Hydrogen: A Viable Fuel?

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Introduction

The objective of the essay is to provide background comprehensive information on the creation, storage and consumption of hydrogen as an energy storage medium (hereafter referred to as fuel). Green Hydrogen is a fuel that does not create any CO2 emissions when produced or consumed. Globally, there exists a demand to eliminate reliance on fossil fuels for energy needs in order to eliminate the creation of greenhouse gases and thus prevent global warming, therefore the use of hydrogen as a fuel can be attractive option to meet this demand. Additionally, there also exists energy insecurity (especially in Europe due to the war in Ukraine and threats of Russian supplied gas no longer being shipped to European markets). Therefore, there exists a demand for alternative fuels aside from traditional fossil fuels. Considering these two points, recently the government of Canada announced a strategic partnership with the Government of Germany to create Green Hydrogen in Canada for export to Germany [1]. Private companies in Germany have also released intent to procure 1 million tons of green ammonia (NH3) from Canada annually [2]. This demand is expected to be met via the construction of a yet to be approved World Energy GH2 wind energy project in Stephenville, NL [3]. Germany also announced plans to partner with Brazil for similar Green hydrogen production [4]. The secondary objective of the essay is to provide an analysis comparing Hydrogen production for Germany in Canada and if it is a viable endeavor. The essay will also examine water consumption needed to produce the hydrogen and what impact this would have on water reserves. According to the United Nations, water scarcity is an increasing problem on every continent, with 1.42 billion people living in areas of extremely high water vulnerability [5]. Given that Green Hydrogen is produced using freshwater as the input, it makes one wonder if using Hydrogen as a scaled fuel will exacerbate the existing water shortage.

Technical Information

Hydrogen is not a naturally occurring source of energy and therefore must be generated using inputs from other primary energy sources. Figure 1 outlines traditional methods of generating hydrogen for use as a fuel [6]. There are many methods of creating Hydrogen, however not all of these methods can be considered as sustainable given that hydrogen can be derived from fossil fuels. Grey hydrogen is hydrogen that is produced from natural gas and emits carbon dioxide in the process of creating it [7]. Currently, the most popular form is grey hydrogen which is created in a process called steam methane reformation [7]. Blue Hydrogen is considered as Hydrogen that is generated from fossil fuels, but with carbon capture technology implemented to capture and store the harmful greenhouse gases from entering the environment s [7]. Green Hydrogen uses water electrolysis which is a process that makes use of an anode and a cathode separated by an electrolyte [8] to split water into pure hydrogen and oxygen molecules. Water reacts at the anode to form oxygen and positively charged hydrogen ions [8]. At the cathode, the hydrogen ions combine and form hydrogen gas as seen in Figure 2 [8]. Electrolysis can operate at a conversion efficiency of 82% [9]. It has been demonstrated that hydrogen output increases as the temperature of the electrolyte increases [10]. Hydrogen can be used in a combustion process to generate energy, however the flame burns at a very high temperature therefore can react with the nitrogen and oxygen present in the air to form Nitrous Oxide (NOx) [11]. NOx is 300x more potent than CO2 as a greenhouse gas.

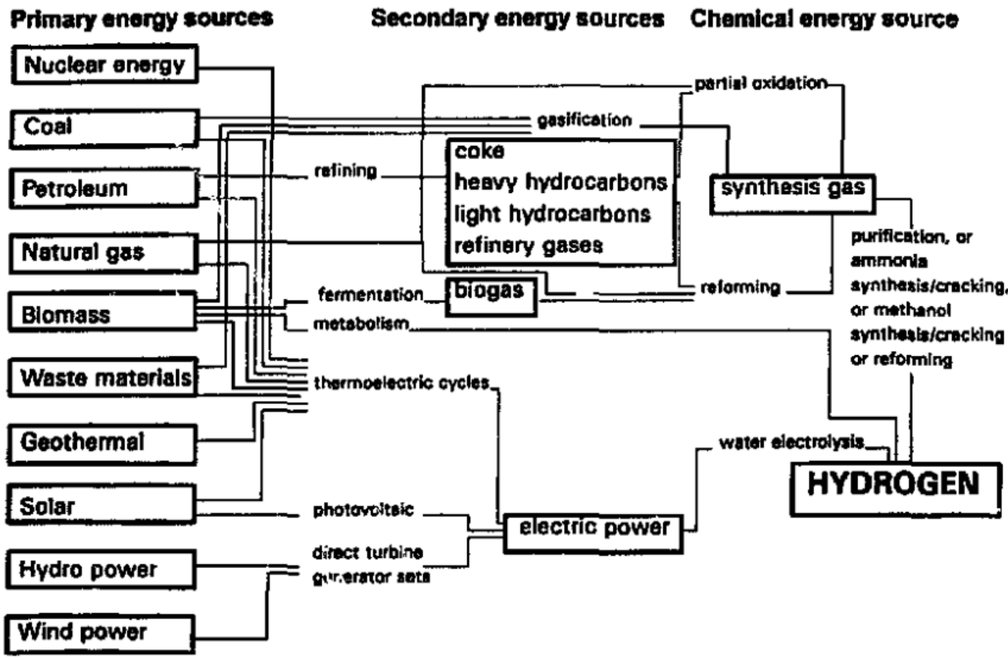

Figure 1 Hydrogen production methods. [6]

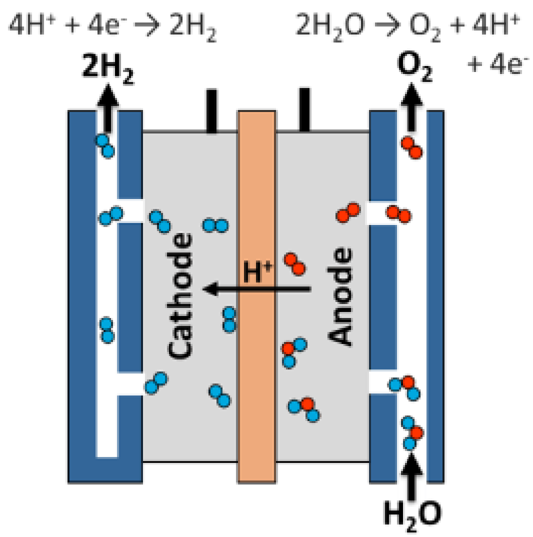

Figure 2 Hydrogen Production by electrolysis [8]

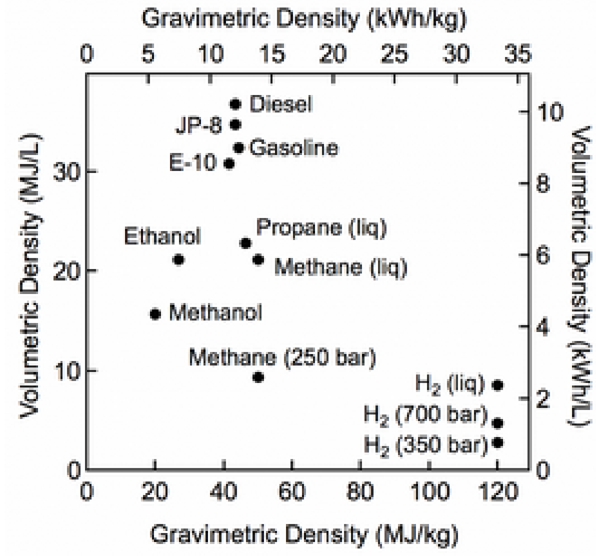

Figure 3 Comparison of specific energy for various fuel types including Hydrogen [12]

Hydrogen has an energy density of 120 MJ/kg [12]. However, one of the main issues with hydrogen as a fuel is that in its gaseous form it occupies a large volume of 11m3 / kg [9] at atmospheric pressure and therefore has a low energy density in terms of volume consumed at 10.9 MJ/m3. Hydrogen can be compressed up to 70 MPa (~10000 psi) [13] or cooled to -252.87°C to form a liquid at 1 bar [14] in order to improve the volumetric energy density. As can be seen in Figure 4, even compressed and liquid hydrogen have a much lower volumetric energy density than traditional fuels. It can also be observed in Figure 4 that the gravimetric energy density is much higher for hydrogen than the gravimetric energy density of traditional fuels. The problem of Hydrogen having a low volumetric energy density is often rectified by converting the H2 gas to Ammonia (NH3) as NH3 has much volumetric higher energy density than that of hydrogen. However, burning NH3 creates Nitrous Oxide (NOx) when burned at high temperatures [15]. Research is ongoing to create to create a catalysed reaction for combustion of NH3 that minimizes NOx produced and sustains combustion but this technology is not commercially viable at present moment [15]. For this reason, the current practice is to use commercially available technology that can decompose NH3 into H2 for fuel cells [15]. Fuel cells produce electrical energy via an electrochemical reaction. The ideal fuel cell can be seen in Figure 3, Where W is electrical work produced [16]. Fuel Cells can also use air or methane as the oxidizer. [16]. It has been found that a fuel cell efficiency can exceed that of a Carnot engine with efficiencies of 79.3%, 75%.7, and 82.1% for hydrogen-oxygen, hydrogen-air and methane-air fuel cells, respectively [16].

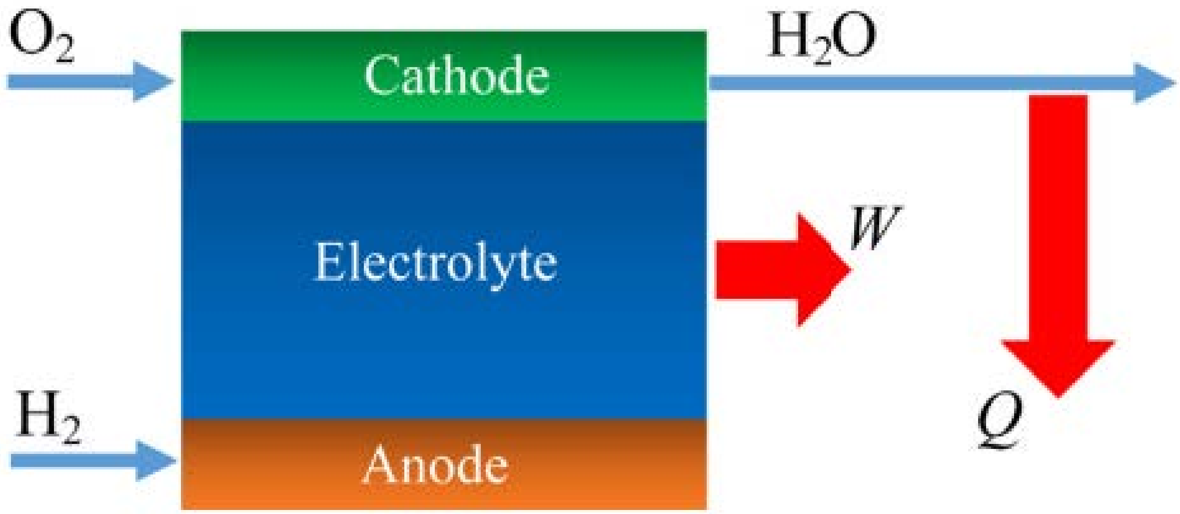

Figure 4 Ideal Fuel Cell [16]

Hydrogen can also be used in the production of synthetic fuels. Using carbon capture technology, CO2 can be obtained from the exhausts of fossil fuel burning processes. This captured CO2 then goes through a chemical process to bond with the hydrogen molecules and form hydrocarbons which can then be used in a combustion process to generate energy [9]. Figure 5 shows the lifecycle of synthetic fuels using solar power as the input energy source.

Figure 5 Synthetic fuel life cycle [9].

Feasibility Analysis

It was stated by the German Chancellor Olaf Scholtz that he expects German energy demand for Green hydrogen to be up to 110 TWh (110 billion kWh) by 2030 [3]. Assuming the proposed GH2 project in Stephenville is meant to supply all of this energy demand, various calculations were completed using this as the target energy export from Canada to Germany via Green Hydrogen. For the purpose of the analysis a fuel cell was used as the final energy conversion process, as it is the only technology currently that can release energy stored in hydrogen without emitting NOx. A hydrogen-air fuel cell will be selected for the purposed of this essay as it is the most practical option (supplying enough O2 could be challenge at this scale). Therefore when an efficiency of 75.7% is used, the real energy demand is 5.23×10^{11} MJ (hereafter referred to as energy demand). The first calculation completed is related to the amount of volume of fuel to be shipped to Germany to meet the energy demand. The second calculation completed relates to how much space and shipping capacity would be needed to store and ship all of the hydrogen or ammonia needed to meet the German green hydrogen demand in 2030. A summary of all constants researched including specific energy, densities of fluids, etc. is included in Table 1 of Appendix A, and are the values used in the following analysis. A system diagram was generated summarizing the lifecycle of Green Hydrogen including the inputs and outputs of how it is produced and used, and is shown in Appendix B. This diagram is the basis for the calculations in the following sections which are summarized in Table 2 of Appendix A. For ease of calculation, the calculation is based on one year's worth of energy production and consumption.

Water Resource Usage

A country is considered water stressed if it withdraws 25% or more of its renewable water supply [5]. Canada has one of the highest volume renewable freshwater resources in the world, while Germany ranks much lower on this list on a per capita basis [17]. Given that it takes approximately 11L of water to produce 1 kg of hydrogen [18], it would take approximately 48 million m3 of freshwater to generate enough hydrogen to meet the energy demand in Germany in 2030. This is equivalent to approximately 0.002% and 0.03% of Canada and Germany's annual renewable water supply, respectively, as derived from available renewable water supply values referenced in Table 2 of Appendix A. These percentages can be considered as negligible when calculating the total renewable water resource consumption with the target of staying under 25% to not be considered as Water Stressed. Therefore, the particular GH2 green hydrogen export project is not a major concern is terms of much water will be consumed and impact on the environment. Expanding this concept further, the entire world's energy demand was approximately 176,431 TWh [19]. The volume of water needed to split into hydrogen to supply this worlds energy demand is 77 billion cubic meters. The total world renewable fresh water supply is 42,809 billion m3 [20]. Therefore it would take approximately 0.1% of the world's renewable freshwater resources to meet the global energy demand with only hydrogen. Based on this small percentage, it can be concluded that water scarcity is a not a concern when it comes to hydrogen production and consumption.

Storage

It is reasonable to assume that the proposed hydrogen transport from Canada to Germany has to be completed by ship. It is not likely that a transatlantic pipe system could be built this century for a reasonable cost. In order to transport The average LNG tanker currently has a storage volume of approximately 150,000 m^3.Assuming the volume capacity would remain similar for transporting either Hydrogen Gas , this value was used to calculate how many trips would be needed to transport the fuel across the Atlantic. For hydrogen at atmospheric pressure, it was found that 319,863 150,000 m3 capacity tankers would be needed. This is clearly not a feasible solution, given that there are only 641 LNG tankers in service today. Therefore, hydrogen must either be compressed, cooled or chemically converted to another compound in order to have chance of taking up a reasonable amount of space for the energy it provides. Hydrogen at atmospheric pressure had a conversion efficiency of approximately 85%, that is to say that 85% of energy put into the creation of the hydrogen gas is still available in the captured hydrogen gas, and the remaining 15% of the input energy was lost to heat. When hydrogen is compressed to a pressure of 70 MPa, and stored in the same 150 000 m3 tanker the amount of tankers to transport the energy to Germany reduces significantly to 765 tankers/ year. When considering the trip from Stephenville, to Hamburg Germany is a 12 day trip by boat, this would take up 4% of the world's tanker capacity, assuming the built ships can handle the high pressure required to transport the pure hydrogen. This is not an insignificant number, considering 4% of the world tanker capacity would be tied up supplying only a fraction of one country's energy demand.

There is also a risk in that gases at higher pressures require robust holding tanks in order to not rupture, and thus comes with additional cost and maintenance. Hydrogen gas is also a colourless, odourless gas which makes it very hard to detect any leaks, which could be a significant problem when the gas is under very high pressure as it is more prone to leak under these high pressures. Hydrogen is very flammable so any undetected (which is hard to do) leak could be catastrophic.

Finally, the case for converting the hydrogen to ammonia, and then back to hydrogen for consumption in a fuel cell was considered. Converting the hydrogen to ammonia greatly reduced the amount of tanker trips needed to transport the fuel across the ocean to 305 in the liquefied ammonia case. However this comes with significant energy losses, with the conversion efficiency only ending up to be 22%. The only way to justify this significant inefficiency is if the cost / kWh supplied is still a reasonable value. There are two major capital expenses considered in the calculation, the first being the cost to construct a wind farm with enough capacity to produce the hydrogen needed to meet the energy demand assuming each wind turbine has a power capacity of 2.75 MW and an annual energy production rate of 10.1 GWh [21] . The second capital cost estimated is the investment required in shipping capacity to transport the fuel across the Atlantic. Table 1 details these estimated costs, using an estimated tanker cost of $190 million [22], and construction cost of. The cost / kWh calculation involves depreciating the assets over a period of 8 years as is standard in accounting calculations:

$$\frac{Cost}{kWh} = \frac{\frac{Tanker\ capital\ cost + Wind\ Turbine\ Cost}{8}}{Total\ Energy\ delivered}$$

It is worth noting that there are other major expenses not accounted for in this calculation such as the cost to build a hydrogen export terminal, operating costs of the power generation and export terminal, maintenance costs, temporary storage facilities, etc. However, even omitting these major expenses, all of the proposed fuel transport methods have a much higher unit cost than what is currently paid per kWh of natural gas in Germany ($0.215 [23]). This means that the current proposal of transporting ammonia to Germany from Canada will cost almost 5x as much as the current price for natural gas. It is unlikely that the average consumer would accept paying such a higher price for a “Green” Fuel.

Table 1 Estimated costs per unit energy delivered derivation

Fuel	**Tankers needed**	**Tanker capital cost**	**Turbines needed**	**Wind Turbine construction cost**	**Cost / kWh supplied**
H2 Atmospheric pressure	10510	$ 1,996,923,945,205.48	16807	$ 35,294,700,000.00	$ 13.99
H2 Compressed	25	$ 4,778,630,136.99	19392	$ 40,723,200,000.00	$ 0.31

NH3	86	$ 16,416,000,000.00	64099	$ 134,607,900,000.00	$ 1.04
NH3 liquid	10	$ 1,905,205,479.45	68225	$143,272,500,000.00	$ 1.00

Conclusions and Recommendations

It is clear that although in the media and by politicians Green Hydrogen is touted as a promising solution to climate change, there are still some major concerns with adopting it for widespread use. It is possible that the announcement made by Canada's and Germany's leaders was purely a political move to send a message to the Russian leadership that Germany is serious about getting off Russian gas, even if the move to Hydrogen produced in Canada does not make financial sense. The biggest issue with using hydrogen as a sustainable fuel is the volume (space) required to house all of the hydrogen needed to power our daily lives. Given that the overall lifecycle efficiency of exporting ammonia for the use of energy consumption in Germany is less than 25%, it is recommended to evaluate the use of fuels that can store electricity that has been generated domestically, instead of converting electricity to hydrogen, then to ammonia, back to hydrogen and then used in a fuel cell. It realistically only makes sense to use hydrogen as a fuel when it does not need to be transported long distances, as the storing of hydrogen requires very high pressures which can be dangerous or low temperatures that are difficult to maintain. Given the low efficiency of converting back and forth between hydrogen and ammonia, the low energy density, high pressures or low temperatures required; hydrogen should also only be used when there is no other fuel available to be used, such as pumped hydro, gravity storage systems, batteries, etc. To that end, fuel cell cars could still be a reasonable application of hydrogen as a fuel, given that the other energy storage methods mentioned above are not applicable, except for battery storage systems. However, given that there is an anticipated battery shortage, fuel cell cars can be used to fill in this gap and complement battery electric vehicles in order to accelerate the transition to a carbon neutral world. Alternatively, with the elimination of government subsidies for the fossil fuel industry, and those subsidies applied to the green hydrogen industry, it may make the price more attractive for the average consumer and increase demand for the fuel. This high cost / low efficiency highlights the difficulties when it comes to energy policy. There is a need to eliminate the reliance on fossil fuels but it is very difficult for the average person to do so when the sustainable technologies are so much more expensive.

Knowing that the main problem with Hydrogen is storage, it would be interesting to study the time required for the electrolysis reaction to take place, with the intent of developing on-demand hydrogen plant. If the electrolysis process takes a sufficiently short time and can be started and stopped easily, Hydrogen could be used a busy traffic area with water available such as the 401 corridor along Ontario. If the electrolysis reaction was quick enough, the hydrogen could be extracted from the lake, and into a fuel cell powered car, much like filling your car up with gas only the hydrogen is being generated in real time.

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Appendix A

Table 2 Summary of assumed and defined input variables

Variable / Constant Input	**Value**
kWh needed by Germany [3]	1.4531E+11
MJ Needed by Germany (kWh*3.6)	5.23118E+11
kWh/kg hydrogen produced [9]	39
kWh/kg to compress hydrogen [13]	6
L water / kg hydrogen produced	11
LNG Tankers in the world [24]	641
LNG tanker capacity (tankers*days)	233965
days to transport Stephenville to Hamburg https://sea-distances.org/	12

Assumed boat kW https://ships.jobmarineman.com/cygnus-passage-9376294/	22930
Assumed power utilization	60%
Average capacity of a tanker (m3) [24]	150000
Density LNG kg/m3 [25]	430
Weight of LNG in tanker (kg) tanker*density	64500000
kg H2 / kg NH3 [26]	0.177
kWh Haber-Bosch process/kg ammonia [27]	15
Canada Renewable water supply [17]	2.792E+12
Germany Renewable water supply [17]	1.88E+11
Energy required to crack ammonia kWh/kg (includes loss of hydrogen) [29]	1.4
Power output 2.75MW Turbine [21]	1.01E+07
Cost/ Wind turbine [30]	2.10E+06
LNG carrier cost [22]	$ 190,000,000.00
kWh /kg compress Ammonia (assumed)	1.5

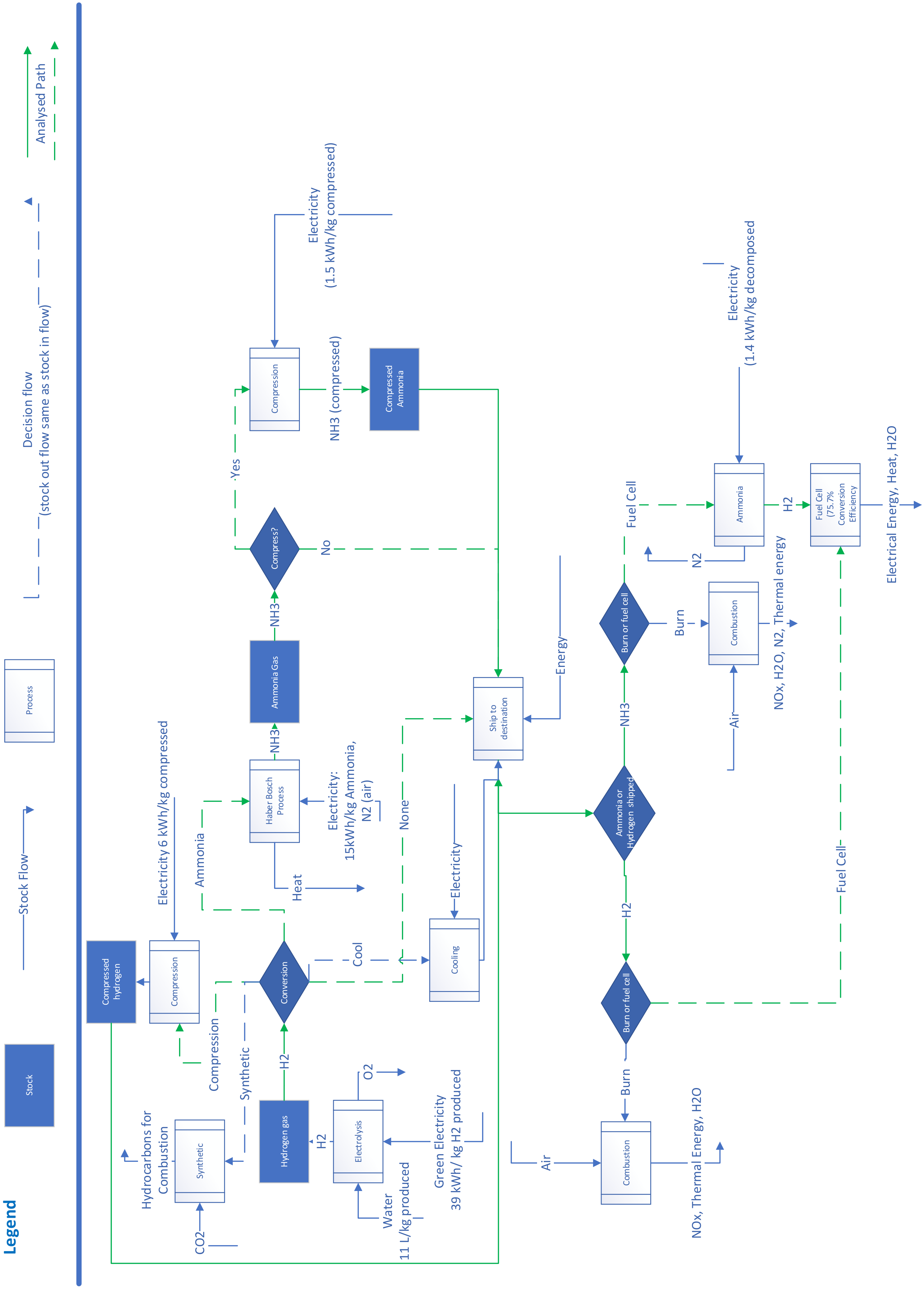
Table 3 Comparison of calculated and constant values related to energy conversion of Hydrogen and Ammonia compounds

Fuel	**H2 Atmospheric pressure**	**H2 Compressed**	**NH3**	**NH3 liquid**
Energy Density MJ/kg	120	120	18.8	18.8
Density kg/m3	0.09	38.00	70.60	609.00
Density MJ/m3	10.91	4560.00	1327.28	11449.20

Kg needed to supply German demand	4359313077.94	4359313077.94	27825402625.14	27825402625.14
kg hydrogen needed	4359313077.94	4359313077.94	4925096264.65	4925096264.65
m3 to supply Germany	47952443857.33	114718765.21	394127515.94	45690316.30
# of tankers needed	319683	765	2628	305
kWh/tanker	454545.40	189948282.26	55293164.36	476427658.79
Tanker-days	3836196.00	9180.00	31536.00	3660.00
World Tanker capacity consumed	1639.6%	3.9%	13.5%	1.6%
Weight/Tanker	13636.36	5698448.47	10588052.75	91230828.28
Weight Ratio to LNG tanker	0%	9%	16%	141%
kWh needed to transport Stephenville to Hamburg	838	350062	650435	5604407
Transportation Energy as a % of total load.	0.2%	0.2%	1.2%	1.2%
Total kWh needed	170013210039.63	196169088507.27	648416007809.14	690159065718.83
Tankers needed	10510.13	25.15	86.40	10.03
Tanker capital cost	$ 1,996,923,945,205.48	$ 4,778,630,136.99	$ 16,416,000,000.00	$ 1,905,205,479.45
Turbines needed	16807	19392	64099	68225
Wind Turbine construction cost	$ 35,294,700,000.00	$ 40,723,200,000.00	$ 134,607,900,000.00	$ 143,272,500,000.00
Cost / kWh supplied	$ 13.99	$ 0.31	$ 1.04	$ 1.00
Conversion Efficiency	85%	74%	22%	21%

Water Needed (m3)	4.80E+07	47952443.86	54176058.91	54176058.91
% of Canada renewable water	0.0017%	0.0017%	0.0019%	0.0019%
% of german renewable water	0.026%	0.026%	0.029%	0.029%

Appendix B


Legend
Stock
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Stock Flow
Decision flow
(stock out flow same as stock in flow)
Analysed Path
Compressed hydrogen
Compression
Electricity 6 kWh/kg compressed
Synthetic
Hydrocarbons for Combustion
CO2
Hydrogen gas
H2
Electrolysis
O2
Water
11 L/kg produced
Green Electricity
39 kWh/ kg H2 produced
H2
Conversion
Compression
Synthetic
Ammonia
None
Cool
Cooling
Electricity
Haber Bosch Process
Electricity:
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N2 (air)
Heat
NH3
Ammonia Gas
NH3
Compress?
Yes
No
Compression
Electricity
(1.5 kWh/kg compressed)
NH3 (compressed)
Compressed Ammonia
Ship to destination
Energy
Ammonia or Hydrogen shipped
NH3
H2
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N2
H2
Fuel Cell (75.7% Conversion Efficiency)
Electrical Energy, Heat, H2O