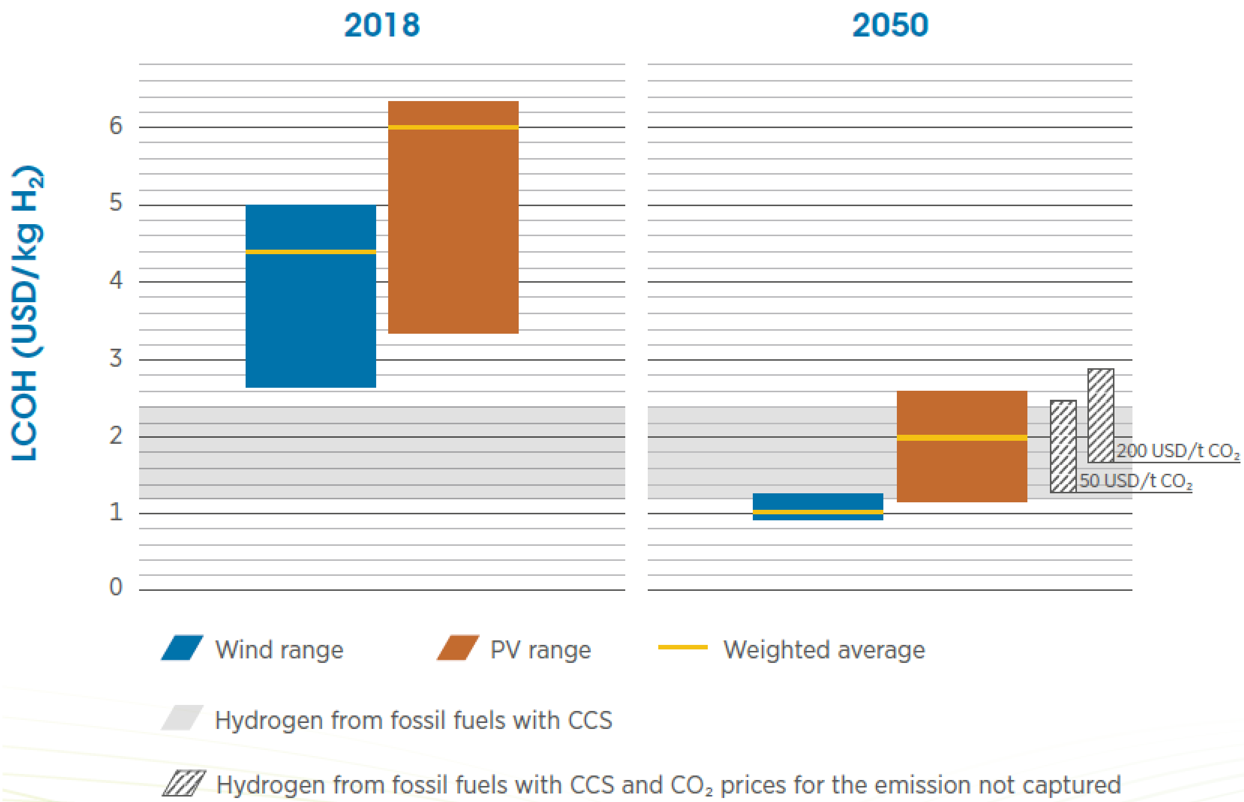

Figure 2 - Cost of hydrogen production from fossils fuels and renewable energy sources.

4. How much water and hydrogen would be required to replace 20% of the natural gas produced in Alberta?

Approximately 65% of Canada's total natural gas production is based in Alberta (297.3 million m^3/day) [15]. In 2019, 46% of Alberta's production was consumed within Alberta [16]. If 20% of Alberta's natural gas consumption was replaced by hydrogen on an equivalent energy basis, approximately 8.62 Kt of H2/day would be required. For electrolysis, assuming a ratio of 15.5 L of water per kg of H2, 134,000 m^3 of water would be required per day (sample calculations in Appendix B). For SMR, assuming a plant designed to use 13.2 L H20 /kg H2, 114,000 m^3 of water would be required per day. By comparison, about 740,000 m^3 of water is consumed per day in Alberta in the oil and gas industry, and 66,750 m^3 of water is consumed per day by the City of Calgary; this value assumes 85% of municipal water withdrawals are treated and returned to the river [12].

Figures 3 and 4 provide context for how much water would be consumed in hydrogen production under various scenarios and technologies. Figure 3 shows the total consumptive use of water in Alberta today, and Figure 4 shows the potential consumptive use for various hydrogen production technologies and under various scenarios for provincial penetration and export.

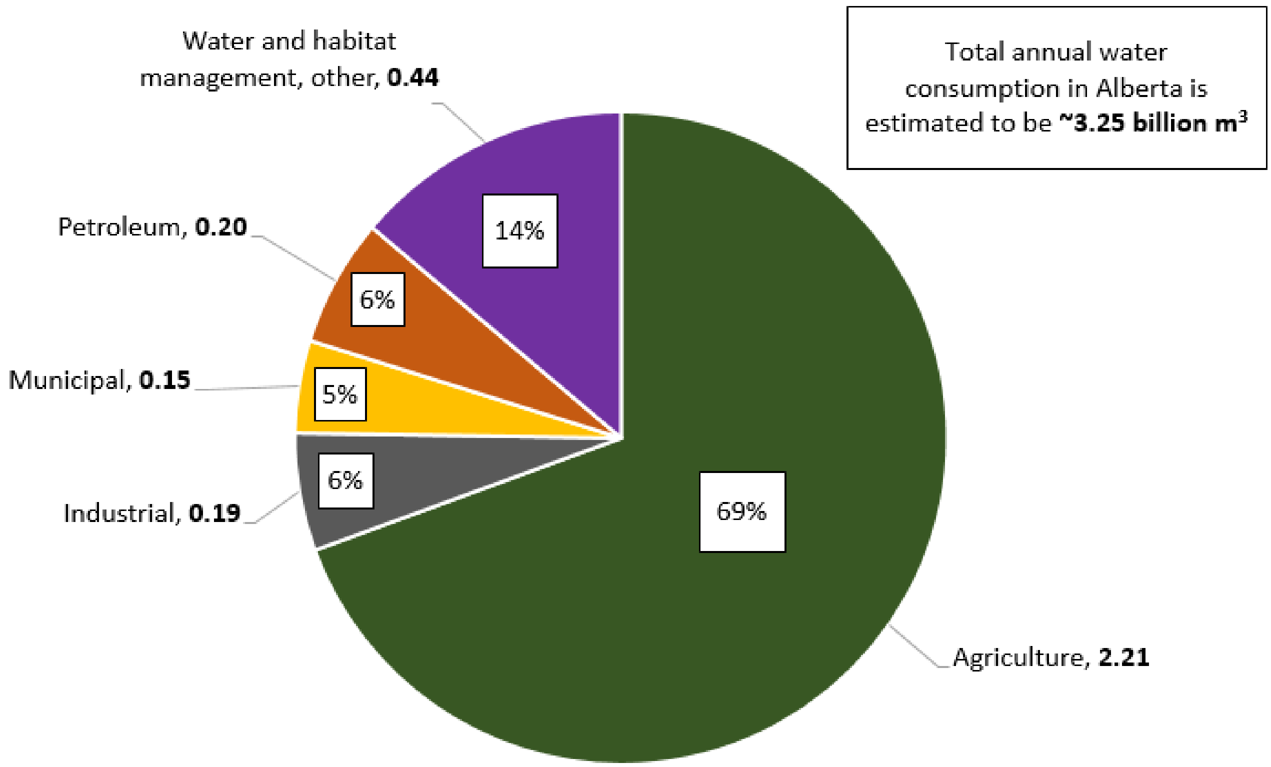

Figure 3 – Current annual water consumption in Alberta by industry [17].

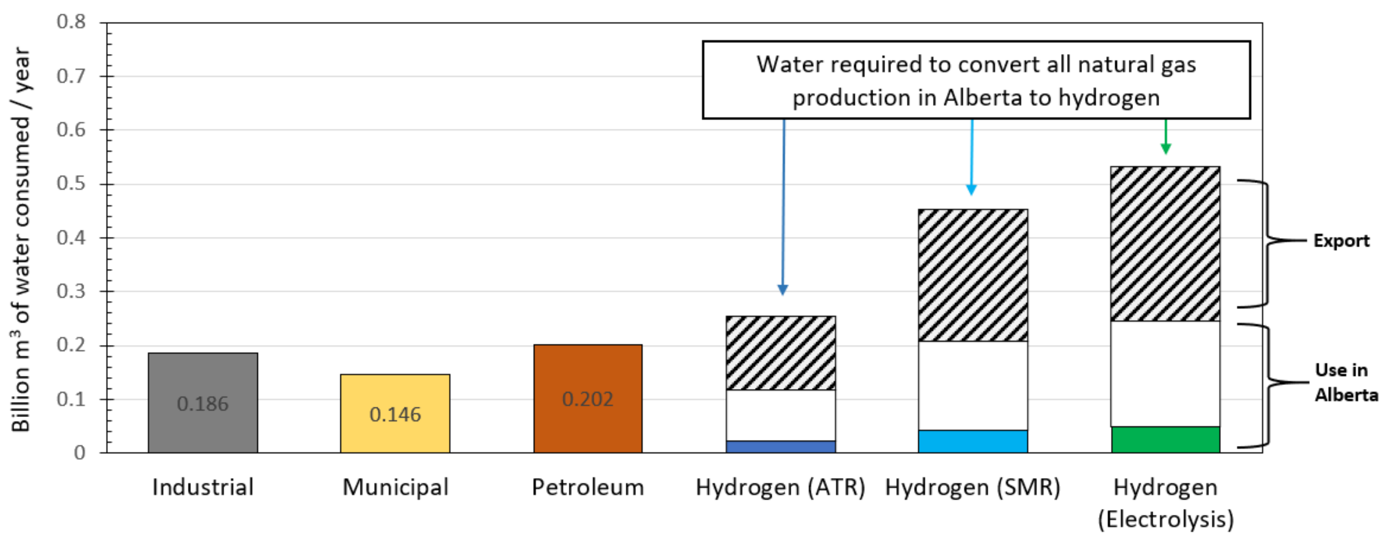

Figure 4 - Annual water consumption in Alberta, including projected demands for hydrogen production.

In short, the numbers are significant compared to the current industrial, municipal and petroleum consumptive uses in Alberta. It is important to understand how much these other consumptive uses will be reduced due to the conversion to a hydrogen based economy. This will be the subject of additional research and future reporting.

5. Conclusions and context for Alberta

Water governance in Alberta is based on the 1999 Water Act [18] and the Water for Life Strategy [19], adopted in 2003. The Water Act prescribes how water licences are to be issued and reported on, as well as the processes for licence transfers and allocations. The Act also clearly states that there is to be no movement of water across watershed boundaries, that is between basins, unless approved by Cabinet. Therefore, water cannot be moved from a water rich basin to a water stressed basin.

The Water for Life strategy lays out the three key priorities for water in the province:

- Safe, secure drinking water for all *(i.e. Municipal use)*
- Healthy aquatic ecosystems *(i.e. environmental protection)*
- Water for a sustainable economy *(i.e. all other uses for agriculture, energy, resource development, industry)*

The current provincial policy direction indicates that agriculture is a key investment priority, and agriculture consumes 67% of freshwater in the province as shown in Figure 3. That means that hydrogen production will be competing for water with other sources of energy production, resource development and industrial development.

In addition, water supply and demand varies regionally across Alberta. In certain parts of the province, specifically the South Saskatchewan River basin, surface water availability has been stressed by climate and by increased use to the point that the basin has been closed for new surface water licences since 2007. Figure 5 shows where water is available for licensing across Alberta. Based on these projected demands of water for the production of hydrogen, water availability in Alberta will need to be carefully considered when planning the transition to a hydrogen future. For example, it would be difficult to envision a large hydrogen production facility being approved in the South Saskatchewan River basin, although there is some potential for facilities in the Red Deer basin. The North Saskatchewan River basin can support growth in hydrogen production, but this may be restricted in some reaches of the river, particularly downstream of Edmonton. The Athabasca, Beaver, Peace, Slave, and Hay River basins are all able to support significant growth unconstrained by the availability of water, except in specific tributaries (e.g. the Wapiti River in the Peace River basin).

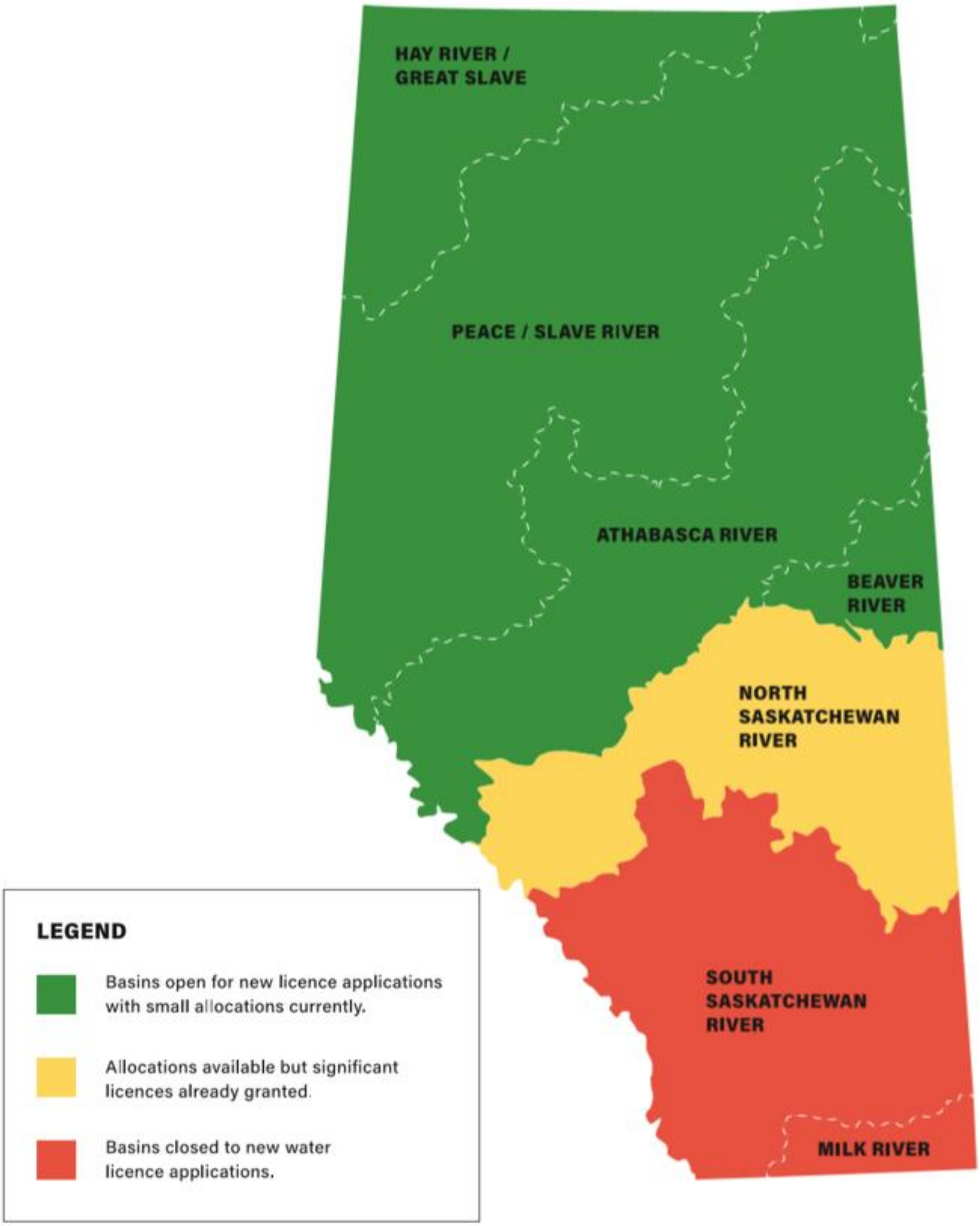

Figure 5 - Water availability in Alberta.

Summary

Hydrogen has the potential to significantly progress our transition to a lower carbon economy. Many experts believe that the development of a hydrogen economy will be a critical requirement to ensure Canada meets its goal of achieving net-zero emissions by 2050. However, there are still many logistical hurdles remaining to develop hydrogen infrastructure to the scale required to make its production economical, and to have a significant impact on the national reduction of emissions. One of the less obvious hurdles will be the water consumption required for hydrogen production. This paper reviewed three of the most likely methods for large scale hydrogen production (electrolysis, SMR and ATR) and the associated water consumption. The results of this water consumption analysis showed that water could be a limiting factor in the transition to a hydrogen future, depending on where the hydrogen is produced and how much existing consumption is reduced by converting current energy use to equivalent hydrogen energy.

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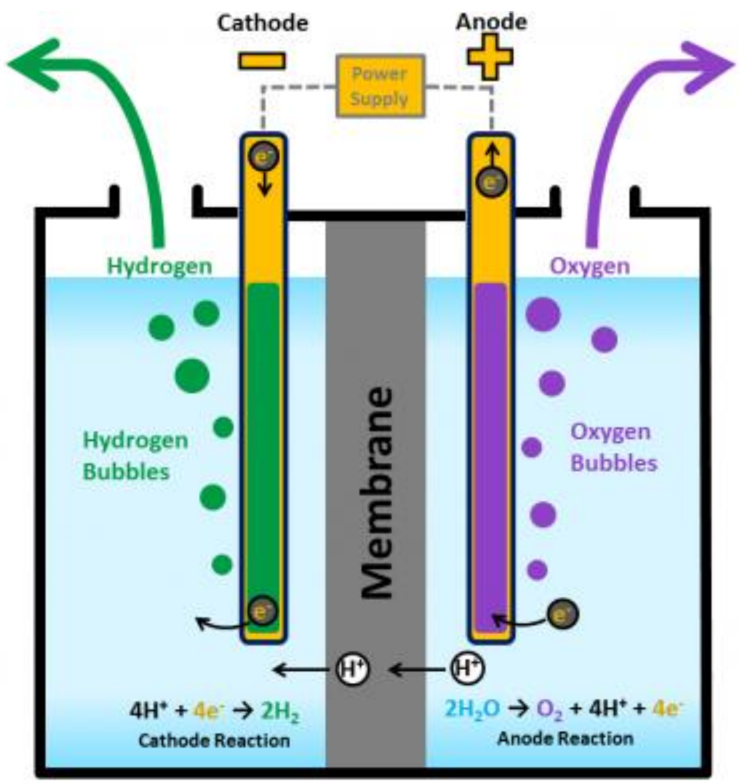
Appendix A

How does the process of electrolysis work to produce hydrogen from water?

Similar to fuels cells, electrolyzers consist of an anode and a cathode separated by and electrolyte. Different electrolyzers function in slightly different ways, mainly due to the different type of electrolyte material involved. Existing electrolyzer technologies include alkaline electrolyzers (AEC), proton exchange, or polymer electrolyte membrane electrolyzers (PEM) and solid oxide electrolyzers (SOEC). A study which reviewed the opinions of ten hydrogen exports from both industry and academia found that AEC is currently the most widely used technology; however, they expect PEM to be the industry leading technology by 2030 [20]. An example of the reaction taking place in a (PEM) electrolyzer is shown in Figure 1 [5, 21].



Appendix B

Sample calculations assuming electrolysis *(rounded to the nearest 10^3)*

1. Convert natural gas production to consumption in Alberta from imperial to metric units: 0.46*297.3 million m^3/day = 136,770,000 m^3/day

2. Assume a standard density of natural gas [22] = 0.8 kg/m^3

3. Calculate the mass of natural gas: 136,770,000 m^3/day * 0.8 kg/m^3 = 109,416,000 kg/d CH4

4. Determine equivalent weight of hydrogen based on heating values (refer to Figure 1): 109,416,000 kg/d * (13.1/33.3) = 43,126,000 kg H2/day

5. Convert to weight of water using 15.5 kg of water per kg of H2: 43,126,000 kg/day * 15.5 = 668,453,000 kg of water

6. Convert to volume of water: 668,453,000 kg/day / 1000 kg/m3 = 668,453 m^3/day

7. Convert to 20% of total consumption in Alberta 1,453,172 m3/day * 0.2 = **134,000 m^3/day**

Table 2 - Heating values for gaseous fuels.

Fuel	Density @0°C/32°F, 1 bar		Higher Heating Value (HHV) (Gross Calorific Value - GCV)					Lower Heating Value (LHV) (Net Calorific Value - NCV)				
Gaseous fuels	**[kg/m³]**	**[g/ft³]**	**[kWh/kg]**	**[MJ/kg]**	**[Btu/lb]**	**[MJ/m³]**	**[Btu/ft³]**	**[kWh/kg]**	**[MJ/kg]**	**[Btu/lb]**	**[MJ/m³]**	**[Btu/ft³]**
Acetylene	1.097	31.1	13.9	49.9	21453	54.7	1468					
Ammonia				22.5	9690							
Hydrogen	0.090	2.55	39.4	141.7	60920	12.7	341	33.3	120.0	51591	10.8	290
Methane	0.716	20.3	15.4	55.5	23874	39.8	1069	13.9	50.0	21496	35.8	964
Natural gas (US market)*	0.777	22.0	14.5	52.2	22446	40.6	1090	13.1	47.1	20262	36.6	983