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Optimization of H_2 Supply and Refuelling Infrastructure for Long Haul Trucks

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Summary

Hydrogen (H_2) as a transportation fuel has significant potential to reduce GHG emissions. However, current H_2 prices are far above the level needed for cost-effective operation of H_2-based transportation. This study investigated how costs in the supply of H_2 for the refuelling of long-haul trucks can be minimized by optimizing the design of the refuelling infrastructure. Scenarios of local and centralized H_2 production were evaluated to investigate whether cost savings from centralized H_2 production on a larger scale would outweigh the additional costs of H_2 transportation to refuelling sites without H_2 production.

Keywords: hydrogen, heavy-duty, truck, infrastructure, simulation

1 Introduction

Around 27% of global CO_2 emissions come from the transportation sector which makes it the second largest emitter [1]. Over the last decade, significant momentum has built for the electrification of passenger vehicles mainly using battery electric technology. However, the use of hydrogen as a transportation fuel has significant potential to support the transition towards a low carbon economy since it does not emit carbon at the end use point of combustion, has good storage life, and it can be transported by roads, ships, or pipelines in gaseous or liquid forms [2].

To drastically reduce emissions and eliminate the use of diesel in the long-haul trucking sector, it is expected that H_2 fuel cell vehicles will be needed as battery electric vehicles cannot provide the same utility as diesel vehicles. Significant studies have been conducted on different aspects of using hydrogen as a clean fuel for long-distance transportation.

- Kumar et al. developed a framework to analyse the supply chain cost of low-carbon hydrogen exports from Alberta to several viable destinations in North America, the Asia-Pacific, and Europe [3]. The supply chain includes all unit operations ranging from hydrogen production with carbon capture and storage, hydrogen pipeline transportation, liquefaction, shipping, and regasification at the destinations. A techno-economic assessment has been conducted to estimate the supply chain cost of different viable pathways considering the energy, material, and capacity.

- An analysis of overseas H_2 supply chains has been conducted by Lim et al. considering the economic (unit H_2 cost), environmental (carbon footprint), and technological aspects [4]. The supply chains include all the operations ranging from H_2 production, ship transportation, to inland distribution. Several supply chains were compared varying the economies of scale, amount of H_2, and distance. Results showed that use of liquid organic hydrogen carrier, liquid hydrogen and ammonia are the most potentially feasible options for H_2 carriers considering these criteria.
- Stolen et al. developed a well to tank analysis to calculate the costs, energy consumption and GHG emissions for supplying hydrogen to fuel cell electric vehicles (FCEVs) [5]. The study followed a holistic approach considering the whole supply chain that includes the storage and transportation of hydrogen. The study discussed different hydrogen infrastructure technologies from ecological and economic points of view. Compression and liquefaction have been mentioned as the state-of-the-art H_2 technology whereas, liquid organic hydrogen carrier (LOHC) has been identified as the most promising H_2 technology for near future from an economic perspective. However, further research is needed regarding the system design of the LOHC-supplied refuelling station and the heat source for dehydrogenation.
- Barbir et al. considered a wide range of hydrogen refuelling station (HRS) capacities and configurations [6]. For example, locating the hydrogen production and charging station within an existing wind farm in Croatia or nearby the end users, or site the hydrogen production within the wind farm and install the charging station nearby the users, etc. The study assumed that hydrogen is delivered to the refuelling station with a tube trailer and when hydrogen was produced within the wind farm a mobile charging station was used for consumers in different locations. The techno-economic analysis of each hydrogen refuelling station configuration was conducted to estimate the levelized cost of hydrogen production – the capital, operational and maintenance costs. Although different HRS configurations have been explored in the study, only water electrolysis of hydrogen production from one existing wind farm in Croatia was considered.
- Hurskainen and Ihonen conducted a techno-economic assessment for point-to-point large scale road transportation of hydrogen [7]. The researchers compared liquid organic hydrogen carriers (LOHC), compressed H_2 gas delivery by trucks and on-site production of hydrogen using water electrolysis. Results showed that the LOHC supply chain was the most economic option for long distance hydrogen transportation by road. However, to achieve economic feasibility, the heat supply method for releasing hydrogen at the end-user site and the investment costs were found as the most critical parameters to consider.
- Qing et al. assessed four possible low-carbon hydrogen supply chains for a hydrogen refuelling station located in Shanghai [8]. The study analysed the feasibility of using hydrogen (renewable) as a transportation fuel for fuel cell vehicles. Two routes considered on-site hydrogen production powered by a stand-alone or grid-connected photovoltaic (PV)-wind generation system separately, whereas the other two routes considered off-site hydrogen supply. The off-site hydrogen is also produced by a stand-alone or grid-connected PV-wind generation system located in the Qinghai Province since it is a rich renewable energy area. The H_2 is then delivered to Shanghai by liquid hydrogen trucks. The study found the off-site production supply chains as feasible options. The study mentioned transporting liquid hydrogen for long distance using trucks is more economical compared to transporting compressed gaseous hydrogen due to its higher energy density. Although this study was focussed on H_2 supply for passenger vehicles, the results would also apply to H_2 supply for long-haul trucks.

The above-mentioned studies focussed on different aspects of H_2 transportation fuel technology such as H_2 production technologies, techno-economic assessments of low-cost hydrogen export by overseas or inland routes, assessments of low carbon hydrogen export from cheaper production locations like Canada, economic, technological, and environmental impacts of H_2 supply chains, and on different storage technologies of H_2. Very few studies have been addressing the significance of the H_2 refuelling infrastructure on the overall H_2 supply chain.

Current H_2 prices are far above the level needed for cost-effective operation of H_2-based transportation. Cost reductions in every part of the H_2 supply chain will be needed to realize a sustainable cost level. This study investigated how costs in the supply of H_2 for the refuelling of long-haul trucks can be minimized by optimizing the design of the supply and refuelling infrastructure. More specifically, scenarios of local and centralized H_2

production were evaluated to investigate whether cost savings from centralized H_2 production on a larger scale would outweigh the additional costs of H_2 transportation to refuelling sites without H_2 production.

2 Method

A simulation model was developed to estimate the H_2 demand for heavy-duty long-haul trucks along major highways in Canada. Over 11,000 km of Canadian major highways were considered (see Fig.1). Data from Provincial Transportation Authorities (like the Ontario Ministry of Transport) were used to estimate the Annual Average Daily Truck Traffic (AADTT) flow for each of the highway segments, resulting in a large range in AADTT values from 500 trucks per day on more quiet highways to 17,000 trucks per day on the busiest segments. The model assumed that each highway should provide the H_2 needed for all trucks that drive that highway.

The required H_2 production per highway segment was then calculated from the truck traffic kilometres driven on that segment and a fixed H_2 consumption of 10 kg/100 km.

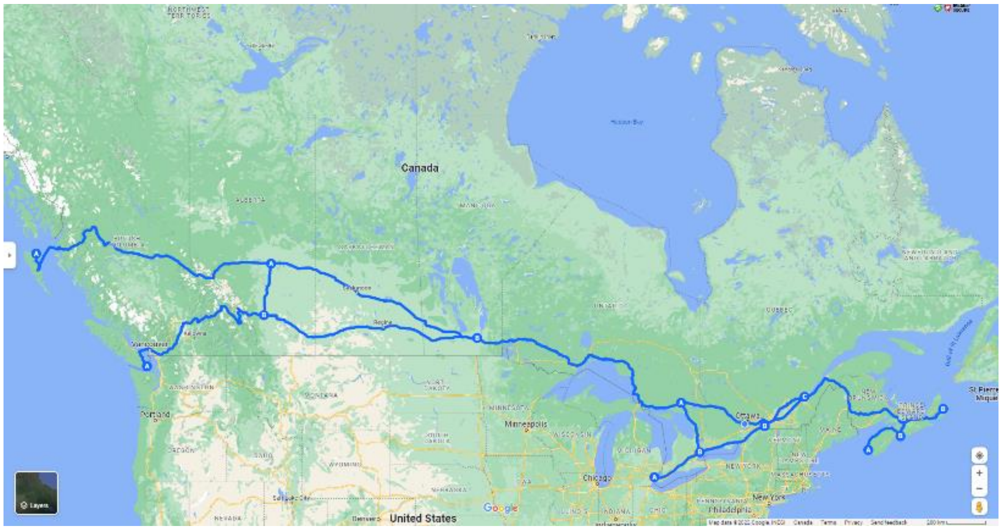

Figure 1: Overview of major highways in Canada

2.1 Hydrogen Refuelling Sites, Production Sites and Pumps

To determine the number of H_2 refuelling sites per highway, the highways were segmented based on the truck traffic flow. To minimize H_2 transportation costs, production sites were co-located with refuelling sites. The standard distance between refuelling sites was assumed to be 100 km. However, the actual distance between refuelling sites on some highway sections was a bit shorter if the segment length was not exactly a multiple of 100 km. Given space constraints on truck rest stops, a maximum of 20 H_2 pumps per refuelling site were allowed, requiring refuelling stations to be placed closer together on the busiest highway sections.

The number of refuelling sites for highway segment i, $N_{R,i}$, was calculated using Eq. 1

$$N_{R,i} = L_i / D_i \qquad (1)$$

in which L_i is the length of highway segment i and D_i the distance between H_2 refuelling sites on that highway segment. Similarly, the number of H_2 production sites for highway segment i, $N_{P,i}$, was calculated:

$$N_{P,i} = N_{R,i} / R_j \qquad (2)$$

with R_j being the number of refuelling sites supplied by a production site in scenario j.

2.2 Scenarios

Different scenarios were developed to investigate the impact of the size of the H_2 production facility on the amount of hydrogen that would need to be transported, the transportation distance, and on the costs of H_2. Larger production sites were placed further apart, effectively increasing the number of refuelling sites that would be supplied by one production facility. Four scenarios were evaluated with a focus on identifying the potential to optimize the H_2 supply and refuelling infrastructure for long haul trucks:

- Scenario 1: Each refuelling site had its own production facility; hence no transportation was required between production and refuelling stations. Production sites were about 100 km from each other.
- Scenario 2: Each production site supplied two refuelling sites, and the distance between production sites was around 200 km. Under this scenario, there were two times as many refuelling sites as production sites, requiring half of the total amount of H_2 produced to be transported to a neighbouring refuelling site over 100 km distance (one-way) away.
- Scenario 3: Each production site supplied H_2 to three refuelling sites, and there was generally one production site per 300 km of highway. With three times as many refuelling sites as production sites, two thirds of all refuelling sites needed to have their H_2 transported from the neighbouring production site, which was placed at the middle location of the three refuelling sites. The H_2 transportation distance was 100 km (one-way).
- Scenario 5: Each production site supplied five different refuelling sites, because production sites were placed about 500 km apart. Under this scenario, there were five times as many refuelling sites as production sites, requiring four fifths of all the H_2 to be transported to neighbouring refuelling sites from the central H_2 production station. On average, the H_2 was transported over 150 km (one-way), as the distance to the closest refuelling sites was 100 km, and 200 km to the outer refuelling sites.

2.3 Hydrogen Production Cost, Transportation Cost and Dispensing Cost

In the economic analysis, total H_2 costs were calculated as the sum of the production costs, transportation costs, and dispensing/refuelling costs.

$$TC_H = C_P + C_T + C_R \qquad (3)$$

Here, TC_H, C_P, C_T and C_R are the total H_2 cost, H_2 production costs, costs for transportation of H_2 from production to refuelling sites, and H_2 refuelling/dispensing costs respectively.

For the H_2 production costs, a correlation between the costs of production and the production volume was used, see Figure 2.

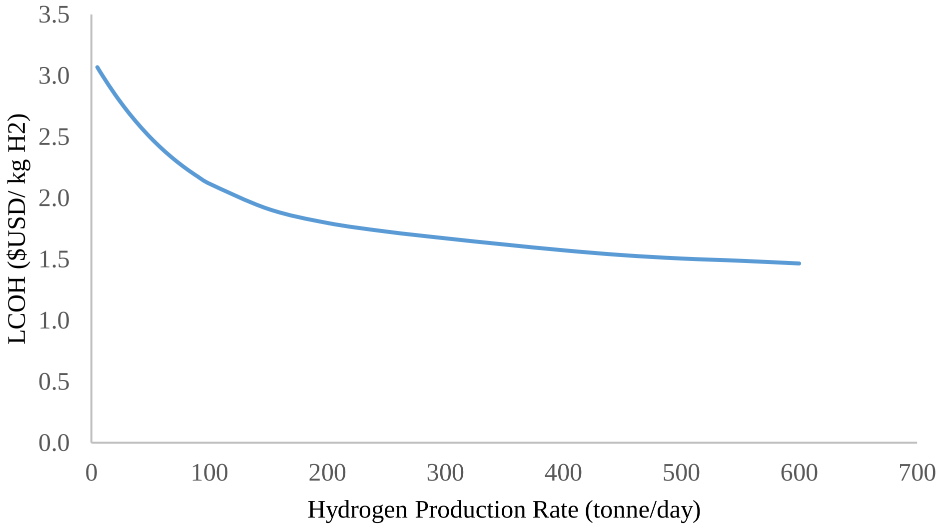

Figure 2: Levelized Costs of H_2 Production, based on [9]

The transportation cost included the capital cost for the H_2 trailer, the driver salary, and fuel costs. The driver salary was calculated based on the total time spent on the job, which included driving time, loading and unloading time. An average truck speed of 50 km/hr was used to calculate driving time. A total period of three hours for loading and unloading the trailer was considered in the calculations. The truck trailer used for the H_2 transportation had a capacity of 4000 kg H_2.

The H_2 dispensing costs were based on the capital costs for the H_2 refuelling facilities as given in Table 1. The costs depended on the size of the refuelling facility. The cost to install one H_2 pump (with sufficient storage) per refuelling facility was estimated to be 1 million US$. Adding capacity would be increasingly less expensive for the first five pumps, after which the costs of additional pumps (plus required storage) was assumed to be stable at 0.5 US$ per pump.

Table 1: Hydrogen refuelling facility cost (in US$) based on number of pumps.

Number of pumps	Cost added pump (M$)	Total cost (M$)
1	1	1.0
2	0.9	1.9
3	0.8	2.7
4	0.7	3.4
5	0.6	4.0
6	0.5	4.5
7+	0.5	…

The time to refuel a long-haul truck was considered to be equal to the time it takes to get diesel i.e., 15 minutes. One pump was assumed to be able to refuel 48 trucks per day. During peak hours the pumps were assumed to be fully in use.

3 Results

3.1 Hydrogen Production and Refuelling Sites

Different scenarios were evaluated for local and centralized H_2 production (as explained in Section 2.2), varying the size of the production facility, the distance between production sites, and the number of refuelling sites that were supplied by one production site (see Table 2). For Scenario 1, where the H_2 required for each refuelling site is produced locally, there is no need for any H_2 transportation. For the other scenarios, the H_2 transportation distances were determined based upon the number of H_2 refuelling sites that did not have on-site production and their distances to the nearest H_2 production site.

The results in Table 2 show a clear reduction in the number of production sites for scenarios in which one production site would supply an increasing number of refuelling sites. However, this reduction is not linear, because the number of required H_2 production sites was evaluated per highway segment. If a highway segment was smaller than the standard distance between two production sites under a certain scenario, it would still get its own production facility. Similarly, if the length of the highway segment was 1.5 times the standard distance between production sites, the segment would get two production sites.

Table 2: Number of production and refuelling sites for the scenarios evaluated.

	Approximate distance between refuelling sites (km)	Number of refuelling sites	Number of pumps	Number of refuelling sites per production site	Approximate distance between production sites (km)	Number of production sites
Scenario 1	100	125	843	1	100	125
Scenario 2	100	125	843	2	200	67
Scenario 3	100	125	843	3	300	51
Scenario 5	100	125	843	5	500	38

3.2 Overall H_2 Costs and Potential Cost Savings Across Scenarios

The total cost per kg of hydrogen dispensed for each of the scenarios are presented in Table 3. The cost numbers shown here are *average* costs over the total highway network for all H_2 dispensed, taking into account the full range of H_2 prices from production facilities of different sizes, and distributing the H_2 transportation costs over all H_2 dispensed.

H_2 production costs varied significantly across the evaluated scenarios. The average H_2 production cost ranged from 1.72 US$/kg to 2.11 US$/kg, with the lowest cost for Scenario 5, which had on average the highest production volume per production facility.

The H_2 production cost comprises the large majority of the total H_2 cost. Depending on the scenario, around 91-97% of the H_2 costs were incurred in the H_2 production stage. Additional research on methods to reduce the H_2 production cost is thus recommended.

The H_2 transportation cost displayed in Table 3 represents the *average* cost for transportation per kg of H_2 dispensed, regardless of whether the kg of H_2 was actually transported or produced on-site. This is the reason the transportation costs for Scenario 3 are higher than for Scenario 2. Although the transportation distance is the same under both scenarios, *more* H_2 is transported under Scenario 3 leading to a higher average transportation cost.

The H_2 dispensing cost was the same for all scenarios, because each scenario had the same number of refuelling sites.

The overall cost of hydrogen at the pump is the result of different H_2 production and transportation costs for the scenarios evaluated. The results in Table 3 indicate that the H_2 transportation costs were relatively low in comparison to the savings in H_2 production costs from H_2 production at a larger scale at a centralized location. Cost reductions of 6.6%, 9.4%, and 12.4% were obtained in Scenarios 2, 3, 5 respectively, compared to Scenario 1 where all H_2 is produced on-site.

The results of this study indicate that Scenario 5 was the most optimum scenario. In this scenario, H_2 production facilities were placed approximately 500 km from each other and would supply H_2 to five refuelling sites. Additional research is required to investigate if additional cost savings would be possible from producing H_2 at even larger scales.

Table 3: Total H_2 cost per kg dispensed and H_2 costs savings across scenarios

Scenario	Number of production sites	Average H_2 production volume (ton/day)	Average H_2 production costs ($/kg)	Average H_2 transport. costs ($/kg)	Average H_2 dispensing costs ($/kg)	Total H_2 costs ($/kg)	H_2 costs savings (%)
Scenario 1	125	23.8	2.11		0.05	2.17	
Scenario 2	67	44.5	1.90	0.07	0.05	2.02	6.6%
Scenario 3	51	58.4	1.83	0.08	0.05	1.96	9.4%
Scenario 5	38	78.4	1.72	0.12	0.05	1.90	12.4%

4 Conclusions

In this study we analysed how costs in the supply of H_2 for the refuelling of long-haul trucks can be minimized by optimizing the design of the refuelling infrastructure. Centralized H_2 production was found to provide clear cost savings from economies of scale over local production, despite the additional costs for H_2 transportation.

When production sites were placed 500 km apart, total H_2 cost were 12.4% lower than for local H_2 production at each refuelling site.

Additional research investigating H_2 production at an even larger scale is recommended.

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