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Hydrogen utilization in various transportation modes with emissions comparisons for Ontario, Canada

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ABSTRACT

The paper compares the atmospheric emissions of different hydrogen production scenarios for various transportation modes in a case study for Ontario, Canada. Hydrogen demand scenarios are based on historical data of the various transportation modes. Predicting the CO_2 emissions for a market with hydrogen vehicles against a purely fossil fuel market outlines the benefits of utilizing hydrogen. For road vehicles less than 4,500 kg in weight, emissions from a thermochemical production fraction of 20% produced a 9.8% decrease in CO_2 emissions (or over 3,000 kilotonnes), compared to a 100% fossil fuel market. When these studies are applied to other transportation modes such as rail, air and marine, similar trends are observed. The largest benefits occur from automobiles and rail, where increasing carbon emission trends were reversed due to the increasing hydrogen propulsion base. Further decreases in carbon dioxide emissions could be realized by lower emitting production sources such as nuclear thermochemical production and electrolysis from wind, solar, and hydro.

1. Introduction

Carbon dioxide emissions have a major role in adversely impacting the environment. Increased growth in the transportation sector which is primarily powered by fossil energy has contributed to a rising amount of carbon emissions over the years. As the need for cheaper and better transportation grows with population, the current growth of fossil fuel demand is not sustainable. While the complete conversion to another potentially cleaner source of energy is not feasible in the short term, it is important to evaluate the benefits of a progressive adoption rate.

Hydrogen has been frequently cited as a potentially major solution to help reduce carbon emissions from the transportation sector. Like electricity, hydrogen is an energy carrier that makes it possible to transport and use energy in a mode of transportation such as an automobile. An important challenge is to produce hydrogen economically using low carbon emitting sources. These sources can be renewable energy methods such as solar and wind power. Other sources can include power plant waste heat such as nuclear plants, or natural gas which is a relatively low carbon fossil fuel. While there is no perfect "silver bullet", there are sources which are nearly emission free and there are sources which can produce few or no emissions. Using electrolysis to produce hydrogen from renewable sources is one possible way to produce little or no carbon emissions, but economically this is challenging on a large scale. While it may be cheaper to produce hydrogen using natural gas through steam methane reforming (SMR), there are significant carbon emissions in SMR. Economically it also becomes increasingly unsustainable when commodity prices increase for natural gas. Therefore it is important to

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evaluate the impacts of a hydrogen market with a production mix that combines all of these above sources.

The purpose of this paper is to analyze the impact of using hydrogen in various transportation modes. Specifically, CO_2 emissions from a market with hydrogen propulsion are compared against a market with no hydrogen vehicles. These results will help to evaluate the impacts of converting to hydrogen propulsion methods, as well as to evaluate the impacts of using different hydrogen production methods. The case study will be Ontario, Canada. The main objective is to examine how much impact hydrogen could have on reducing CO_2 emissions if it is adopted at a fair pace in the next 12–15 years.

There have been many past studies which have focused on specific transportation modes such as Marin et al. [1], where rail electrification and hydrogen were compared against diesel locomotives. In this case, complete conversion of the GO Transit rail system was considered and the hydrogen benefits per train km were summarized. The main hydrogen production scenario was the copper–chlorine thermochemical cycle. Others such as Hajimiragha [2] have studied the feasibility of electrolytic hydrogen production for the transportation sector. Here only one method of hydrogen is analyzed and the transportation sector demand is taken in its entirety. Studies in other geographic locations such as California have examined the economic effects of hydrogen cars, regardless of the hydrogen production methods [3].

Fowler et al. [4] examined the emissions involved for automobiles in Ontario [4]. Predictive models were developed to predict hydrogen vehicle market share over time, up to 2025. The main production method for hydrogen was electrolysis using the Ontario electricity grid. The study provides a useful comparison for automobiles under 4500 kg, which will be further explored in this paper. Another study [5] for New Zealand concentrated on road vehicles consuming hydrogen from electrolysis up until 2050. Various demand scenarios were produced and assumptions were made for hydrogen consumption for each class of vehicle. Emphasis was given on hydrogen demand and electricity demand to produce hydrogen. Fowler et al. [6] also examined an energy demand model for plug-in fuel cell vehicles. In this paper, a model for a fleet which has a hub at a commercial building is developed to estimate energy requirements. This model could be used to estimate both emissions and costs associated with hydrogen conversion.

Past vehicle studies investigated the energy use emissions and costs associated with hydrogen vehicles [7]. Vehicle hydrogen studies have been performed for various geographical locations such as South Korea [8]. A model was developed to compare emissions and energy demand for different government policy and fuel price scenarios. A study of the economics of hydrogen production, storage and delivery was conducted by Balat [9] for transportation use. Also a summary of environmental benefits was outlined, with key points stressed to show the potential benefits of renewable hydrogen production. Other transportation modes such as airplanes have also been considered for hydrogen conversion. In a report by the Swiss Federal Institute of Reactor Research, a pilot project analyzed the Zurich Airport [10]. The report analyzed a practical application of liquefied hydrogen use in aircraft. While a pilot project could be supported at the airport, various large scale adoption challenges required economic and logistical problems to be solved. All of these studies outlined the importance and beneficial impact of hydrogen in the transportation sector environmentally.

To our knowledge, few studies have compared various hydrogen transportation modes and demand scenarios in a comprehensive manner. In some studies, only certain production scenarios are considered or not considered at all. In order to see which transportation mode can benefit the most from hydrogen conversion, a detailed comparison would be beneficial by using the same production scenarios for each mode. In this paper, various production scenarios are investigated with hydrogen production from steam methane reforming (SMR), electrolysis of water, and thermochemical splitting of water (Copper–Chlorine cycle). The production fractions of each of these methods are varied to determine the resulting trends which occur.

2. Analysis

2.1. *Developing the hydrogen scenarios*

Using historical data, predictive models will be made to evaluate impacts of hydrogen conversion from 2008 to 2020. Various scenarios are made for hydrogen production methods and vehicle market shares.

The first part involves a selection among three production scenarios which would be used for each transportation mode. The following scenarios are analyzed for hydrogen production:

1. 5% electrolysis, 5% Cu–Cl, 90% SMR;
2. 10% electrolysis, 10% Cu–Cl, 80% SMR;
3. 10% electrolysis, 20% Cu–Cl, 70% SMR.

The next part of the methodology establishes a rate of hydrogen market share increase which could be used for comparison purposes. For automobiles less than 4,500 kg: 1.25% market share in 2009, percentage increases at 1.25% per year until 2020 where the final percentage is assumed 15%. For rail transportation: 1.25% market share in 2009, percentage increases at 1.25% per year until 2020 where the final percentage is also 15%. For air transportation: 1.25% market share in 2009, percentage increases at 1.25% per year until 2020 where the final percentage will be again 15%. For marine transportation: again 1.25% market share in 2009, percentage increases at 1.25% per year until 2020 where the final percentage will be 15%.

There have been past models which predict the expected market share of hydrogen using software which takes into account economic and social factors, such as those included by Fowler et al. [4] which predicted an automobile market share of 2.8% in 2025. While cost and social factors may limit these results, there are also government incentives and policies (such as carbon taxes and tax incentives) which can increase market share more rapidly. Potential emissions savings are not well known unless certain scenarios are explored in detail to take into account a larger hydrogen market share.

The comparison charts will consist of a 100% fossil fuel market versus a market with increasing hydrogen market share as stated above. Complete conversion to hydrogen vs. a 100% fossil fuel market share will be shown for comparison. The analysis should show the carbon dioxide savings realized when converting some of the market to hydrogen propulsion. Also, data on the amount of hydrogen needed to supply the demand will be shown. Each transportation mode will be compared for all three production scenarios. Another goal is to better understand the effects of hydrogen production methods with lower carbon emissions intensity.

The next step in the analysis is the development of models based on historical data to estimate the energy needs. This will assist to establish models for hydrogen demand and CO_2 emissions from hydrogen and conventional fuel sources.

2.2. *Automobiles under 4500 kg*

Data from Statistics Canada [11] was gathered for the number of vehicles in Ontario from 1999 to 2009. A trend line was fitted to the data, in order to estimate and extrapolate for future trends. In Eq. (1), y_a is the number of vehicles and x_t is the number of years, where 1999 is equal to $x_t = 1$ and 2020 is equal to $x_t = 22$.

$$y_a = 102,982 * x_t + 6,107,642 \tag{1}$$

Once a relationship was established for the number of cars in Ontario, another relationship was needed for the approximate number of kilometers traveled per year for every car. Historical data was available from Natural Resources Canada [12] for the years 1990–2008. An exponential trend line was fit to the data, which showed an overall decrease in kilometers traveled per year. Equation (2) is a relationship used to extrapolate for the number of kilometers traveled per year, where *x* is the year ($x_t = 1$ for 1999 and $x_t = 22$ for 2020).

$$y_{DT} = 18,557 * e^{-0.009x_t} \tag{2}$$

Using an average fuel efficiency of 10.4 L per 100 km and 2.32 kg of CO_2 per liter of gasoline consumed, the CO_2 emissions per kilometer were found to be 0.2413.

In the case of hydrogen vehicles, hydrogen consumption was assumed to be 80 km per kilogram of hydrogen. Fuel cell efficiency was taken as 40% and the energy content was taken to be 142 MJ/kg. For the production methods, CO_2 emissions per kilogram of hydrogen produced were found to be 0.737 kg for the thermochemical copper–chlorine cycle, 3.13 kg for electrolysis in Ontario and 8.91 kg for steam methane reforming [13–15]. The emissions factor for electrolysis is based on current energy needs for hydrogen from electrolysis (kilogram of hydrogen produced per kilowatt-hour of electrical energy input) and government estimates of CO_2 emissions from all sources in Ontario. Ontario uses nuclear energy for electricity production, as well as hydro, natural gas, solar and wind power that provide the remainder of the electricity supply. Once emissions are factored from all sources, an amount in kilograms of CO_2 per kilowatt-hour produced will be used to determine emissions from electrolysis. Equations (3), (4), and (5) are the relations used to calculate the mass of hydrogen and emissions for fuel cell vehicles and ICE vehicles. The average fuel cell vehicle consumption was taken as 80 kg/km [16].

$$m_{H_2a} = n_a * y_{DT} * \%H_2/(1,000,000 * C_{H_2}) \tag{3}$$

$$m_{CO_2}\mathrm{ICE} = n_a * \overline{m}_{CO_2}\mathrm{ICE} \tag{4}$$

$$\begin{aligned} m_{CO_2}\mathrm{FCV} = &(m_{H_2a} * \%_{SMR} * E_{SMR}) + (m_{H_2a} * \%_{ELEC} * E_{ELEC}) \\ &+ (m_{H_2a} * \%_{Cu-Cl} * E_{Cu-Cl}) \end{aligned} \tag{5}$$

2.3. *Rail transportation*

A different approach was taken to estimate rail energy use, emissions and hydrogen demand. There is data available for regional railways such as GO Transit, Ontario, in terms of distance traveled and fuel consumption per unit distance. If other railways are analyzed, another approach would be to use data on the total fuel consumption. Data from Statistics Canada is organized in 4 railway groups consisting of Canadian National Railway, Canadian Pacific Railway, Via Rail and Regional Railways. The amount of diesel fuel used for Ontario was selected [20]. The average efficiency of a locomotive engine was taken to be 40%. Lower heating values and the density for diesel fuel were taken to be 43 MJ/kg and 0.83 kg/L [17]. CO_2 emissions per unit volume (diesel) were taken to be 3.07 kg/L [1].

Using historical data from 1990 to 2008, a relationship was found to help extrapolate for the amount of useful energy consumed. This is the energy used to power the locomotive and does not include waste heat. This was necessary to calculate the hydrogen demand to propel the locomotive and not just supply the total amount of energy consumed. For all of the rail categories, Eqs. (7)–(10) model the useful energy consumption with x_t being the number of years from 1990.

The relationship to calculate useful energy is shown in Eq. (6). Equations (7)–(10) are the energy models used to develop the emissions and hydrogen demand predictions.

$$H_uR = \left(y_{xf} * \mathrm{LHV}_D * \rho_D * 0.4\right) / 1E6 \tag{6}$$

$$y_{CNe} = 3,850.8 * x_t^{0.1179} \tag{7}$$

$$y_{CPe} = 4,223.8 * x_t^{-0.007} \tag{8}$$

$$y_{VIAe} = 418.17 * x_t^{0.0187} \tag{9}$$

$$y_{Re} = 482.35 * x_t^{-0.055} \tag{10}$$

Once the useful energy models were established, hydrogen demand was calculated by using a 40% fuel cell efficiency and 142 MJ/kg energy content. The assumption used for hydrogen conversion to propulsion is a fuel cell vehicle, since this yields higher efficiency than combustion. As discussed earlier, for the hydrogen production methods, CO_2 emissions per kilogram of hydrogen produced were found to be 0.737 kg for the thermochemical copper–chlorine cycle, 3.13 kg for electrolysis in Ontario and 8.91 kg for steam methane reforming [13–15].

$$m_{H_2R} = \frac{(y_{xe}/0.4)}{142} * 1,000 * \%_{H_2} \quad (11)$$

$$m_{CO_2}FCR = (m_{H_2r} * \%_{SMR} * E_{SMR}) + (m_{H_2r} * \%_{ELEC} * E_{ELEC}) + (m_{H_2r} * \%_{Cu-Cl} * E_{Cu-Cl}) \quad (12)$$

The models were used to calculate CO_2 emissions, although for better accuracy, models for the diesel fuel consumption were also used to calculate CO_2 emissions for diesel operation. Equations (13)–(16) are the models used for diesel fuel consumption of each the railway categories. Equation (17) is used to convert fuel volume to emissions in metric tonnes.

$$y_{CNf} = 25,2145 * x_t^{0.1179} \quad (13)$$

$$y_{CPf} = 27,6571 * x_t^{-0.007} \quad (14)$$

$$y_{VIAf} = 27,382 * x_t^{0.0187} \quad (15)$$

$$y_{Rf} = 31584 * x_t^{-0.055} \quad (16)$$

$$m_{CO_2}R = y_{xf} * E_D \quad (17)$$

2.4. *Air transportation*

Using data from Natural Resources Canada, the energy consumption was available for the province of Ontario [21]. Using this data, a model was developed to analyze the future total energy consumption. Passenger and freight are combined in one consumption model.

$$y_{AIRe} = 41.84 * x_t^{0.1985} \quad (18)$$

The average efficiency for jet propulsion was taken to be 35%. This figure was used to calculate the energy needed for propulsion only. The total hydrogen fuel input was calculated by using a common figure of 40% efficiency and 142 MJ/kg energy content [18]. For this analysis, fuel cells are assumed for hydrogen propulsion. Emissions for hydrogen remained similar as the previous two transportation modes. Jet fuel figures used for emissions were 2.52 kg CO_2 per liter of fuel (or 6.27×10^7 kg per petajoule of fuel burned), while the energy content was taken as 35.1 MJ/L [18].

$$H_uAIR = y_{AIRe} * 0.35 \quad (19)$$

$$m_{h_2}AIR = \frac{(H_uAIR/0.4) * \%h_2 * 1,000,000}{142} \quad (20)$$

$$m_{CO_2}FCA = (m_{h_2}AIR * \%_{SMR} * E_{SMR}) + (m_{h_2}AIR * \%_{ELEC} * E_{ELEC}) + (m_{h_2}AIR * \%_{Cu-Cl} * E_{Cu-Cl}) \quad (21)$$

$$m_{CO_2}AIR = \frac{y_{AIRe} * 6.72 * 10^7}{1,000,000} \quad (22)$$

2.5. *Marine transportation*

Using energy consumption data for Ontario from Natural Resources Canada, a consumption model was developed for freight marine transportation [22]. Diesel was the primary fuel used in the data; therefore 40% efficiency was used to calculate useful energy consumption. The fuel cell efficiency was assumed to be 40% with 142 MJ/kg energy content. Again fuel cells were assumed to provide the conversion from hydrogen to propulsion. CO_2 emissions for diesel were the same as for rail transportation at 3.07 kg CO_2 per liter of diesel burned.

$$y_{ME} = 22.312 * e^{-0.049 * x_t} \quad (23)$$

$$m_{H_{2M}} = \frac{y_{ME} * \%H_2 * 1,000,000}{142} \quad (24)$$

$$m_{CO_2}FCM = (m_{H_2M} * \%_{SMR} * E_{SMR}) + (m_{H_{2M}} * \%_{ELEC} * E_{ELEC}) + (m_{H_{2M}} * \%_{Cu-Cl} * E_{Cu-Cl}) \quad (25)$$

$$m_{CO_2M} = \frac{y_{ME} * E_D * 1,000,000}{LHV_D} \quad (26)$$

3. Results and discussion

For road vehicles the data included the number of vehicles on the road, average distance traveled, and average fuel efficiency. Table 1 summarizes the main problem parameters. Fig. 1 illustrates the emissions output comparison between all three hydrogen production scenarios and a 100% fossil fuel scenario. Each hydrogen production scenario curve represents the emissions output of a market with combined fossil fuel and hydrogen propulsion. The 100% fossil fuel curve represents a market in essence with no hydrogen propulsion share. The amount of cars and car growth rates are the same for both 100% internal combustion propulsion and hydrogen scenarios. As time increases, the hydrogen propulsion market share increases, which causes the fossil fuel share to decrease. For the hydrogen propulsion scenarios, the emissions associated with hydrogen propulsion are determined and added to the emissions for the remaining fossil fuel amount. All three hydrogen curves have the same market share increase as stated in Section 2.1. The same analysis will be performed for the rest of the transportation modes with figures showing a comparison of carbon dioxide emissions.

In 2020, a 15% market share of hydrogen cars supplied by a 5% Cu–Cl production scenario will reduce CO_2 by about 8.6% or 2,700 kilotonnes. Fig. 1 also shows the second scenario where both electrolysis and copper–chlorine cycle results are increased to a 10% production share. The percent difference

Table 1 – Parameters for automobiles < 4500 kg.

Parameter	Units	Value
CO_2 emissions per unit distance (gasoline) [19]	kg/km	0.2413
CO_2 emissions per kilogram of hydrogen for electrolysis [14, 15]	$kgCO_2/kgH_2$	3.13
CO_2 emissions for steam methane reforming [14]	kg/kgH_2	8.91
CO_2 emissions for Copper–Chlorine Cycle [13]	kg/kgH_2	0.737
Hydrogen vehicle consumption	km/kg H_2	80

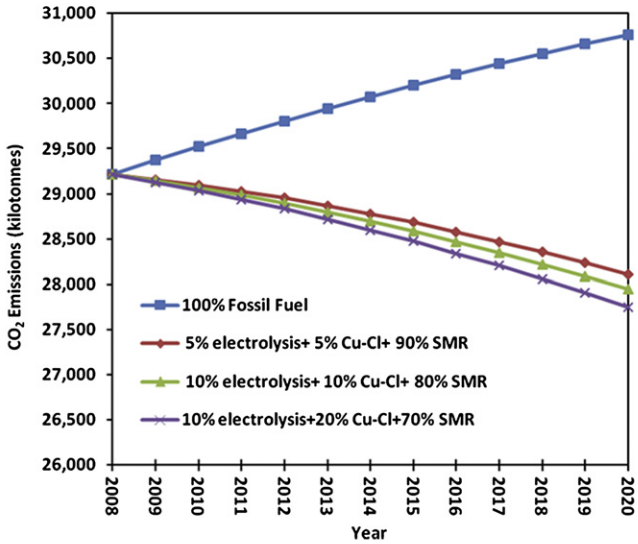

Fig. 1 – CO_2 emissions comparison for vehicles under 4500 kg.

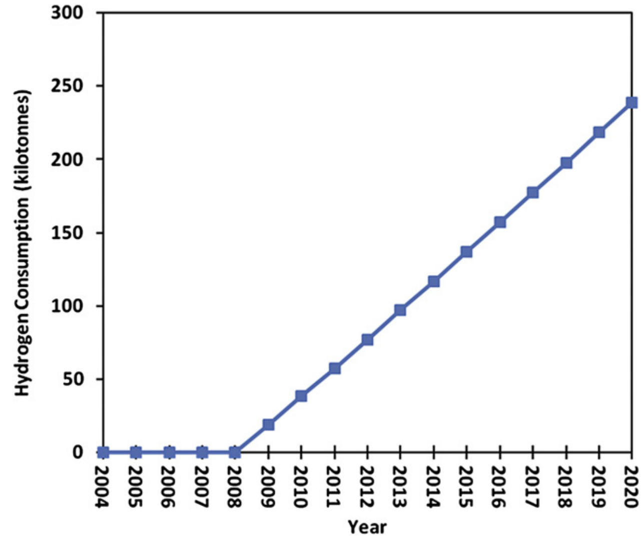

Fig. 3 – Hydrogen demand for vehicles under 4500 kg in kilotonnes of hydrogen.

between the two curves is 9.2% or 2,800 kilotonnes in 2020. This is a difference of 6.3% over the previous production scenario. The last scenario has the copper–chlorine cycle share increasing another 10%–20%. In 2020, there is a 9.8% reduction of CO_2 emissions or 3,000 kilotonnes. This is a difference of about 6.9% over the previous scenario. In the case of Fig. 2 where 100% of automobiles are converted to hydrogen, there is a 65.3% reduction in emissions over internal combustion engines. This is about 20,000 kilotonnes of CO_2 offset by the use of hydrogen in this particular production scenario. In Fig. 2 the hydrogen production scenario has the Cu–Cl cycle supplying 20% of the hydrogen demand.

Hydrogen demand for the increasing market share of hydrogen vehicles is shown in Fig. 3. In 2009, the hydrogen demand is around 19 kilotonnes and it increases to 240 kilotonnes in 2020. Overall, the comparisons showed that the CO_2 emissions decreased regardless of the production scenario. This is due to the hydrogen market share increasing with time. The rate of hydrogen increase results in emissions dropping even though the number of cars on the road is increasing. This is a positive trend since the hydrogen market share does not need to be large to have a major reduction of emissions. This also shows that the production mix does not need to have large amount of low CO_2 methods such as Cu–Cl production or electrolysis to have a significant impact. While increasing the share of production for these methods will have increased benefits, an economic balance can be achieved while still providing a decrease in emissions.

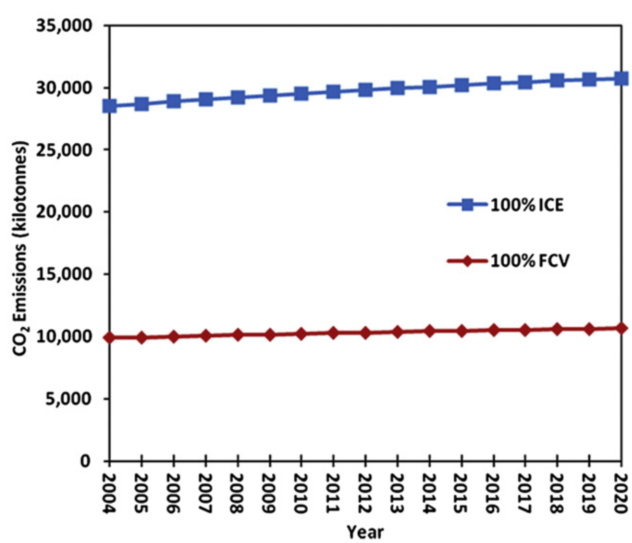

Fig. 2 – CO_2 emissions for third hydrogen production scenario (20% Cu–Cl) with all vehicles converted to hydrogen (kilotonnes).

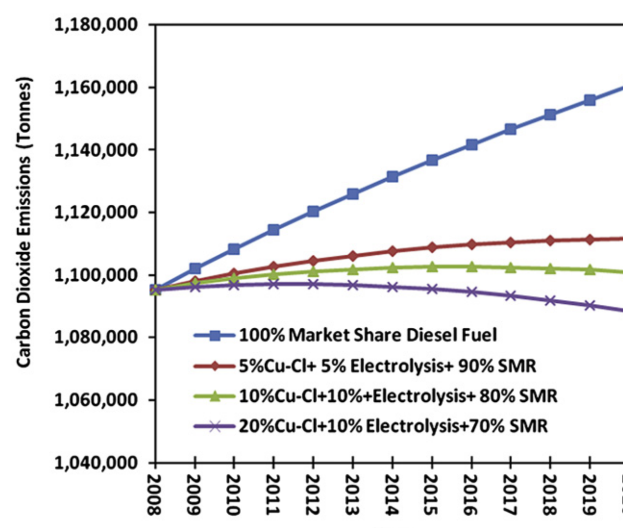

Fig. 4 – Canadian National Railway CO_2 emissions comparison against 100% diesel scenario (tonnes).

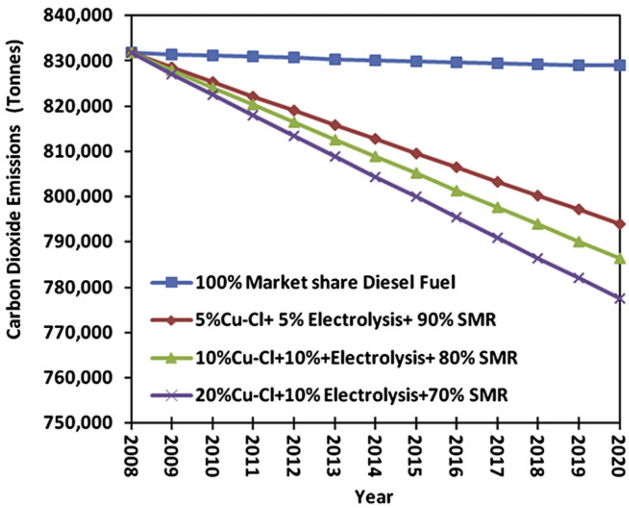

Fig. 5 – Canadian Pacific Railway CO_2 emissions comparison against 100% diesel scenario (tonnes).

In comparison to Fowler et al. [4], the hydrogen vehicle share in 2020 was 1.67% and also electrolysis was the only hydrogen production method. Emissions at the highest hydrogen vehicle share of 2.8% yielded a 3.5% reduction in CO_2 emissions over conventional sources. In this study, a reduction of 2.4% was realized at a 2.8% hydrogen vehicle share. A 2.8% hydrogen vehicle share occurs between 2010 and 2011 in this study. While this may not be the case at the current time, the purpose of the study is to show the potential impact of hydrogen conversion. The difference occurs wherein the study of Fowler et al. [4] used 2005 emissions, whereas in this case, the expected emissions for 2010 were used. A difference in the emission factor for electrolysis in kilograms of CO_2 per kilogram of hydrogen produced also explains the difference in results.

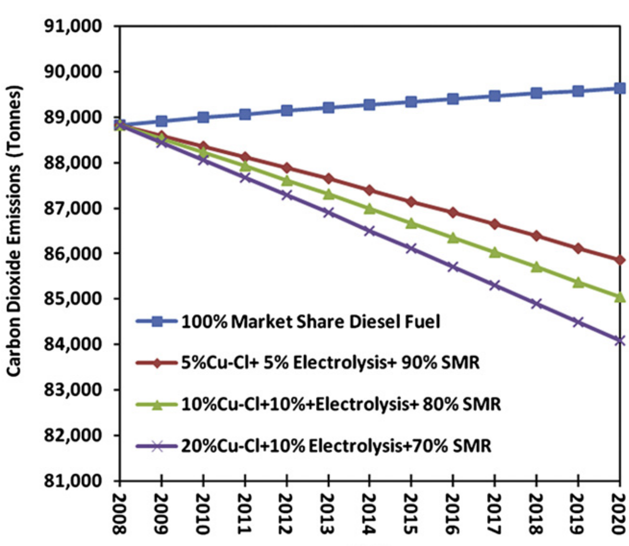

Fig. 6 – VIA Rail CO_2 emissions comparison against 100% diesel scenario (tonnes).

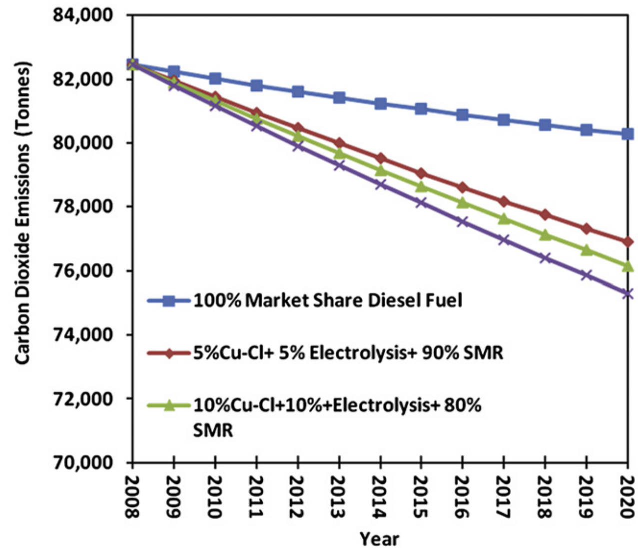

Fig. 7 – Regional Railways CO_2 emissions comparison against 100% diesel scenario (tonnes).

The same hydrogen market share scenario was used in the rail transportation mode. There are 4 rail categories analyzed: Canadian Pacific, Canadian National, VIA Rail and regional railways. Figs. 4–11 show the CO_2 emissions comparison for each railway. All production scenarios used the same energy requirements based of the diesel fuel demand data. Starting with Canadian National Railway (CN), Fig. 4 displays the CO_2 emissions comparison of increasing the hydrogen market share (0–15%) against 100% diesel fuel propulsion from 2008 to 2020. For the first production scenario of 5% Cu–Cl share, the rate of hydrogen market share increase does not result in a decreasing CO_2 emissions trend. When increasing the production scenario with lower emitting production sources

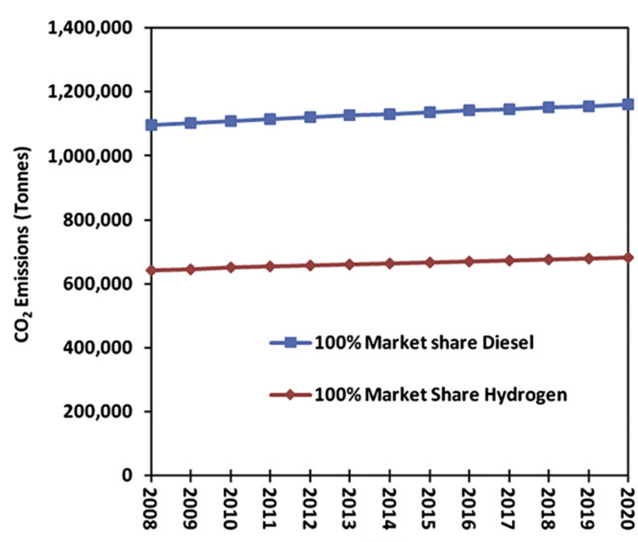

Fig. 8 – Canadian National 100% Hydrogen Market Share CO_2 emissions comparison with 20% Cu–Cl production scenario (tonnes).

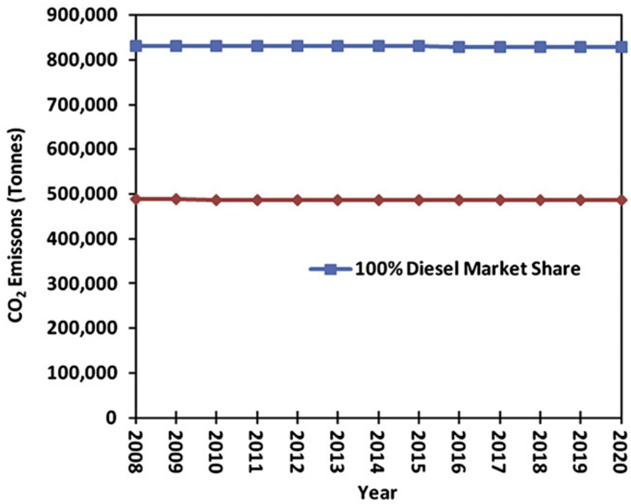

Fig. 9 – Canadian Pacific 100% Hydrogen Market Share CO_2 emissions comparison with 20% Cu–Cl production scenario (tonnes).

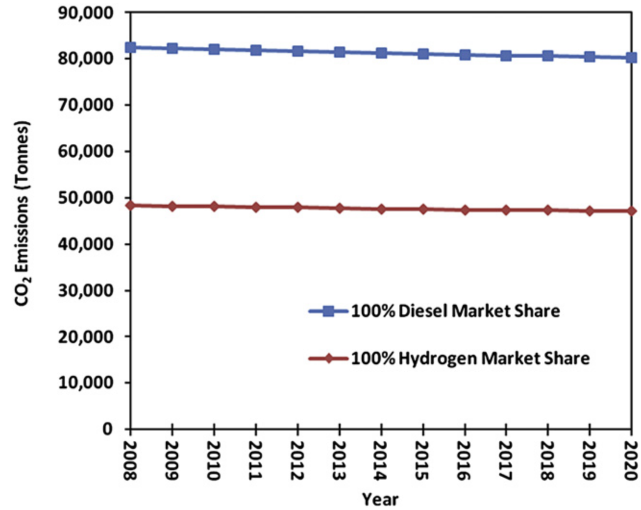

Fig. 11 – Regional Railways 100% Hydrogen CO_2 emissions comparison with 20% Cu–Cl hydrogen production scenario (tonnes).

such as electrolysis and the Cu–Cl cycle, the emissions trend begins to decrease with an increasing hydrogen market share. Therefore, environmentally it is possible to realize significant benefits if the production scenarios contain 10% or more Cu–Cl production of hydrogen. The total CO_2 emissions offset in 2020 for CN is 49,000, 59,000, and 72,000 tonnes for each of the production scenarios. A 6.2% decrease in CO_2 emissions can be realized in 2020 using the production scenario with 20% Cu–Cl production share. The 5% and 10% Cu–Cl scenarios provided 4.2% and 5.1% decreases in emissions. When comparing against 100% hydrogen market share from 20% Cu–Cl production, the total CO_2 emissions decrease is 480,000 tonnes or 41.3% in 2020 (Fig. 8).

The Canadian Pacific railway had a slightly decreasing diesel fuel trend, therefore energy needs and hydrogen demand also had a decreasing trend. CO_2 emissions (Fig. 5) for both fuel scenarios decreased although the rate of decrease was faster when the hydrogen market share increased. Overall CO_2 emissions savings over 100% diesel propulsion compared with 5%, 10% and 20% Cu–Cl production are expected to be 35,000, 42,000 and 51,000 tonnes of CO_2 in 2020. A 100% hydrogen market share with production from 20% Cu–Cl provided a reduction of 340,000 tonnes or 41.3% (Fig. 9).

The VIA rail models indicated an increase in energy needs over the years, which led to increased hydrogen demand and increased emissions from diesel fuel. The CO_2 emissions comparison in Fig. 6 shows an increase trend for 100% diesel fuel market share, although all hydrogen production scenarios provide a decreasing trend with increasing hydrogen market share. For the 5%, 10% and 20% Cu–Cl

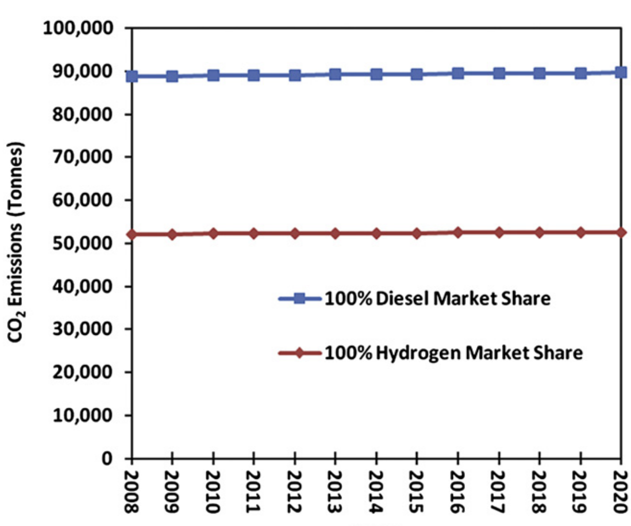

Fig. 10 – VIA Rail 100% Hydrogen Market Share CO_2 Emissions Comparison with 20% Cu–Cl hydrogen production scenario (tonnes).

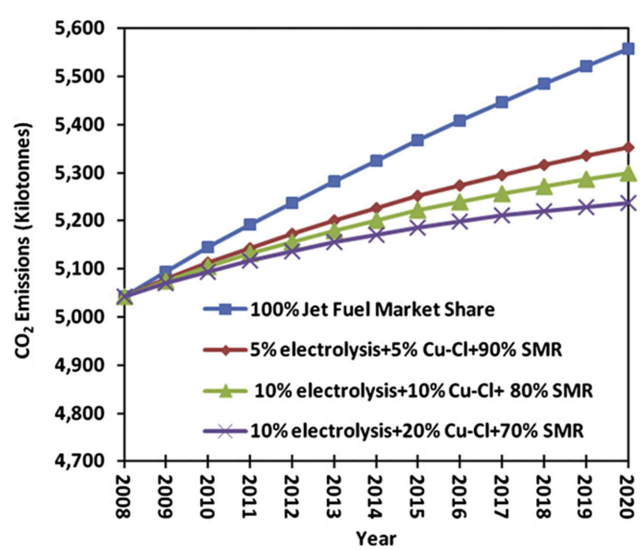

Fig. 12 – Air transportation CO_2 emissions comparison for all production scenarios with 100% jet fuel scenario (kilotonnes).

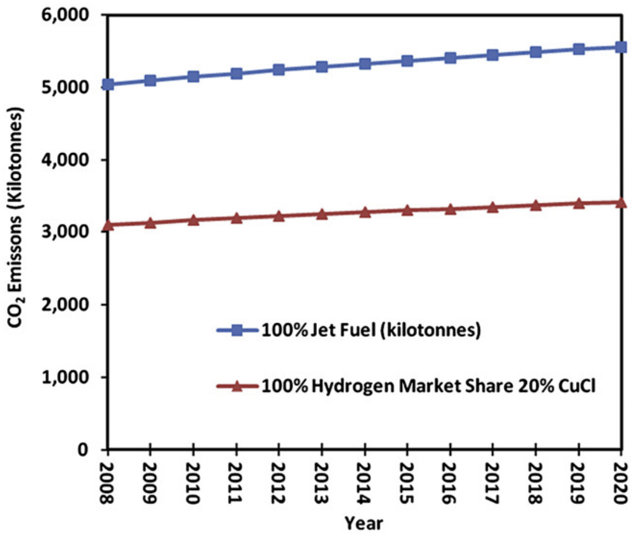

Fig. 13 – Air Transportation 100% Hydrogen Market Share CO_2 emissions comparison with 20% Cu–Cl hydrogen production scenario (kilotonnes).

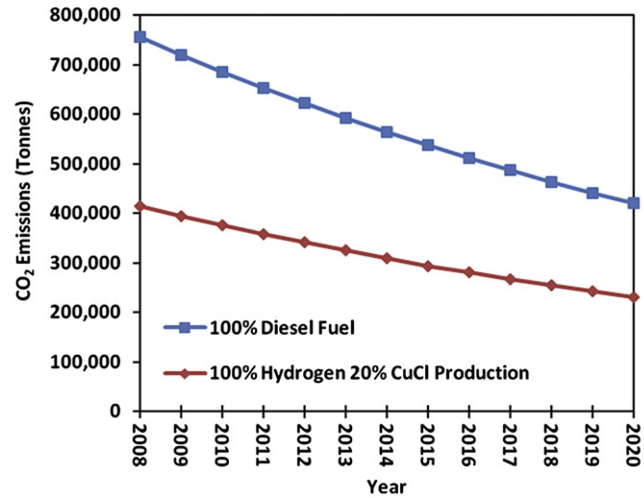

Fig. 15 – Marine Transportation 100% Hydrogen Market Share CO_2 emissions comparison with 20% Cu–Cl hydrogen production scenario (tonnes).

production scenarios, the CO_2 emissions reductions are expected to be 3,800, 4,600, and 5600 tonnes in 2020. A comparison with 100% hydrogen market share and 20% Cu–Cl production provided a 37,047 (41.3%) tonne reduction of CO_2 emissions in 2020 (Fig. 10).

Regional railways overall had a decreasing fuel demand trend, which led to a decreasing trend for overall diesel fuel emissions. Fig. 7 shows that increased hydrogen market share increases the rate of the CO_2 emissions reduction. Overall emissions decreases, by considering the 5%, 10%, and 20% Cu–Cl production scenarios, are expected to be 3,400, 4,000, and 5000 tonnes of CO_2 in 2020. Complete conversion to hydrogen energy will reduce CO_2 emissions by 33,000 tonnes in 2020 as shown in Fig. 11.

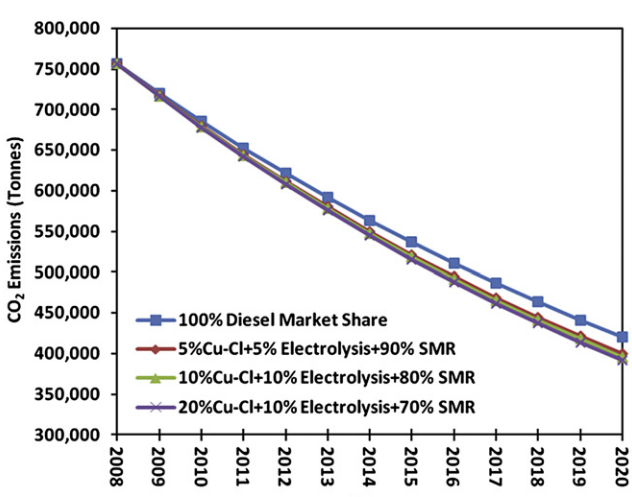

Fig. 14 – Marine Transportation CO_2 emissions comparison for hydrogen production scenarios with 100% diesel operation (tonnes).

The energy model for the air transportation sector showed an increasing energy demand. Emissions from jet fuel and hydrogen demand would also show increases with time. Fig. 12 shows the comparison of CO_2 emissions with increasing hydrogen market share against 100% jet fuel market share. Due to the large rate of energy demand, all hydrogen scenarios show an increasing trend. Even with the increasing trend, all hydrogen scenarios are able to provide a reduction in CO_2 emissions. Increasing the production share of the Cu–Cl cycle will begin to change the CO_2 emissions trend toward a decreasing rate. Compared to a 100% jet fuel market in 2020, a 5%, 10% and 20% Cu–Cl production scenario reduces CO_2 emissions by 3.7%, 4.7%, and 5.8%. This corresponds to a CO_2 reduction of 210, 260, and 320 kilotonnes over jet fuel propulsion. Complete conversion to hydrogen resulted in a 38.5% decrease in emissions or 2,143 kilotonnes in 2020 (Fig. 13).

The energy consumption model for the marine sector showed a large drop in energy demand based on historical data. Overall emissions and hydrogen demand showed decreasing trends. When comparing emissions against a 100% diesel fuel market share, the 5% Cu–Cl production scenario reduced emissions by 4.9% or 21,000 tonnes. Production scenarios with 10% and 20% production share reduced the emissions by 5.8 and 6.7% (24,000 and 28,000 tonnes) over diesel fuel (Fig. 14). Overall emissions reductions with a 100% hydrogen market share were 45.1% or 190,000 tonnes in 2020 (Fig. 15). While there is a sharp decreasing trend, overall there are emissions reductions.

4. Conclusions

Overall the modes which benefited most in the production scenarios were automobiles under 4,500 kg, CN Rail and VIA Rail. The emissions models for these modes forecasted an increasing trend in CO_2 emissions using current propulsion methods. When the hydrogen production scenarios were introduced with the increasing hydrogen propulsion market share, the increasing emissions trends were reversed. For these modes, as time increased, the emissions decreased when compared to a 100% fossil fuel market share. For automobiles, all hydrogen production scenarios were able to reverse the increasing CO_2 emissions trend. In the best case, CO_2 emissions can be reduced by close to 10% with only 15% hydrogen market share. This comparison is between a market which remains using gasoline, and a production scenario with 20% copper–chlorine production. In the automobile scenarios, significant CO_2 reduction was realized with conservative production estimates. Savings varied from 8.6% to nearly 10% in 2020 when increasing the production share of low carbon emitting sources. The total savings ranged from 2,700 to 3,000 kilotonnes. Increasing the share of thermochemical copper–chlorine production further will result in larger benefits since the emission factor is the lowest of the three production methods. Given the amount of nuclear capacity in Ontario, there is significant capacity to provide the demand through the copper–chlorine cycle.

In the case of rail transportation, Canadian National Railways had the largest increasing CO_2 trend. The first hydrogen scenario was not able to reverse the trend with 15% hydrogen market share in 2020. The last two scenarios with increased copper–chlorine production were able to change the trend to a decreasing trend by 2020. When compared against Canadian National, VIA Rail did not have such a rising trend. This led to all hydrogen scenarios reducing the CO_2 emissions, as the market share increased to 15%. In the best case scenario, over 6% savings could be achieved in 2020 over fossil fuel propulsion. Overall, all transportation modes benefited from decreased carbon emissions. Transportation modes like marine and certain rail companies had decreasing trends in carbon emissions due to the decreasing energy demand. Hydrogen would not benefit these modes as much as automobiles, CN, and VIA since their emissions were already decreasing. In contrast, air transport energy demand was high and increasing rapidly with time, which led to a high rate of carbon emissions. Even with the scenarios presented in this paper, the emissions trend was still increasing. Reversing the trend would require increasing the share of hydrogen.

Producing hydrogen from other sources such as wind and hydro will also reduce environmental impacts. This study has shown the benefits of low carbon hydrogen production methods providing 5–20% of the demand, when applied to a small percentage of the market. The potential to significantly reduce carbon emissions are further realizable as the market share of hydrogen vehicles increases and thermochemical production methods are increased.

Nomenclature

- C_{h_2} — Fuel cell vehicle average hydrogen consumption, kg/km
- E_{Cu-Cl} — Emissions of kilogram CO_2 per kilogram of hydrogen produced for Copper–Chlorine cycle
- E_{ELEC} — Emissions of kilogram CO_2 per kilogram of hydrogen produced for electrolysis
- E_D — Emissions of CO_2 in kilograms per liter of diesel fuel
- E_{SMR} — Emissions of kilogram CO_2 per kilogram of hydrogen produced for steam methane reforming
- H_uAIR — Useful energy needed for air transportation, petajoules
- H_uR — Rail useful energy used for propulsion, Terajoules
- LHV_D — Lower heating value of diesel, kJ/kg
- m_{CO_2}AIR — Mass of CO_2 emissions from jet fuel consumption air transport, tonne
- $\overline{m}_{CO_2}$ICE — Emissions per vehicle for Vehicles $<$ 4,500 kg, kg/km
- m_{CO_2}ICE — Total emissions in kilotonnes for internal combustion engines
- m_{CO_2}FCA — Mass of CO_2 emission from hydrogen production for air transport, tonne
- m_{CO_2}FCM — Mass of CO_2 emissions from hydrogen production for marine transport, tonne
- m_{CO_2}FCR — Mass of CO_2 emissions from hydrogen production for rail transportation, tonne
- m_{CO_2}FCV — Total emissions in kilotonnes for hydrogen powered automobiles
- m_{h_2a} — Total hydrogen demand for automobiles $<$ 4,500 kg, kilotonnes
- m_{CO_2M} — Mass of CO_2 emissions for diesel consumption in marine transport, tonne
- m_{CO_2}R — Mass of CO_2 emissions from diesel operation of rail transport, tonne
- m_{h_2}AIR — Mass of hydrogen demand for air transport, tonne
- m_{h_2M} — Mass of hydrogen for marine transportation, tonne
- m_{h_2r} — Mass of hydrogen in metric tonnes for rail transportation, tonne
- n_a — Number of automobiles $<$ 4,500 kg
- x_t — Number of years
- y_a — Number of automobiles $<$ 4,500 kg
- y_{AIRe} — Total amount of energy needed for air transportation, petajoules
- y_{CNe} — Useful energy needed for Canadian National Rail, terajolues (propulsion energy)
- y_{CPe} — Useful energy needed for Canadian Pacific Railway, terajolues (propulsion energy)
- y_{CNf} — Diesel fuel amount in liters X 1,000 for Canadian National Railway
- y_{CPf} — Diesel fuel amount in liters X 1,000 for Canadian Pacific Railway
- y_{DT} — Number of kilometers traveled per year per automobile
- y_{Me} — Total amount of energy needed for marine transportation, petajoules
- y_{Re} — Useful energy needed for Regional Railways, terajolues (propulsion energy)
- y_{Rf} — Diesel fuel amount in liters X 1,000 for Regional Railways
- y_{VIAe} — Useful energy needed for VIA Rail, terajolues (propulsion energy)
- y_{VIAf} — Diesel fuel amount in liters X 1,000 for VIA rail
- y_{xe} — Useful energy needed for x rail category (eg. $x = CN$)
- y_{xf} — Volume of diesel fuel in liters x 1000 for each rail category x (e.g., x = CN)
- ρ_D — Density of diesel, kg/m^3

$\%_{Cu-Cl}$ Percentage of thermochemical Copper–Chlorine cycle production share
$\%_{ELEC}$ Percentage of electrolysis production share
$\%_{h_2}$ Percentage of transportation mode hydrogen propelled
$\%_{SMR}$ Percentage of steam methane reforming production share

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