Hydrogen Gas Refuelling Infrastructure for Heavy-Duty Trucks: A Feasibility Analysis[1]

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ABSTRACT

In view of serious environmental problems occurring around the world and in particular climate change caused significantly by dangerous CO_2 emissions into the biosphere in the developmental process, it has become imperative to identify alternative and cleaner sources of energy. It is now indisputable that there cannot be sustained development or meaningful growth without a commitment to preserve the environment. Compressed hydrogen is being considered as a potential fuel for heavy-duty applications because it will substantially reduce toxic greenhouse gas emissions and other pollutant emissions. The cost of hydrogen will be a main element in the acceptance of compressed hydrogen internal combustion engine (ICE) vehicles in the marketplace since of its effect on the levelized cost of driving. The cost of

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hydrogen at the pump is determined by its production cost, which is mainly a function of the feedstock and process utilised, the distribution cost and the refuelling station cost.

This paper investigates the feasibility of developing a nationwide network of hydrogen refuelling infrastructure with the aim to assist for a conversion of long-haul, heavy-duty (LHHD) truck fleet from diesel fuel to hydrogen. This initiative is taken in order to reduce vehicle emissions and support commitments to the climate plans reinforcing active transportation infrastructure together with new transit infrastructure and zero emission vehicles.

Two methods based on constant and variable traffics, using data about hydrogen infrastructure and ICE vehicles, were created to estimate fuelling conditions for LHHD truck fleet. Furthermore, a thorough economic study was carried out on several test cases to evaluate how diverse variables affect the final selling price of hydrogen. This gave understanding of what elements go into pricing of hydrogen and if it can compete with diesel in the trucking market.

Results revealed that the cost to purchase green hydrogen is the utmost part in the pump price of hydrogen. Due to the variety in hydrogen production, there is no defined cost, which renders estimates difficult. Moreover, it was found that the pump price of green hydrogen is on average 239% more expensive than diesel fuel.

Future work should concentrate on the costs and logistics of high-capacity hydrogen refuelling stations, which is required to deliver fuel to a fleet of LHHD trucks. A breakdown of hydrogen production costs and the requirements of a LHHD truck fleet, may possibly give further precise predictions than those made in this work.

The methodology proposed and models created in this feasibility study may serve as a valuable tool for future techno-economics of hydrogen refuelling stations for other types of ICE fleets or fuel cell vehicles.

Keywords: *Compressed hydrogen; infrastructure; refuelling station; internal combustion engine (ICE); long-haul, heavy duty (LHHD) trucks; techno-economics; levelized cost*

1. INTRODUCTION

Climate change stays a serious problem touching every facet of the natural environment. It is recognised that climate change is the direct consequence of natural sources, but mainly relatable to anthropogenic actions, and several scientific studies definitely ascerta in that global warming is accountable to harshly changing the balance in the Earth's climate via emissions of harmful greenhouse gases (GHGs).

On December 12th, 2015, about 195 countries signed the Paris Agreement. The main objective being to limit the global temperature increase to 1.5°C from pre-industrial levels [1]. From then, many states have been performing research to identify which sectors can be improved to help attain this target. Vehicles are one main part of concern, both domestically and internationally. Road freight transport represents a substantial part of total energy utilisation in the transport sector. Nearly 45% of total transport energy use links to freight transport, with heavy-duty vehicles (HDVs) consuming in excess of half of that energy [1]. Additionally, road freight transport relies much on fossil fuels; with medium and heavy freight trucks representing 24% of total oil-based fuel utilisation. Diesel is the principal fuel employed in road freight transport, accounting for 84% of all oil commodities consumed; and in proportion to half of the total diesel demand. In spite of the small share in road vehicles, medium-duty vehicles (MDVs) and HDVs contribute exceedingly to transport GHG and air pollutant emissions, and fossil fuel consumption. This is caused by high truck fuel consumption, significant annual travelled ranges and prolonged idling times. In the European Union, HDVs represent 30% of on-road GHG emissions, despite accounting for merely 4% of the road vehicle fleet. Also in the United States, MDVs and HDVs constitute 26% of transport GHG emissions. Additionally, road freight trucks generate half of particulate matter (PM) emissions and one third of NO_x emissions of the transport sector in cities. In addition, diesel exhaust emission is classified as carcinogenic to humans (Group 1) by the World Health Organization (WHO) [2–5]. Furthermore, in Canada, in 2018, the transport sector was the second largest source of GHG emissions, accounting for 25% (185 mega tonnes of carbon dioxide equivalent) of total national emissions. Between 1990 and 2018, GHG emissions from the transportation sector grew by 53%. The growth in emissions was mostly driven by increases from freight trucks and passenger light trucks [6].

All the time, most of merchandises carried by road in North America are transferred by heavy-duty truck. In effect, trucks transport about 90% of totally customer goods and foods transacted from Canada to the United States. Though stock travel by truck is obviously a pillar of the economy, it is likewise a main cause of GHGs: more than 10.5% of GHG emissions emanate from cargo transport, besides mostly of these emissions derive from heavy-duty trucks. With truck activities intensifying and less vehicle efficiency improvements compared to light vehicles, emissions from cargo are projected to circumvent those from commuter transport through near 2030. Reinforcing a change to a purer trucking segment needs to be a leader of climate action plans across the planet if total emissions are to be reduced by around 45% from 2010 levels on or after 2030 [7–9].

The topic of application for this paper is on long-haul, heavy-duty (LHHD) trucks, particularly converting the main source of fuel from diesel to hydrogen. Hydrogen was chosen as it can be used as an energy carrier in modified internal combustion engines (ICEs), which helps eliminate the need to purchase new vehicles. The existing diesel engines can be easily modified to support hydrogen fuel, making the adoption of hydrogen both easier and more cost-effective than implementing fuel cells [10–13].

One obstacle, with converting LHHD truck fleet to hydrogen, is the lack of current refuelling infrastructure. Irrespective of the percentage of the truck fleet that is adapted to hydrogen, it is required to have a refuelling network that is safe, accessible, and economically feasible. The final selling price of hydrogen is a sound criterion to the feasibility of investing such an infrastructure. If this selling price is proved to be viable compared to that of diesel, then it can be stated that it is economically justified to execute such a project. Elements that go into the final selling price of hydrogen comprise the project capital costs, operational costs, and the amount of fuel required to support LHHD truck fleet.

While there have been numerous works on the technical, economic and ecological aspects related to hydrogen vehicles and refuelling infrastructure [14–32], there is a lack of feasibility studies on hydrogen refuelling infrastructure for ICE-powered LHHD trucks. Hence, this paper seeks to assess the feasibility of realising a nationwide network of hydrogen refuelling stations with the purpose to assist in the conversion of LHHD truck fleet from diesel fuel to hydrogen. This initiative is taken in order to reduce vehicle emissions and support commitments to the climate plans supporting active transportation infrastructure, together with new transit infrastructure, and zero emission vehicles. Two methods based on constant traffic and variable traffic, with data on hydrogen infrastructure and vehicles, are created to estimate fuelling conditions for LHHD truck fleet. In addition, a detailed economic analysis was performed on several test cases to evaluate how diverse variables affect the final selling price of hydrogen. This will provide insight with the understanding of what factors go into pricing hydrogen and if it can compete against diesel in the trucking market.

The structure of this paper is as follows: in Section 2, some background information on hydrogen ICE-based vehicles and refuelling stations is provided. Sections 3 and 4 discuss in detail the technical and economic analyses, as well as the results and their discussion; while the conclusions are presented in Section 5.

2. OVERVIEW ON COMPRESSED HYDROGEN GAS VEHICLES AND REFELLING STATIONS

This section presents background overviews and input data for the case study on LHHD transport trucks, hydrogen ICE vehicle, hydrogen gas production and hydrogen refuelling infrastructure.

2.1 Long-Haul, Heavy-Duty Transport Trucks

For the input data needed for the evaluation of the hydrogen infrastructure, a case study was considered for the LHHD ICE truck fleet. As the focus of this study, LHHD trucks can be defined as those that weigh more than 14,971 kg [33] and travel more than 320 km to make a delivery [34]. It is estimated that a fleet of 70,000 LHHD trucks is in operation [35]. According to a 2018 analysis of trucking in the U.S., nearly 90% of respondents used diesel, or a bio-diesel blend, as their source of fuel [36]. From this figure, it will be assumed that all of LHHD trucks use diesel. A database on road transportation showed that the average fuel efficiency for heavy-duty trucks is 0.309 L/km [37].

Any given heavy-duty truck has the capacity to hold 470 to 1100 L of fuel, split between two evenly loaded tanks on either side of the truck cabin [38]. Due to the nature of long-haul driving, it is assumed that trucks will have the capacity to hold, the higher value, 1100 L of fuel. This would better accommodate the long distances travelled and would give more security to truck drivers if they are distant from a refuelling station.

Truck drivers either operate on a 7-day or 14-day schedule, which for this analysis a 7-day schedule will be assumed. The Ministry of Transportation requires that an operator must take 10 hours rest after a maximum 14-hour shift, where a maximum of 13 hours can be spent actively driving [39]. While an operator can theoretically drive for 13 hours, packing, unpacking, refuelling, and checks all take time and will reduce the time spent driving. Using the 7-day schedule and the 2 weeks of vacation entitled to each employee [40], as estimate can be made as to how many days per year an operator can be driving, which comes to 298 days per year. Another report analysing LHHD trucks estimates that on average, an operator will drive 825 km per day [35].

An interesting factor that must be taken into account, specifically with long-haul vehicles, is the time spent per day idling. Idling is defined as having the engine run slowly while disconnected from a load [41]. According to a report by the U.S. Department of Energy, idling a heavy-duty truck will consume about 3 litres of diesel per hour [42]. If it is assumed that a truck will idle for 11 hours per day, then this idling consumes 11.5% of the total fuel used per day. This is significant enough to be taken into consideration during further analysis.

2.2 Overview on Hydrogen Vehicles

Hydrogen vehicles are defined as any vehicle that uses hydrogen (in either liquid or gaseous state) as its source of fuel. The main components include the internal combustion engine, the fuel tank, and the various control systems. Hydrogen internal combustion engines use a spark-ignition system, in contrast to compression-ignited engines seen with diesel powered trucks. The spark plugs should be cold-rated, meaning that between sparks the temperature is as low as possible, in order to avoid pre-ignition [10,11]. Due to hydrogen's very low pressure, fuel tanks may be pressurised up to 70 MPa [43] to hold more fuel.

Due to a lack of data on the fuel economy for hydrogen LHHD trucks, an estimate was done using other available data. The difference in fuel economics for diesel pickup trucks (0.103 L/km [44] and diesel LHHD trucks (0.309 L/km) was found to be 200%. This was applied to the fuel economy of a hydrogen pickup truck, which was found to be, on average, 0.117 DLE/km [45,46], resulting in a hydrogen LHHD truck fuel economy of 0.351 DLE/km, where DLE is the diesel equivalent, in litres, of hydrogen used.

A metric that helps with the comparison between hydrogen and diesel vehicles is the storage volume ratio. This is the ratio of the hydrogen and diesel volumes needed to store an equivalent amount of energy, and was found using the energy mass equivalence between hydrogen and gasoline (1 kg hydrogen = 2.8 kg gasoline [14,47]), the density of compressed hydrogen (41 kg/m^3 [48]), the density of diesel (0.85 kg/L [14]), and the specific energy densities of gasoline and diesel (46.4 MJ/kg and 45.6 MJ/kg, respectively [14,48]). The resulting ratio is 7.28 L hydrogen/L diesel.

2.3 Overview on Hydrogen Gas Production

Hydrogen is the most abundant element and lightest element in the universe. On Earth however, it is rarely found isolated, and requires some variety of process to extract. Common extraction processes include natural gas reforming, electrolysis, biomass gasification, and coal gasification. Differences between these may include the cost to operate, process efficiency, and total greenhouse emissions produced. Figure 1 [46] shows the total greenhouse emissions for different hydrogen production pathways, compared to those of conventional vehicle fuels [46]. Note that there is no “Pump-to-Wheels” emissions for the hydrogen pathways as it does not produce greenhouse gas emissions like those found with conventional fuels when combusted in an internal combustion engine.

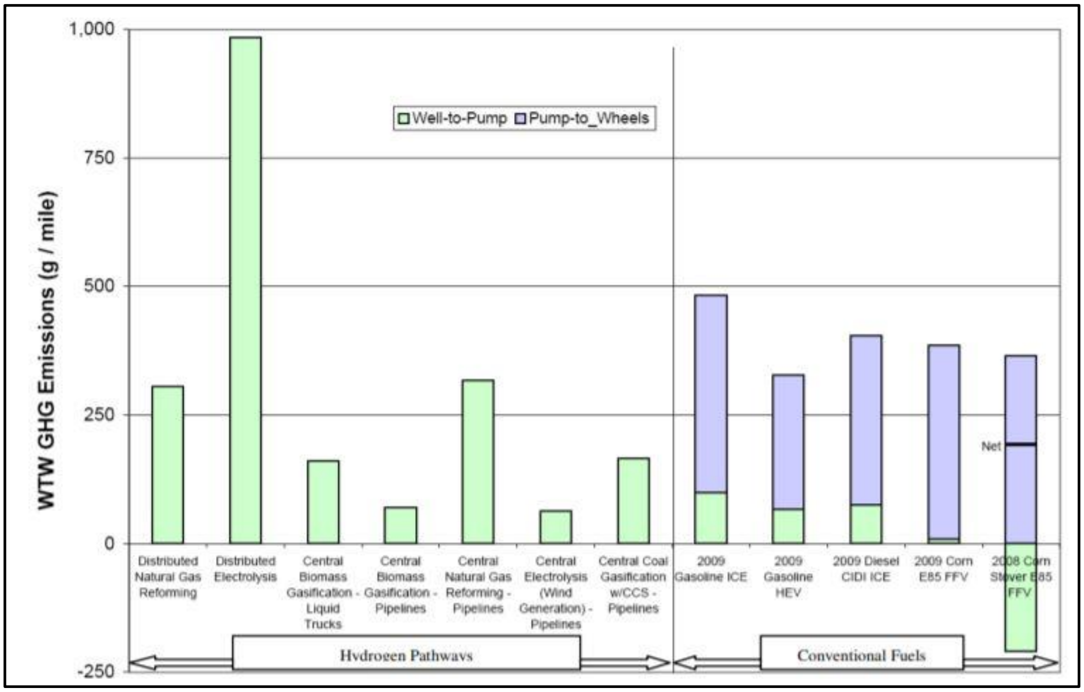

Fig. 1 Greenhouse gas emissions of hydrogen production pathways compared to those from conventional fuels.

Each hydrogen production pathway involves separating hydrogen from some compound. Natural gas (hydrocarbon gas mixture consisting primarily of methane, but usually containing varying amounts of other higher alkanes, and sometimes a minor percentage of carbon dioxide, nitrogen, hydrogen sulphide, or helium), can be combined with high temperature, high pressure steam, in the presence of a catalyst, to form hydrogen and carbon monoxide. While the hydrogen is separated, the carbon monoxide is further reacted with steam and a catalyst, called the water-gas shift reaction, to produce more hydrogen and carbon dioxide. This described process is called natural gas reforming [15–17,50]. The resulting carbon dioxide can be captured or released to the atmosphere.

Water (H_2O), can also be used to produce hydrogen in a reaction called electrolysis. The first step in the process occurs at the anode, in which water reacts to produce oxygen gas and positively charged hydrogen ions. The hydrogen ions then travel through a membrane where they will react at the cathode to produce hydrogen gas. An electrolyser, a system that produces hydrogen via electrolysis, can have a liquid electrolyte (typically an alkaline solution of sodium or potassium hydroxide), or a solid electrolyte (polymer electrolyte membrane (PEM) or ceramic) [15–17,51,52]. Figure 2 [52] illustrates a diagram of the process.

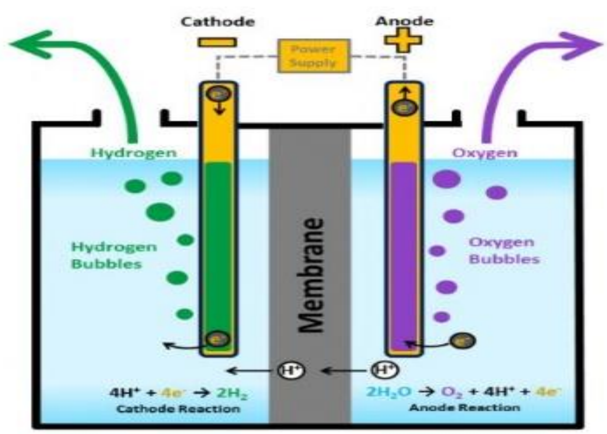

Fig. 2. Diagram of electrolysis process in a liquid electrolyte.

An organic compound, in this situation biomass or coal, can be reacted with high temperature oxygen gas and steam. This will form hydrogen, carbon dioxide, and carbon monoxide. The hydrogen is captured, the carbon dioxide is captured or released, while the water-gas shift reaction converts the carbon monoxide to more hydrogen and carbon dioxide. This process is called gasification [15–17,53,54].

Regardless of the hydrogen production pathway, the process can occur at a central facility, or locally where it is needed. A central scheme can increase the scope of production by producing hydrogen at large facilities that take advantage of bulk processes to reduce costs per unit. However, hydrogen needs to be transported to its destination via pipeline or trucks. This will increase the operational fees due to the need to install a dedicated hydrogen pipeline, or operate a fleet of hydrogen tanker trucks. A distributed process, one where hydrogen is produced on demand where it is needed, eliminates the need to deliver hydrogen over long distances. This, however, increases operational costs due to more equipment and lower production output. Hydrogen costs vary with the production pathway. Since this study is analysing the production of green hydrogen using renewable sources, only sources that use renewable methane or biomass will be considered. As a low estimate for the cost of green hydrogen a price of \$226.32/m^3 was used [55]. As a high estimate for the cost of green hydrogen a price of \$298.08/m^3 was used [52]. As an average estimate for the cost of green hydrogen a price of \$261.93/m^3 was used [47,52,55,56].

2.4 Hydrogen Refuelling Infrastructure

Hydrogen stations are built to refuel vehicles at similar rates to those used by diesel stations. Hydrogen is typically dispensed at 34.5 MPa [47], however, large vehicle storage tanks can accommodate pressures up to 70 MPa [29–32]. The refuelling station footprint will depend on whether hydrogen is being produced on site, or being delivered. However, each refuelling station will consist of a compressor, storage tanks, and at least one dispenser, as well as a small building to store maintenance items and a workspace for employees. Figure 3 [56] shows the basic components and configurations of gaseous refuelling stations.

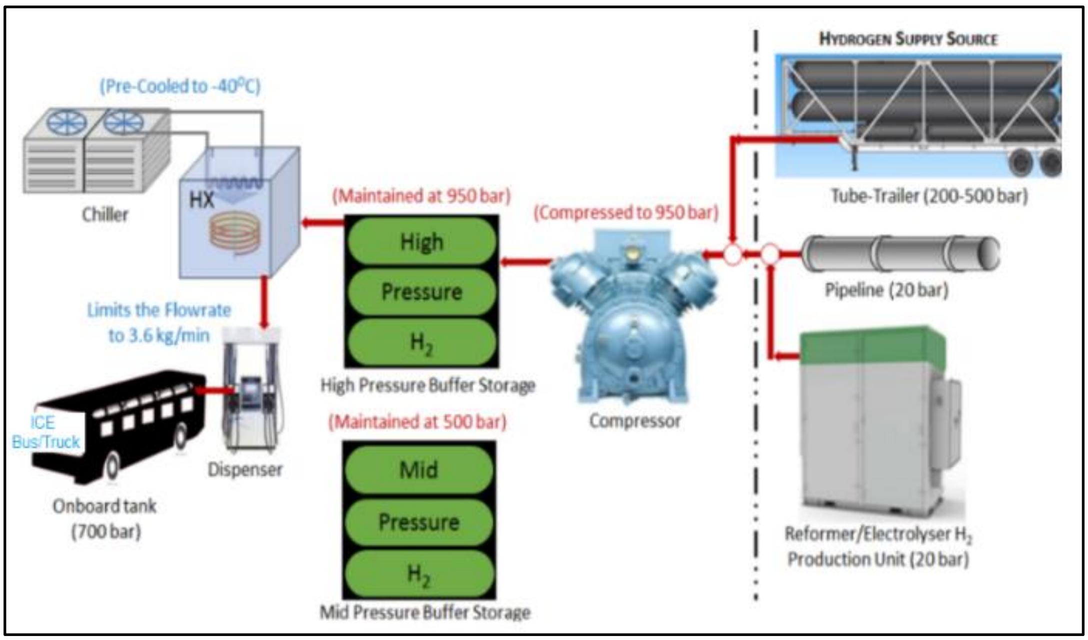

Fig. 3. Schematic illustration of gaseous hydrogen refuelling station configurations.

Without a reliable network of refuelling infrastructure, managing a vehicle fleet is nearly impossible. Many factors go into the design of a national refuelling system, many of which depend heavily on the type of vehicles being used and the surrounding road infrastructure. Canada is a unique country in part because 66% of the population live within 100 km of the U.S. border [58]. This allows for a highway system that is relatively simple when compared to other countries, such as the U.S. In order to simplify the analysis, it was assumed that LHHD trucks only travelled along the Trans-Canada Highway and Highway 401. The former moves traffic along the southern border from British Columbia to Newfoundland and Labrador, while the 401 facilitates heavy traffic from North-Eastern U.S., through Southern Ontario, and into Quebec.

Hydrogen refuelling stations will have different cost factors, when compared to diesel refuelling stations. Most refuelling stations that have been implemented have a relatively low capacity. This is because of the small market that uses the infrastructure. For this study, as can be seen in the next section, refuelling stations will need to be significantly larger than what currently exists. This results in a lack of information on the capital costs required for large-capacity hydrogen refuelling stations. To compensate for this, a cost model was developed, so that capital costs can be estimated for this work.

3. TECHNICAL ANALYSIS

A technical analysis was carried out to estimate the number of hydrogen refuelling stations that would be needed to assist in converting fleet of LHHD vehicles to hydrogen. Two methods based on constant and variable traffics were created with the aim to compare results for diverse conditions. For each method, five cases were built to analyse the results at varying fleet penetration levels of 10%, 25%, 50%, 75%, and 100%. Fleet penetration is expressed as the percentage of LHHD truck fleet that becomes converted to operate on hydrogen.

For this study, refuelling stations will need to be significantly larger than what currently exists. A cost model was created in order to determine the capital costs. A linear relationship was assumed between the storage capacity of a refuelling station and its capital cost. Data for the model was taken from a report by the National Renewable Energy Laboratory [28], and consisted of CAD$6.97 million for a 1,500 kg capacity station and CAD$4.26 million for a 600 kg capacity station. From these two points, a linear equation was created, as shown by Eq. (1).

$$y = 2.453333 + 0.003011111x \quad (1)$$

where y is the capital cost of a refuelling station in millions of Canadian dollars and x is the capacity of the refuelling station in kilograms.

Table 1 summarises the data used in the analysis.

TABLE 1. Input data summary

Description	Value	Unit
Long-haul, heavy-duty truck fleet size	70,000	trucks
Diesel engine average fuel efficiency	0.309	L/km
Hydrogen engine average fuel efficiency	0.351	L/km
Diesel fuel capacity	1100	L
Average distance travelled per day per truck	825	km
% of fuel tank that gets filled at refuelling stations	75	%
Time one truck spends at fuel pump	0.25	h
Operating hours of refuelling stations/day	24	h
Days spent driving per year	298	days/year
Days spent before refuelling	2	days
Fuel consumed per day while idling	33	L

3.1 Constant Traffic Method

This method examines to determine the storage capacity of three pre-determined cases. The first case assumes 87 refuelling stations exist, this is one station every 100 km. The second case assumes 44 refuelling stations exist, this is one every 200 km. The third case assumes 29 refuelling stations exist, this is one every 300 km. This is all done under the assumption that the traffic distribution of LHHD trucks does not change with geography. The basis for this assumption is the nature of long-haul trucks as they drive long distances to deliver cargo, instead of travelling within a region delivering cargo.

To obtain the number of storage capacities, first it was needed to find the total consumption of fuel throughout the truck fleet. This was done, as presented in Eq. (2), by summing the fuel consumed per day while driving and idling, then multiplying that value by the fleet size.

$$V_{fc} = \frac{n_t * r_V}{1000} * (\eta_f * d_d + t_i * \dot{V}_i) \quad (2)$$

where V_{fc} is the total volume of hydrogen consumed [m^3/day], n_t is the fleet size, r_V is the volume ratio of hydrogen to diesel [L H_2/L Diesel], η_f is the fuel economy of hydrogen engines [L/km], d_d is the distance travelled by a truck per day [km/truck/day], t_i is the time spent per truck per day idling [h/day], and $\dot{V}_i$ is the fuel consumption rate while idling [DLE/h].

With the total fuel consumption per day for the truck fleet, the storage capacities can be found by dividing the number of refuelling stations by the fuel consumption per day, as can be seen in Eq. (3).

$$V_{rs} = \frac{V_{fc}}{n_{rs}} \quad (3)$$

where n_{rs} is the number of refuelling stations required, V_{rs} is the volume of hydrogen each refuelling station can hold [m^3], and V_{fc} is the total volume of hydrogen consumed per day by the LHHD truck fleet [m^3].

The results of the analysis are shown in Table 2. As can be seen, the stations required for a refuelling network, even at the lowest penetration level of 10%, is much greater than what was defined by the National Renewable Energy Laboratory's report as a large station capacity of 1,500 kg [28].

TABLE 2. Results from technical analysis using the constant traffic method

Number of refuelling stations	% of Truck fleet converted	Number of trucks	Total H_2 required per day [m^3]	Storage capacity per station [m^3]	Storage capacity per station [kg]
86	10	7,000	16,455.2	190.3	7,800.5
	25	17,500	41,138.1	475.6	19,501.2
	50	35,000	82,276.1	951.3	39,002.5
	75	52,500	123,414.3	1,426.9	58,503.7
	100	70,000	164,552.4	1,902.6	78,005.0
43	10	7,000	16,455.2	380.5	15,601.0
	25	17,500	41,138.1	951.3	39,002.5
	50	35,500	82,276.1	1,902.6	78,005.0
	75	52,500	123,414.3	2,853.8	117,007.4
	100	70,000	164,552.4	3,805.1	156,009.9
29	10	7,000	16,455.2	570.8	23,401.5
	25	17,500	41,138.1	1,426.9	58,503.7
	50	35,000	82,276.1	2,853.8	117,007.4
	75	52,500	123,414.3	4,280.8	175,511.1
	100	70,000	164,552.4	5,707.7	234,014.8

3.2 Variable Traffic Method

This method examines to find the number of hydrogen refuelling stations required to suit LHHD truck fleet by evaluating the traffic distribution with respect to geography, along major highways. As mentioned in previous section, the Trans-Canada highway and highway 401 were presumed to be the only highways used by LHHD trucks, which totals 8,649 km [59,60]. The Ontario Ministry of Transportation (MTO) established a database, which indicates the annual average daily traffic (AADT) for each stretch of known highway in Ontario [61]. The 401 was considered and plotted to obtain patterns in traffic profiles. Sections were visually created to help with the analysis, as shown in Fig. 4.

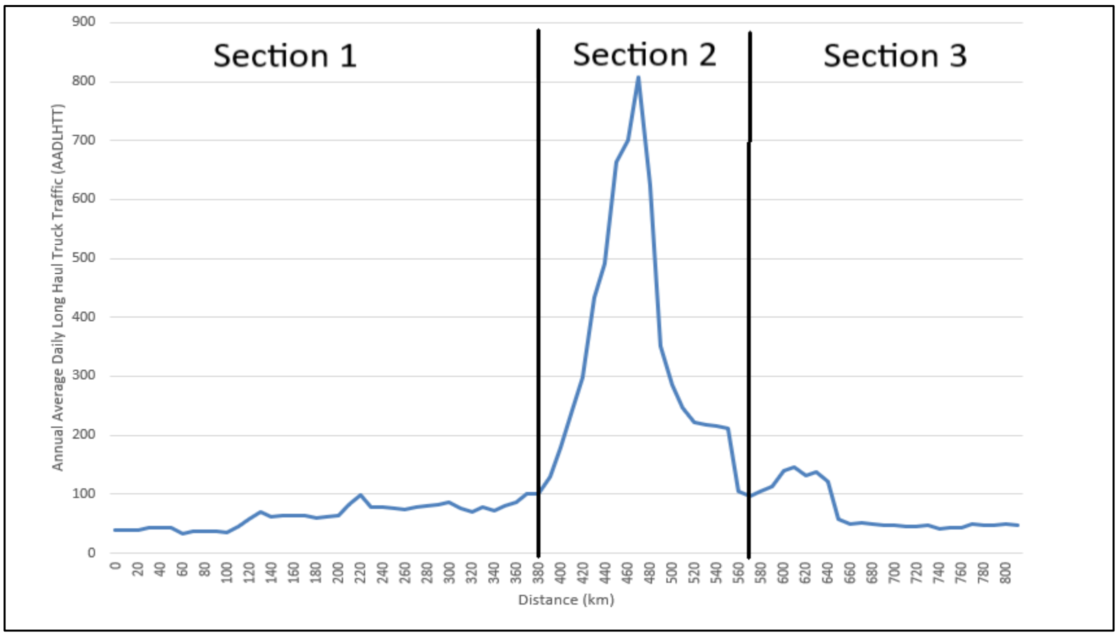

Fig. 4. LHHD traffic distribution along Highway 401 (Ontario, Canada).

To process the data, the average distance between existing truck stops was needed. This differs from the first analysis as arbitrary distances were assumed previously. Rather, it defines the number of refuelling stations needed, and then estimates the capacity necessitated to assist the fleet. The mean distance was acquired using a database of Esso truck stops, and totalled to 110 km [62]. An hypothesis was made that Esso would set up a truck stop network so that, if required, trucks would simply have to depend on Esso for fuel, hence rising revenue for the company.

By means of these data, the number of refuelling stations per section was found by dividing the length of the section by the average truck stop distance then rounding up to the nearest whole number, shown by Eq. (4).

$$n_{rs} = \left\lceil \frac{d_s}{d_{avg}} \right\rceil \quad (4)$$

where d_s is the length of the section [km], d_{avg} is the average distance between refuelling stations [km/station], and $\lceil\,\rceil$ is the ceiling function.

The total volume of hydrogen required per day, is estimated using a derived equation, Eq. (5) below:

$$V_{fc} = \frac{d_s * \eta_f * r_V * \dot{n}_t}{1000} \quad (5)$$

where V_{fc} is the total volume of hydrogen consumed by the LHHD truck fleet per day [m^3], d_s is the distance between refuelling stations [km], η_f is the fuel economy of hydrogen engines [L/km], r_V is the volume ratio of hydrogen to diesel [L H_2/L Diesel] and $\dot{n}_t$ is the average number of trucks that pass through a section per day.

There was no consolidated database, similar to the one MTO provided for highway 401 that existed for the Trans-Canada Highway. Because of that, paths from Fig. 4 were utilised to the Trans-Canada Highway. It was supposed that within 100 km on either side of a major city resting along the Trans-Canada Highway, traffic would be similar to that found from Fig.

4. It was then assumed that the rest of the highway would have similar traffic to that found in sections 1 and 3 from Fig. 4, Eqs. 4 and 5 were used using these hypotheses. Table 3 provides a summary of the results from the technical analysis using the Variable Traffic method. The results indicate that there will be an initial phase when all 81 refuelling stations are constructed to accommodate 86 kg of hydrogen each. Afterwards, as more trucks are converted to hydrogen, upgrades will take place to expand the capacity of each refuelling station.

Table 3. Results from technical analysis using the variable traffic method

% of truck fleet converted	Number of trucks	Number of stations required	Storage capacity per station [kg]
10	7,000	81	86
25	17,500	81	216
50	35,000	81	432
75	52,500	81	648
100	70,000	81	864

4. ECONOMIC ANALYSIS

The aim of the economic analysis is to evaluate the final selling price of hydrogen to guarantee that the investment made to install the infrastructure is recovered. To define this, the annual income needed to fulfil this objective was found by means of a variation of the net present value (NPV) equation, per Eq. (6) [63].

$$I = \frac{-(B + C\sum_{n=1}^{n_{max}}(1+i)^{-n})}{\sum_{n=1}^{n_{max}}(1+i)^{-n}} \quad (6)$$

where I is the annual income [$/year], B is the total investment required [$], C is the annual cost [$/year], i is the rate of return, n is the number of years since the initial investment, which iterates up to n_{max} which is the lifecycle of the infrastructure. Table 4 presents the inputs to Eq. (6) as either a value or an equation.

Table 4. Input data for the economic analysis

Variable	Description	Value/equation
B	Total investment required [$]	Number of stations * capital per station
C	Annual costs [$/year]	(fuel consumed per year * fuel purchase rate) / (1 – maintenance cost %)
i	Rate of return	6%
n_{max}	Infrastructure lifecycle (years)	20
-	Cost of maintenance [%]	27.5 [64]

Using Eq. (6) to find the annual income required for the project, the final selling price of hydrogen could be estimated by dividing the annual income by the total volume of fuel consumed per year, as provided in Eq. (7).

$$\$F = \frac{I}{\eta_f * d_d * n_t * n_d} \tag{7}$$

where $\$F$ is the final selling price of hydrogen [$/DLE], η_f is the fuel economy of hydrogen engines [L/km], d_d is the distance travelled by a truck per day [km/truck/day], n_t is the fleet size and n_d is the number of days a LHHD truck is driving per year.

4.1 Initial Analysis and Results

A baseline case, using technical data taken from the constant traffic method, was evaluated using Eqs. (6) and (7). Table 5 presents the input data and results (pump price [$/DLE]). It can be seen that the final selling price of hydrogen is not expected to vary significantly with variations to fleet penetration, hydrogen refuelling station storage capacity, or the capital cost per hydrogen refuelling station. A further variable that may vary considerably is the cost to purchase hydrogen from suppliers. After this preliminary analysis, it was presumed that this is the utmost influencing element to the final selling price of hydrogen.

Table 5. Results from an initial economic analysis using data taken from the Constant Traffic method

Number of refuelling stations	% of Truck fleet converted	Number of trucks	Capacity per station [kg]	Cost per station [MCAD$]	Pump price [CAD$/DLE]
86	10	7,000	7,800	25.9	2.95
	25	17,500	19,501	61.2	2.93
	50	35,000	39,002	119.9	2.92
	75	52,500	58,504	178.6	2.92
	100	70,000	78,005	237.3	2.92
43	10	7,000	15,601	49.4	2.93
	25	17,500	39,002	119.9	2.92
	50	35,000	78,005	237.3	2.92
	75	52,500	117,007	354.8	2.92
	100	70,000	156,010	482.2	2.92
29	10	7,000	23,401	72.9	2.93
	25	17,500	58,504	178.6	2.92
	50	35,000	117,007	354.8	2.92
	75	52,500	175,511	530.9	2.92
	100	70,000	234,015	707.1	2.92

The analysis performed in previous section was applied to six diverse cases. This was to understand the influences that the purchase price of hydrogen had on its final selling price. Data from both the Constant Traffic Method and the Variable Traffic Method were utilised for that analysis. Since the previous section revealed that fleet penetration, storage capacity, and capital cost do not substantially alter the price of fuel, a single scenario was taken from each method to be utilised in this evaluation. Cases 1, 2, and 3 used a scenario of 100% fleet penetration and 44 refuelling stations, from the Constant Traffic Method. Case 1 assumed a purchase price of hydrogen at the lower estimate of CAD$226.32/m^3. Case 2 assumed an average purchase price of hydrogen at CAD$261.93/m^3. Case 3 assumed a purchase price of hydrogen at the higher estimate of CAD$298.08/m^3. Cases 4, 5, and 6 used a scenario of 100% fleet penetration and 81 refuelling stations, from the Variable Traffic Method. Similar alterations in the purchase price of hydrogen were used in cases 4, 5, and 6, as were used in cases 1, 2, and 3. A summary of the input data is given in Table 6. The results are reported in Table 7 and Fig. 5. The selling price of hydrogen for the six different cases are compared to that of tax-free and taxed diesel [60], with everything normalised to the cost per DLE. The results show that the price of hydrogen can vary from CAD$2.3/DLE to CAD$3.3/DLE, and rises linearly by CAD$.05/DLE for every CAD$1/GJ rise in the cost of hydrogen. These results reveal that the price of hydrogen is expected to remain higher than that of diesel, even with lower hydrogen costs.

Table 6. Case input data for the economic analysis

Case	Method	Number of refuelling stations	Number of trucks	Capital per station [MCAD$]	Cost of hydrogen [CAD$/m^3]
1	Constant	44	70,000	472.2	226.32
2	Traffic	44	70,000	472.2	261.93
3	Method	44	70,000	472.2	298.08
4	Variable	81	70,000	4.6	226.32
5	Traffic	81	70,000	4.6	261.93
6	Method	81	70,000	4.6	298.08

Table 7. Tax-free and taxed selling price results of hydrogen from economic analysis on different cases

Case	Technical method	Purchase price of H_2 [$/DLE]	Tax-free selling price of H_2 [$/DLE]	Difference from tax-free selling price of diesel [%]	Taxed price of H_2 [$/DLE]
Diesel	-	-	0.823	0.0	1.2
1	Constant Traffic	1.6476	2.572	212.7	3.730
2		1.9069	2.930	256.1	4.249
3		2.1700	3.293	300.3	4.775
4	Variable Traffic	1.6476	2.278	176.9	3.303
5		1.9069	2.636	220.3	3.821
6		2.1700	2.999	264.5	4.348

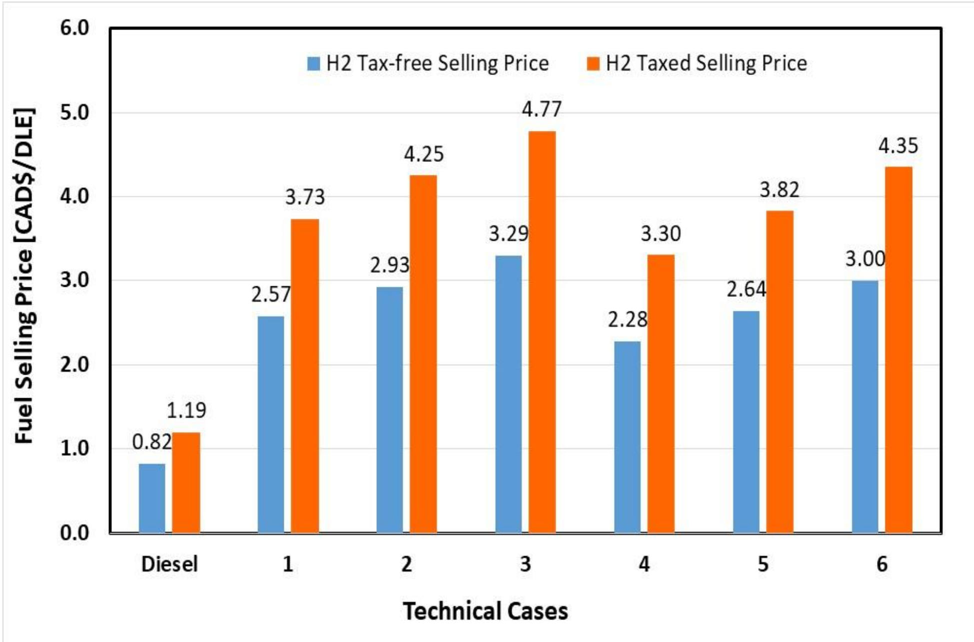

Fig. 5. Tax-free and taxed selling price results of hydrogen from economic analysis on different cases.

4.2 Sensitivity Analysis and Results

A sensitivity analysis was performed on the same previous six economic cases in order to conclude if other variables were important in the calculation of the final selling price of hydrogen. The sensitivity analysis provides an overview of the effects of the parameters on the net present value of the investment, selling price of hydrogen, benefit-cost ratio, and the payback period. For each case, the project capital cost, annual income, annual expenses, and presumed interest rate were varied by ±20%, and the selling price of hydrogen was re-estimated. The different scenarios that are considered for the sensitivity analysis are provided in Table 7.

Table 7. Sensitivity scenarios

Sensitivity scenario	Deviation
1	Baseline case
2	20% increase in capital cost
3	20% decrease in capital cost
4	20% increase in annual income
5	20% decrease in annual income
6	20% increase in annual expenses
7	20% decrease in annual expenses
8	20% increase in interest rate
9	20% decrease in interest rate

The annual cash flow, present values and annual equivalent cost can be estimated using the following equations [63]. The annual equivalent cost is a decisive factor to estimate the cost of hydrogen. It can be calculated as follows:

$$AEC = \frac{IC_c \times i}{1-(1+i)^{-n}} \quad (8)$$

where IC_c is the initial investment, i is the interest rate and n is the economic lifetime of the infrastructure.

The net present value (NPV) of all the cash flows can be estimated as follows:

$$NPV = (B-C) * \left(\frac{1-(1+i)^{-n}}{i}\right) - IC_c \quad (9)$$

where NPV is the net present value of the investment, B is benefit of the investment each year and C is the cost of investment each year.

Benefit-cost ratio (BCR) is an indicator of the ratio of the present values of the benefit cash flows and cost cash flows. It is calculated as follows:

$$BCR = \frac{B * \left(\frac{1-(1+i)^{-n}}{i}\right)}{C * \left(\frac{1-(1+i)^{-n}}{i}\right) + IC_C} \tag{10}$$

The payback period (PB) is the total years required for NPV to reach 0. It is estimated by solving the equation below:

$$NPV = 0 = (B - C) * \left(\frac{1-(1+i)^{-PB}}{i}\right) - IC_c \tag{11}$$

The internal rate of return (IRR) is the critical rate of interest where NPV=$0. For investment to be financially feasible, IRR has to be more than or equal to the interest rate. It is assessed by solving the formula below:

$$NPV = 0 = (B - C) * \left(\frac{1-(1+IRR)^{-n}}{IRR}\right) - IC_c \tag{12}$$

Negative cash flow signifies expenditure, and positive cash flow denotes benefits. The NPV = 0 at 20 years that is fixed to be the payback period for this economic study.

Tables A.1–A.6 in Appendix A provide the results of investment criteria of all Cases 1–6 having each 9 scenarios. Figures 6–11 present the selling price of hydrogen for the different cases based on the sensitivity analysis. Results indicate that variations in the study capital cost and interest rate do not modify the final selling price of hydrogen. On the other hand, increasing or decreasing the annual income or annual expenses raised or reduced the final selling price of hydrogen by the same factor, which is to be anticipated. The negative NPV implies that one is in debt on its investment. This means that rising annual benefit and reducing investment cost, annual benefit and interest rate increase NPV. The tax-free selling prices of hydrogen are in the range of CAD$2.06–3.82 for Scenarios 1–3, and CAD$1.82–3.60–for Scenarios 4–6. The taxed selling prices are in the range of CAD$3.09–5.73 for Scenarios 1–3, and CAD$2.64–5.13 for Scenarios 4–6.

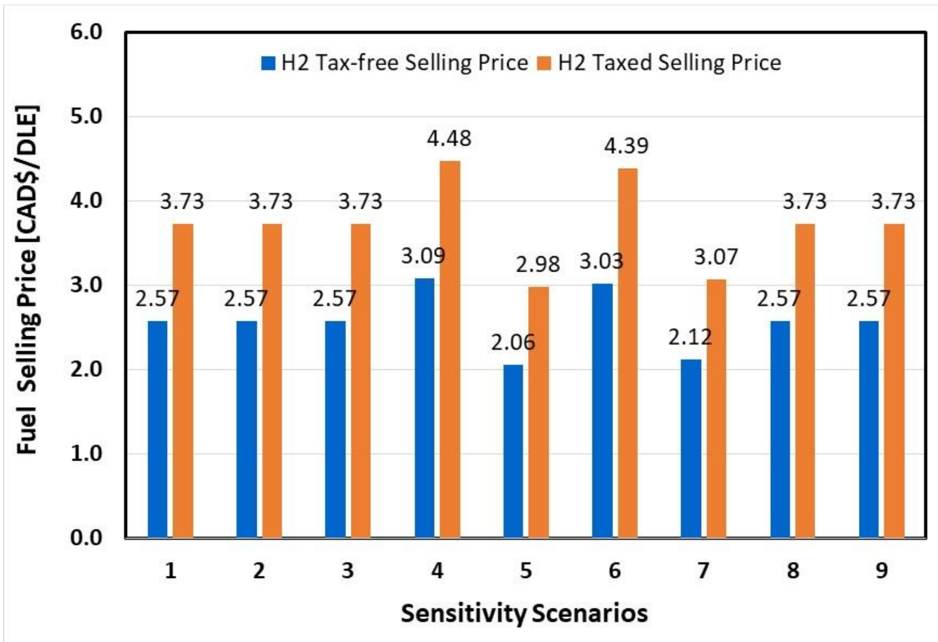

Fig. 6. Selling price results of hydrogen from economic analysis on different scenarios for Case 1.

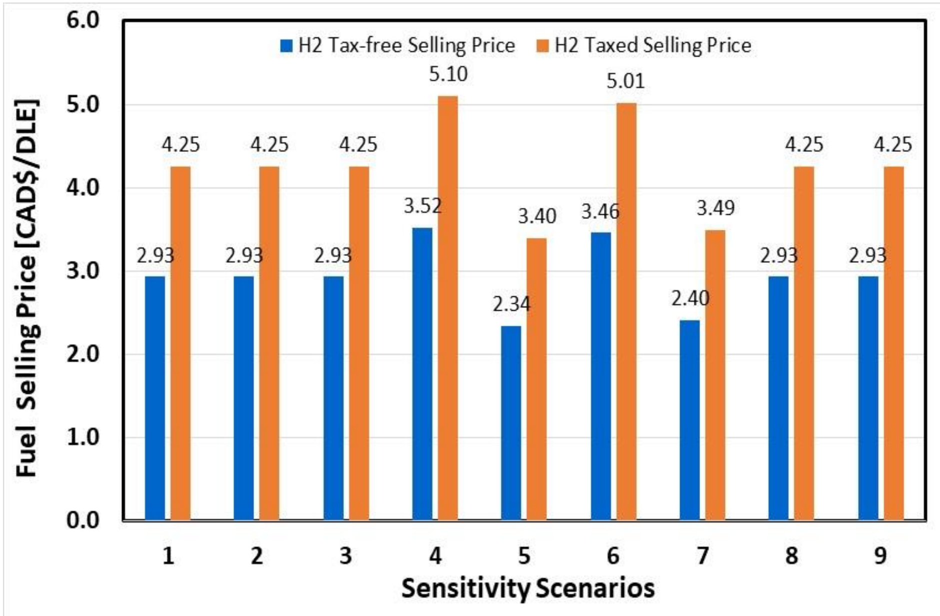

Fig. 7. Selling price results of hydrogen from economic analysis on different scenarios for Case 2.

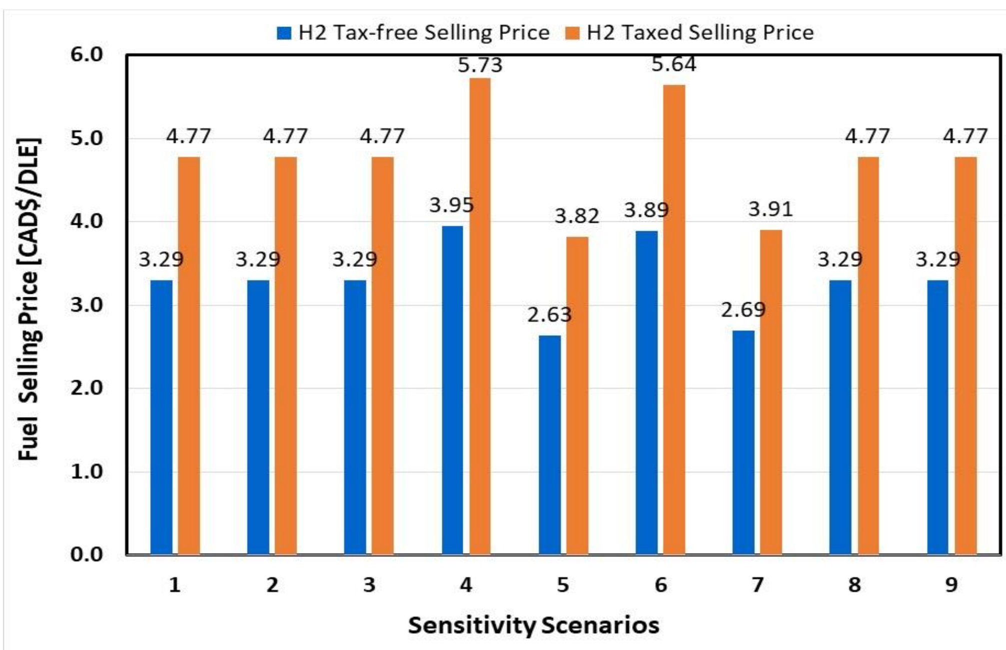

Fig. 8. Selling price results of hydrogen from economic analysis on different scenarios for Case 3.

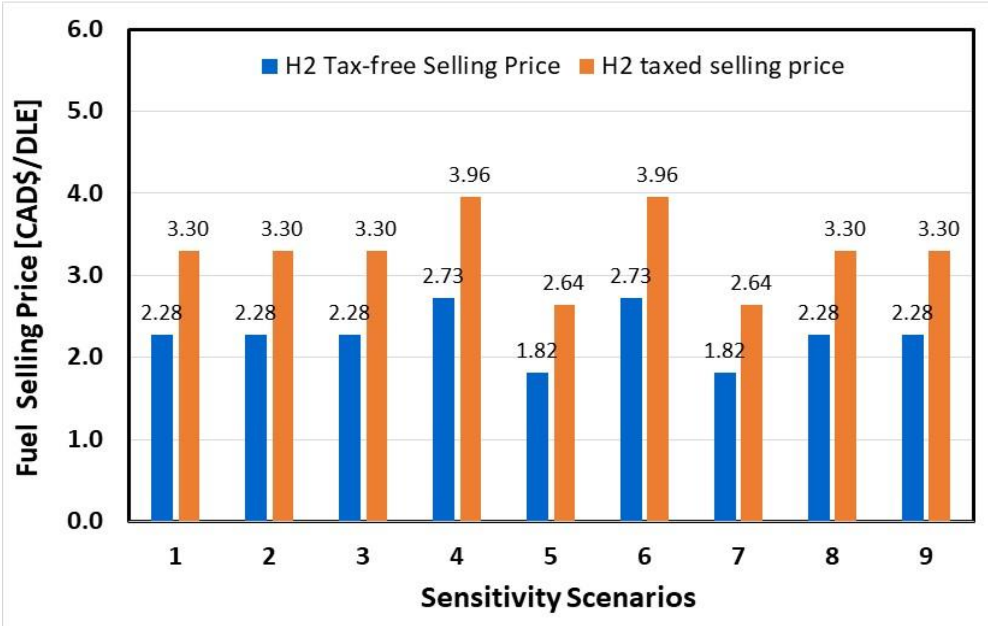

Fig. 9. Selling price results of hydrogen from economic analysis on different scenarios for Case 4.

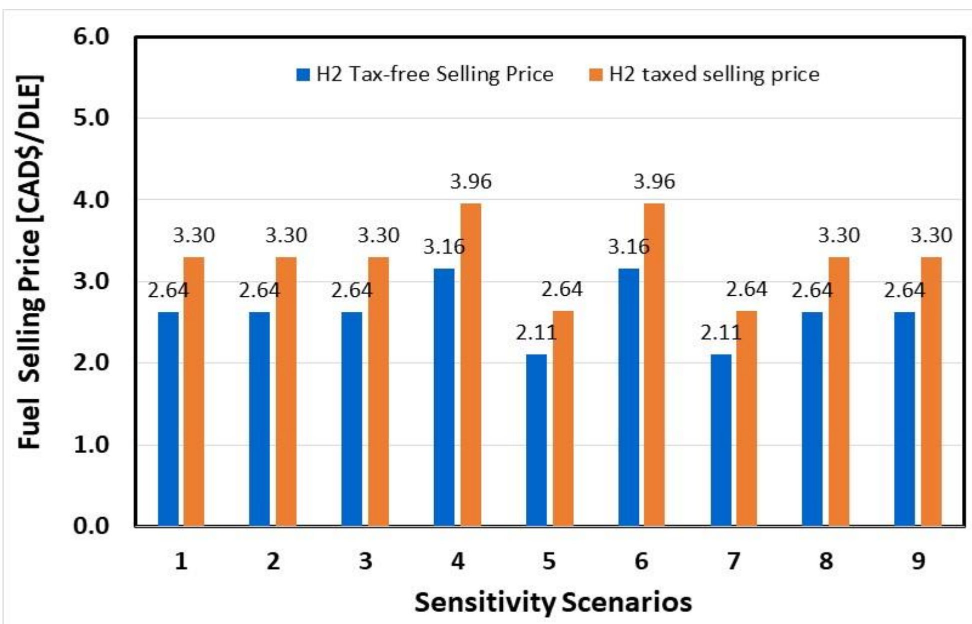

Fig. 10. Selling price results of hydrogen from economic analysis on different scenarios for Case 5.

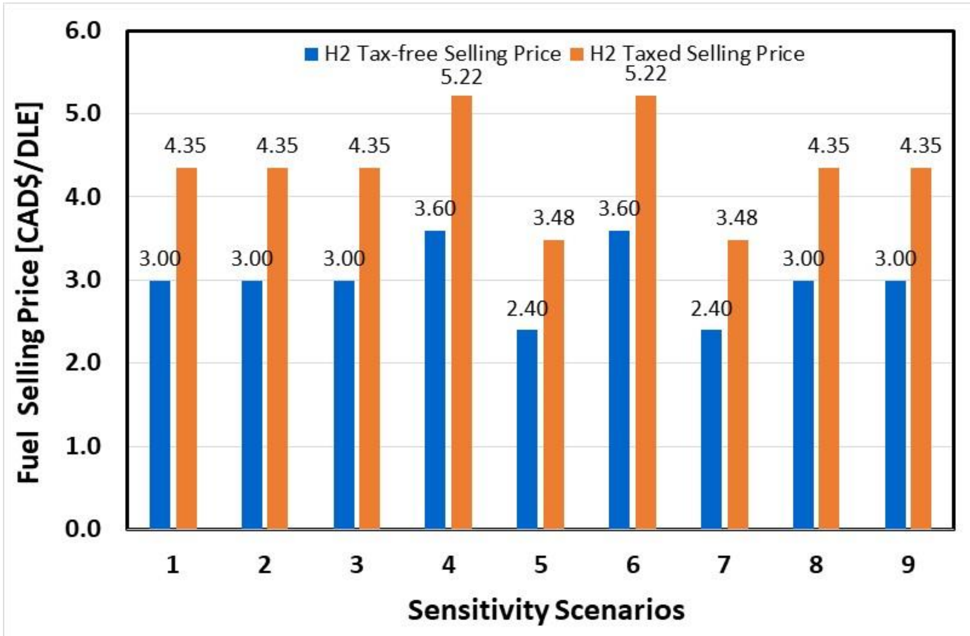

Fig. 11. Selling price results of hydrogen from economic analysis on different scenarios for Case 6.

5. CONCLUSIONS

The objective of this study was to investigate the viability of setting up a nationwide network of hydrogen refuelling stations to assist switching LHHD fleet from diesel fuel to hydrogen. Two methods based on constant and variable traffics were created to evaluate the capacity and number of refuelling stations required for different levels of fleet conversion. Subsequently, two detailed economic studies were performed on six technical cases, to assess the final selling price of hydrogen, with subsequent sensitivity analysis on each case. The prices predicted by the study was compared to the current cost of diesel.

Results from the techno-economic analysis revealed that hydrogen prices can vary significantly, from about CAD$2.3/DLE to CAD$3.3/DLE, practically only contingent on the price of hydrogen, compared to CAD$0.82/DLE for diesel. On average, hydrogen is 239% more expensive than diesel. This is due to the diverse costs related with various production methods for hydrogen, and these results showed a rise in hydrogen of CAD$0.05/DLE for every CAD$1/GJ rise in hydrogen. It should also be mentioned that the data gaps on capital costs for hydrogen refuelling stations constrain the precision of the assessments.

Future work will concentrate on green hydrogen production potential and effect of implementation of various types of production processes on the cost to sell hydrogen to vehicle refuelling stations. An analysis on the capital costs of larger scale hydrogen refuelling stations, as opposed to the current capacities being studied, would greatly increase the accuracy of the results found in this study.

The methodology proposed in this feasibility study might be used for prospect techno-economics of hydrogen refuelling infrastructure for other ICE vehicles. It is expected that these results help to propose basic rules and guidance in the assessment of hydrogen refuelling stations for other ICE and fuel cell vehicle fleets or those powered with renewable fuels.

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CONFLICT OF INTEREST

There are no conflicts of interest.

NOMENCLATURE

AADT	Average annual daily traffic [vehicle/day]
AB	Annual benefit [$]
AC	Annual cost [$]
AEC	Annual equivalent cost [$]
B	Total investment [$]
BCR	Benefit-cost ratio
C	Annual cost per year [$/year]
CO_2	Carbon dioxide
d_d	Distance travelled by a truck per day [km/truck/day]
d_h	Total distance of highway taken into consideration [km]
d_s	Distance between refuelling stations [km]
DLE	Diesel litres equivalent [L]
$\$F$	Final selling price [$]
$FT\%$	Percentage of fuel from a truck's fuel tank that is required to reach the next hydrogen refuelling station [%]
GHG	Greenhouse gas
HDV	Heavy-duty vehicle
H_2	Hydrogen
I	Annual income [$/year]

IC_c	Initial investment [$]
ICE	Internal combustion engine
IR	Interest rate [%]
IRR	Internal rate of return [%]
i	Rate of return [%]
LHHD	Long-haul, heavy-duty
NPV	Net present value [$]
NO_x	Nitrogen oxides
n	Number of years since the initial investment [years]
n_d	Number of days a LHHD truck is driving per year [days/year]
η_f	Fuel economy of hydrogen engines [L/km]
n_{max}	Lifecycle of the infrastructure [years]
n_{rs}	Number of refuelling stations required [-]
n_t	Fleet size [-]
$\dot{n}_t$	Average number of trucks that pass through a section per day
MDVs	Medium-duty vehicles
MTO	Ontario Ministry of Transportation
PB	Payback period [years]
PEM	Polymer electrolyte membrane
PM	Particulate matter
r_V	Volume ratio of hydrogen to diesel [L H_2/L Diesel]
t_i	Time spent per truck per day idling [h/day]

V_{fc}	Total volume of hydrogen consumed [m^3/day]
$\dot{V}_i$	Fuel consumption rate while idling [DLE/h]
V_{rs}	Volume of hydrogen each refuelling station can hold
V_t	Volume of hydrogen truck's fuel tank [m^3]
WHO	World Health Organization
x	Capacity of the refuelling station [kg]
y	Capital cost of a refuelling station [M$]

APPENDIX A

Table A.1 Investment criteria of all scenarios for Case 1

Scenario	NPV with assumed interest rate and assumed lifecycle [CAD$]	IR [%]	BCR [-]	IRR so NPV=0 after 20 years [%]	NPV factor [-]
1	0	6.0%	1.30	6.0%	12.30
2	-4,155,360,000.0	6.0%	1.30	3.9%	14.23
3	4,155,360,000.0	6.0%	1.30	8.9%	10.48
4	35,646,044,941.7	6.0%	1.65	23.3%	9.71
5	-35,646,044,941.7	6.0%	0.98		6.21
6	0.00	6.0%	1.25	6.0%	12.30
7	0.00	6.0%	1.40	6.0%	12.30
8	0.00	7.2%	1.30	6.0%	12.04
9	0.00	4.8%	1.30	6.0%	13.05

Table A.1. *cont'd*

Scenario	NPV with assumed interest rate and calculated PB [CAD$]	PB using assumed IR [years]	H2 tax-free selling price CAD$/DLE	H2 taxed selling price CAD$/DLE
1	0.00	23	2.5724	3.7300
2	1,759,192.8	33	2.5724	3.7300
3	226,238,506.3	17	2.5724	3.7300
4	2,916,863,872.8	15	3.0869	4.4760
5	-29,405,653,929.3	∞	2.0580	2.9840
6	0.00	23	3.0270	4.3891
7	0.00	23	2.1179	3.0710
8	267,404,843.5	29	2.5724	3.7300
9	768,701,872.8	21	2.5724	3.7300

BCR: Benefit-cost ratio; IR: Interest rate; IRR: Internal rate return; NPV: net present value; PB: Payback period

Table A.2. Investment criteria of all scenarios for Case 2

Scenario	NPV with assumed interest rate and assumed lifecycle [CAD$]	IR [%]	BCR [-]	IRR so NPV=0 after 20 years [%]	NPV factor [-]
1	0.0	6.0%	1.26	6.0%	11.47
2	-4,155,360,000.0	6.0%	1.26	3.9%	13.76
3	4,155,360,000.0	6.0%	1.26	8.9%	9.29
4	40,600,902,182.7	6.0%	1.99	24.7%	4.21
5	-40,600,902,182.7	6.0%	0.95		6.21
6	0.00	6.0%	1.21	6.0%	11.47
7	0.00	6.0%	1.33	6.0%	11.47
8	0.00	7.2%	1.26	6.0%	11.61
9	0.00	4.8%	1.26	6.0%	11.87

Table A.2. *cont'd*

Scenario	NPV with assumed interest rate and calculated PB [CAD$]	PB using assumed IR [years]	H2 tax-free selling price CAD$/DLE	H2 taxed selling price CAD$/DLE
1	0.00	20	2.9300	4.2485
2	1,676,808.3	30	2.9300	4.2485
3	215,643,566.2	14	2.9300	4.2485
4	1,764,349,585.0	5	3.5160	5.0982
5	-31,509,531,698.5	∞	2.3440	3.3988
6	0.0	20	3.4560	5.0113
7	0.0	20	2.4040	3.4858
8	254,882,049.1	26	2.9300	4.2485
9	732,702,915.5	18	2.9300	4.2485

Table A.3. Investment criteria of all scenarios for Case 3

Scenario	NPV with assumed interest rate and assumed lifecycle [CAD$]	IR [%]	BCR [-]	IRR so NPV=0 after 20 years [%]	NPV factor [-]
1	0.0	6.0%	1.23	6.0%	11.47
2	-4,359,520,000.0	6.0%	1.23	3.9%	13.76
3	4,359,520,000.0	6.0%	1.23	8.9%	9.29
4	45,835,056,264.7	6.0%	1.97	26.8%	4.21
5	-45,835,056,264.7	6.0%	0.94		6.21
6	0.00	6.0%	1.19	6.0%	11.47
7	0.00	6.0%	1.30	6.0%	11.47
8	0.00	7.2%	1.23	6.0%	11.61
9	0.00	4.8%	1.23	6.0%	11.87

Table A.3. *cont'd*

Scenario	NPV with assumed interest rate and calculated PB [CAD$]	PB using assumed IR [years]	H2 tax-free selling price CAD$/DLE	H2 taxed selling price CAD$/DLE
1	0.00	20	3.2930	4.7749
2	1,676,808.3	30	3.2930	4.7749
3	215,643,566.2	14	3.2930	4.7749
4	3,611,630,356.0	5	3.9516	5.7298
5	-34,232,761,049.8	∞	2.6344	3.8199
6	0.00	20	3.8916	5.6429
7	0.00	20	2.6944	3.9069
8	254,882,049.1	26	3.2930	4.7749
9	732,702,915.5	18	3.2930	4.7749

Table A.4. Investment criteria of all scenarios for Case 4

Scenario	NPV with assumed interest rate and assumed lifecycle [CAD$]	IR [%]	BCR [-]	IRR so NPV=0 after 20 years [%]	NPV factor [-]
1	0.0	6.0%	1.00	6.0%	11.47
2	-74,520,000.0	6.0%	1.00	3.9%	13.76
3	74,520,000.00	6.0%	1.00	8.9%	9.29
4	31,563,813,518.7	6.0%	1.51	747.3%	1.83
5	-31,563,813,518.7	6.0%	0.80		6.21
6	0.0	6.0%	1.00	6.0%	11.47
7	0.0	6.0%	1.01	6.0%	11.47
8	0.0	7.2%	1.00	6.0%	11.61
9	0.0	4.8%	1.00	6.0%	11.87

Table A.4. *cont'd*

Scenario	NPV with assumed interest rate and calculated PB [CAD$]	PB using assumed IR [years]	H2 tax-free selling price CAD$/DLE	H2 taxed selling price CAD$/DLE
1	0.0	20	2.2778	3.3029
2	30,071.0	30	2.2778	3.3029
3	3,867,236.2	14	2.2778	3.3029
4	4,732,228,988.9	2	2.7334	3.9634
5	-17,259,464,432.1	∞	1.8223	2.6423
6	0.0	20	2.7323	3.9619
7	0.0	20	1.8233	2.6439
8	4,570,918.1	26	2.2778	3.3029
9	13,139,901.5	18	2.2778	3.3029

Table A.5. Investment criteria of all scenarios for Case 5

Scenario	NPV with assumed interest rate and assumed lifecycle [CAD$]	IR [%]	BCR [-]	IRR so NPV=0 after 20 years [%]	NPV factor [-]
1	0.0	6.0%	1.00	6.0%	11.47
2	-74,520,000.0	6.0%	1.00	3.9%	13.76
3	74,520,000.0	6.0%	1.00	8.9%	9.29
4	36,520,062,182.7	6.0%	1.51	863.3%	1.83
5	-36,520,062,182.7	6.0%	0.80		6.21
6	0.0	6.0%	1.00	6.0%	11.47
7	0.00	6.0%	1.01	6.0%	11.47
8	0.00	7.2%	1.00	6.0%	11.61
9	0.00	4.8%	1.00	6.0%	11.87

Table A.5. *cont'd*

Scenario	NPV with assumed interest rate and calculated PB [CAD$]	PB using assumed IR [years]	H2 tax-free selling price CAD$/DLE	H2 taxed selling price CAD$/DLE
1	0.0	20	2.6355	3.8215
2	30,071.0	30	2.6355	3.8215
3	3,867,236.2	14	2.6355	3.8215
4	5,524,453,258.0	2	3.1626	4.5858
5	-19,942,768,152.6	∞	2.1084	3.0572
6	0.0	20	3.1615	4.5842
7	0.0	20	2.1095	3.0588
8	4,570,918.1	26	2.6355	3.8215
9	13,139,901.5	18	2.6355	3.8215

Table A.6. Investment criteria of all scenarios for Case 6

Scenario	NPV with assumed interest rate and assumed lifecycle [CAD$]	IR [%]	BCR [-]	IRR so NPV=0 after 20 years [%]	NPV factor [-]
1	0.0	6.0%	1.00	6.0%	11.47
2	-74,520,000.0	6.0%	1.00	3.9%	13.76
3	74,520,000.0	6.0%	1.00	8.9%	9.29
4	41,550,056,264.7	6.0%	1.51	980.9%	1.83
5	-41,550,056,264.7	6.0%	0.80		6.21
6	0.0	6.0%	1.00	6.0%	11.47
7	0.0	6.0%	1.00	6.0%	11.47
8	0.0	7.2%	1.00	6.0%	11.61
9	0.0	4.8%	1.00	6.0%	11.87

Table A.6. *cont'd*

Scenario	NPV with assumed interest rate and calculated PB [CAD$]	PB using assumed IR [years]	H2 tax-free selling price CAD$/DLE	H2 taxed selling price CAD$/DLE
1	0.0	20	2.9985	4.3478
2	30,071.0	30	2.9985	4.3478
3	3,867,236.2	14	2.9985	4.3478
4	6,328,465,254.8	2	3.5982	5.2174
5	-22,665,997,503.9	∞	2.3988	3.4783
6	0.0	20	3.5971	5.2159
7	0.0	20	2.3999	3.4798
8	4,570,918.1	26	2.9985	4.3478
9	13,139,901.5	18	2.9985	4.3478

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Table Captions List