Proceedings of the Canadian Society for Mechanical Engineering International Congress
32nd Annual Conference of the Computational Fluid Dynamics Society of Canada
Canadian Society of Rheology Symposium
CSME-CFDSC-CSR 2025
May 25–28, 2025, Montréal, Québec, Canada

Comparing Hydrogen Infrastructure Implementation of Homes and Fuel Cell Truck Fleets

Aamer Akhand[1,4], Xiao-Yu Wu[2,4*], Mehrdad Pirnia[3]
[1]Department of Chemical Engineering, University of Waterloo, Waterloo, Canada
[2]Department of Mechanical and Mechatronics Engineering, University of Waterloo, Waterloo, Canada
[3]Department of Management Science and Engineering, University of Waterloo, Waterloo, Canada
[4] Greener Production Group, University of Waterloo, Waterloo, Canada
*xiaoyu.wu@uwaterloo.ca

Abstract—Hydrogen as an energy storage system continues to gain popularity as a possible future infrastructure strategy to reduce carbon emissions. This work aims to look at how hydrogen can be used in two sectors: the replacement of a class 8 heavy-duty fleet consisting of 56 vehicles and the powering of 4,000 homes using renewables without Ontario power grid connections. The goal is to identify cost effectiveness and possible savings in combining the sectors. It was found that the embodied emissions in renewables energy sources were a large portion of the emissions. However, combining the two sectors allowed for further emission reduction by minimizing the amount of PV panels and wind turbines needed. Due to the high cost of fuel cell electric vehicles (FCEVs) compared to current diesel vehicles, the combined scenario ended up much more expensive and with a worse cost per tonne of carbon emission saved, compared to the home-only scenario.

Keywords-Energy Storage; Hydrogen; FCEVs; Renewable Energy Resources

I. INTRODUCTION

There is a need to reduce carbon emissions to reach climate targets. Large portions of emissions come from buildings and vehicles [1]. Buildings still heavily rely on non-renewables for their electrical needs. On the other hand, there has been a slow transition to electric vehicles, and yet the manufacturing of batteries is a carbon intensive process.

One of the challenges to variable renewable energy sources is their unstable outputs compared to options such as natural gas and coal power plants [2]. There is a concern that renewable energy needs to be oversized for peak loads. But this can also lead to excess production, curtailment and waste. Furthermore, along with an increasing electricity demand because of electrification of homes and vehicles, the relationship between electricity supply and demand is mismatched. Energy storage provides an option to store unused energy until peak load hours.

Production of green hydrogen as an energy storage continues to be a growing field [3]. Water can be split into hydrogen and oxygen via electrolysis. The produced hydrogen is then stored and later can be passed through a fuel cell or engine when needed to produce electricity. By utilizing hydrogen as an energy storage system, the mismatch between supply and demand can be realigned.

This work first showcases two different business-as-usual base scenarios. The first being the emissions and costs from running a heavy-duty class 8 fleet with 56 diesel-powered internal combustion engine vehicles (ICEVs) comprised of dump trucks and other municipal service vehicles. The second base scenario is the costs and emissions associated with powering 4,000 homes using the grid. Against these two base scenarios are three different scenarios involving hydrogen energy storage systems. The first system uses hydrogen fuel cell electric vehicles (FCEVs) to replace the class 8 fleet ICEVs and constructing dedicated refueling stations, which can be for public use in the future. The second is studying how hydrogen can realign the electrical supply and demand mismatch in homes, which reduces the peak electrical demand hours. The final one is to analyze a hybridized version of the two previous scenarios, increasing the demand of the overall system while leveraging any economic savings into each other. All these pathways are examined in a 25-year time span.

Each scenario involving hydrogen is modelled as a mixed integer linear programming problem in Python and is solved using the Gurobi Optimizer package.

II. METHODOLOGY

The Ontario grid mainly relies on nuclear and hydro for its baseline but uses natural gas to meet higher demands throughout the day, e.g., a small peak in the morning around 8 am and a larger peak demand around 6 pm. For grid electricity, we evaluated the annual emission factor (AEF) at an average hourly basis [4], by calculating the emissions of each power generation sources at each hour. Meanwhile, the electricity cost was based on what is paid per kilowatt hour throughout the day, using Ontario's new ultra-low overnight (ULO) electricity plan that provides cheaper electricity on off-peak hours [5]. Fig. 1 graphically showcases the ULO pricing scheme and its high costs during the demand peak around 6 pm.

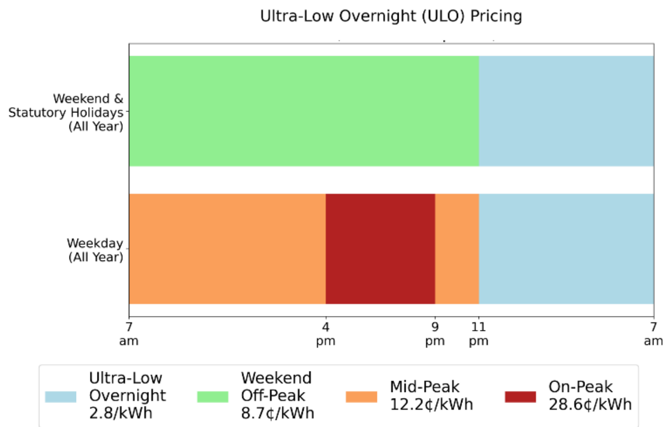

Figure 1. Ultra-Low Overnight Pricing Scheme. [5]

For the scenarios with green hydrogen, a system of renewable energy consisting of wind and solar was used to produce hydrogen. The hourly solar irradiance over the city of Kitchener for each year analyzed was taken from the historic values in 2019. Similarly, the hourly wind power generation from a 1-megawatt wind turbine was also from historic wind values in 2019. Both hourly sets of data were scaled depending on how much renewable energy was installed, similar to what was done in the literature [6, 7].

This study considers the use of proton exchange membrane (PEM) technologies for the hydrogen infrastructure [8], e.g., PEM electrolyzers and fuel cells. The capital costs for fuel cells and electrolyzers were considered to scale linearly with the size of the unit. The fixed operating cost (OPEX) was taken as 1.5% of that capital cost per year. One key aspect of this research is recognizing the embodied emissions in the hydrogen infrastructure. The energy used to produce fuel cell and electrolyzer stacks and the balance of plant was conservatively considered using only electricity from natural gas power plants whose emissions are 486 g/kWh [9].

The hydrogen in these systems would be stored in 2.5 m long cylindrical tanks. They are pressurized at 700 bar, containing up to 24.1 kg of hydrogen gas. They are costed at $4,013 each with 1% operational costs per year [10].

The capital costs for hydrogen FCEVs are expected to decrease with technology development. Three data points, i.e., 2023 market prices, estimated prices in 2030 and 2050, were interpolated for FCEVs [11]. FCEVs start in 2023 at $587,000 per vehicle and trend downwards to $235,000 in 2050 while ICEV price stays stable at $158,250. The embodied emissions for ICEVs and FCEVs are 27 and 40 tonnes of CO_{2eq}, respectively [12]. The higher embodied emissions from the FCEVs occur due to the fuel cell stack component inside of them. However, ICEVs will emit 3.3 kilograms of CO_2 per liter of diesel combusted while FCEVs will have zero tailpipe emissions.

We considered the scenario where vehicles will be replaced at a rate of four vehicles per year. The cost and diesel usage of the 56-vehicle ICEV fleet was given on an annual basis and any replacement vehicles will use and cost the same amount of fuel per year. The amount of diesel required to run the ICEV fleet is converted to an energy equivalent amount of hydrogen based using the engine efficiencies for the FCEV replacements.

Each scenario is designed and optimized to minimize cost, and their costs to abate carbon emissions are compared.

$$Carbon\ Abatement = \left|\frac{Cost_H - Cost_{BAU}}{E_H - E_{BAU}}\right| \quad (1)$$

Where $Cost_H$ and E_H are the optimized cost and emissions of the proposed hydrogen scenario respectively, $Cost_{BAU}$ and E_{BAU} are the cost and total emissions of the business-as-usual scenarios together.

III. Model Description

All cost values in the equations below were calculated as a net present value with a 5% annual interest rate. All components of the hydrogen energy storage system are part of the set {S} and is used in all models involving scenarios with hydrogen. It is comprised of wind and solar energy generation, storage, electrolyzer and fuel cell. All vehicles in the heavy-duty fleet are part of the set {F} which is broken down into sets {DF} and {HF} representing diesel fleet vehicles and hydrogen fleet vehicles, respectively.

A. Grid to Buildings

The total cost of the first business-as-usual base scenario is the summation of the electricity bought from the grid to meet the residential electricity demand over the 25-year period.

$$Cost = \sum_{h=1}^{\mathcal{H}} C_h^G \, D_h^H \quad (2)$$

Where C_h^G represents cost of electricity from the grid using the ultra-low overnight pricing scheme at hour h (¢/kWh), D_h^H represents the total electrical demand of the 4,000 homes at hour h (kWh) and $\mathcal{H}$ represents the hours in the 25-year time span.

The total emission E, in this scenario is calculated using the emission factor of the hour.

$$E = \sum_{h=1}^{\mathcal{H}} e_h D_h^H \quad (3)$$

Where e_h represents the operation emission factor of the grid (gCO_2/kWh) at hour h.

B. Heavy Duty Diesel Fleet

The cost of for the second business-as-usual scenario involving the capital cost of replacing the diesel fleet every year, maintenance costs and cost of fuel.

$$Cost = \sum_{h=1}^{\mathcal{H}} \left(c^{DF} D_h^F\right) + \sum_{i,y\ \forall i \in \{DF\}} \left(R_y C_{i,y} + N_{DF} c_{i,y}\right) \quad (4)$$

Where c^{DF} represents cost of diesel fuel ($/L), D_h^F represents the fuel demand at hour h (L), N_{DF} represents amount of diesel vehicles in the fleet, $C_{i,y}$ represents the capital cost of purchasing component i in year y ($), $c_{i,y}$ represents the fixed operational cost in year y ($), and R_y represents the number of vehicles replaced in year y.

The total emission of this scenario is composed of the embodied emissions of the yearly replacement vehicles and the operational emissions from burning diesel.

$$Emission = \sum_{i,y\ \forall i \in \{DF\}} \left(R_y \hat{E}_{i,y} + e_i \mathcal{F}_{i,y}\right) \quad (5)$$

Where $\hat{E}_{i,y}$ represents embodied emissions of item i in year y (tonne CO_2), e_i represents operational emissions of item i in year y (tonne CO_2/L diesel in the case of diesel vehicles) and $\mathcal{F}_{i,y}$ represents the amount of diesel burned in year y (L).

C. Hydrogen Homes

In all scenarios using hydrogen, the objective function Z is minimized to reduce total cost.

$$Z = \sum_{i,y\ \forall i \in \{S\}} \left(C_{i,y} \hat{P}_{i,y} + c_{i,y} P_{i,y}\right) \quad (6)$$

Where $\hat{P}_{i,y}$ represents the amount of newly installed capacity of component i in year y (kWh for storage, kW for all other components), and $P_{i,y}$ represents the total amount of installed capacity of component i in year y (kWh for storage, kW for all other components).

The total emission of this scenario consists of the embodied emissions of each component as well as the operational emissions.

$$Emission = \sum_{i,y\ \forall i \in \{S\}} \left(\hat{E}_{i,y} \hat{P}_{i,y} + e_{i,y} P_{i,y}\right) \quad (7)$$

D. Hydrogen Fleet

The hydrogen fleet scenario considers the initial state of 56 diesel vehicles. Four of those ICEVs will be retired each year and replaced with FCEVs. The operational costs and emissions of the remaining diesel vehicles during the transition are considered.

$$Z = \sum_{i,y\ \forall i \in \{S\}} \left(C_{i,y} \hat{P}_{i,y} + c_{i,y} P_{i,y}\right) + \sum_{h=1}^{\mathcal{H}} \left(\mathcal{F}_h\ D_h^{DF}\right) + \sum_{i,y\ \forall i \in \{F\}} \left(R_{HF,y} K_{HF,y} + N_i k_{i,y}\right) \quad (8)$$

The total emissions are comprised of the embodied emissions of the replaced vehicles, components for the hydrogen energy storage system and the burned fuel by the ICEVs that are yet to be replaced.

$$E = \sum_{i,y\ \forall i \in \{S\}} \left(\hat{E}_{i,y} \hat{P}_{i,y} + e_{i,y} P_{i,y}\right) + \sum_{i,y\ \forall i \in \{F\}} \left(\hat{E}_{HF,y} \hat{P}_{HF,y} + e_{i,y} \mathcal{F}_y\right) \quad (9)$$

E. Hybridized System

The final scenario combines the previous two hydrogen scenarios.

$$Z = \sum_{i,y\ \forall i \in \{S\}} \left(C_{i,y} \hat{P}_{i,y} + c_{i,y} P_{i,y}\right) + \sum_{h=1}^{\mathcal{H}} \left(\mathcal{F}_h\ D_h^{DF}\right) + \sum_{i,y\ \forall i \in \{F\}} \left(C_{HF,y} \hat{P}_{HF,y} + N c_{i,y}\right) \quad (10)$$

$$E = \sum_{i,y\ \forall i \in \{\ S\}} \left(\hat{E}_{i,y} \hat{P}_{i,y} + e_{i,y} P_{i,y}\right) + \sum_{i,y\ \forall i \in \{F\}} \left(\hat{E}_{HF,y} \hat{P}_{HF,y} + e_{i,y} \mathcal{F}_y\right) \quad (11)$$

The three hydrogen scenarios are optimized to size equipment that will minimize the total cost of each scenario. The constraints are held such that the system will meet the demands at every hour, all renewable energy is accounted for, and the storage maximum is never exceeded.

F. Demand Constraints

For the scenario to be considered valid it had to be able to meet the demands of each sector for every hour.

$$P_{H2,h}^{dch,HF} = D_h^{HF}\ \forall\ h \quad (12)$$

$$P_{H2,h}^{dch,H} \eta_{FC} + P_{W,h}^{H} + P_{PV,h}^{H} = D_h^{H}\ \forall\ h \quad (13)$$

Where $P_{H2}^{dch,i}$ represents the amount of energy discharged from the hydrogen storage into demand *i*: the hydrogen fleet (*HF*) or homes (*H*) (kWh), η_{FC} represents the efficiency of the fuel cell, and P_W and P_{PV} represent the energy from wind and PV, respectively (kWh).

G. Operation Constraints

Operation constraints were included in the mixed integer linear program to avoid nonsensical actions such as charging more than the electrolyzer can handle or discharging more than the current state of charge.

$$P_{PV,h}^{ch} + P_{W,h}^{ch} <= \hat{P}_E \forall\ h \quad (14)$$

$$P_{H2,h}^{dch} <= \hat{P}_{FC} \forall\ h \quad (15)$$

$$P_{H2,h}^{dch} <= SOC_h\ \forall\ h \quad (16)$$

Where $P_{i,h}^{ch}$ represents the amount of energy from i renewable energy that is used for charging the hydrogen energy storage system (kWh), and SOC_h represents the state of charge of the energy storage system (kWh).

H. Renewable Constraints

The two following constraints ensure that all energy from the renewable resources is accounted:

$$P_{PV,h}^{ch} + P_{PV,h}^{H} + P_{PV,h}^{Ct} = \lambda_{PV,h} \hat{P}_{PV} \; \forall \; h \qquad (17)$$

$$P_{W,h}^{ch} + P_{W,h}^{H} + P_{W,h}^{Ct} = \lambda_{W,h} \hat{P}_{W} \; \forall \; h \qquad (18)$$

Where $P_{W,h}^{Ct}$ represents the curtailed energy from i renewable (kWh), and $\lambda_{i,h}$ represents the proportion of the max capacity of the renewable energy that can be capture at hour h from 0 to 100%.

I. State of Charge Constraints

The final two constraints ensure that there is continuity of the amount of energy available in the energy storage system is consistent hour to hour and that state of charge is never higher than the max capacity of the storage system.

$$SOC_{h-1} - P_{H2,h}^{dch,H} \eta_{FC} - P_{H2,h}^{dch,F} + P_{PV,h}^{ch} \eta_E + P_{W,h}^{ch} \eta_E = SOC_h \; \forall \; h \qquad (19)$$

$$SOC_h \leq \hat{P}_{H2,h} \; \forall \; h \qquad (20)$$

IV. Results

A. Grid to Buildings

The 4,000-home base scenario requires electricity purchases from the grid totaling \$66.8 million. The total emissions from the grid are 35,369 tonnes of CO_{2eq}. Fig. 2 shows the amounts of electricity purchased in the four prices in ULO pricing scheme shown in Fig. 1. A large majority of the electricity purchased is during the mid-peak and on-peak demand hours at ¢12.2 and ¢28.6/kWh, respectively. This coincides with high emission intensity of the grid. Therefore, we hypothesized that by shifting the use of grid electricity to off-peak hours, the carbon intensity of the system would decrease.

B. Heavy Duty Diesel Fleet

The cost of fuel and replacing vehicles ends up at \$24 million over the 25-year span. The emissions of the 56-ICEV fleet are 26,606 tonnes of CO_{2eq} where 2,700 tonnes come from the embodied emissions of the new ICEVs. Most emissions are from the daily use of combusting diesel, which may be reduced significantly if ICEVs were replaced with FCEVs that use low-carbon hydrogen.

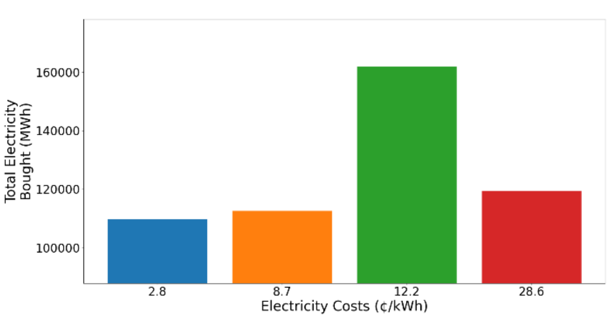

Figure 2. Electricity bought at each price point in the business-as-usual Grid to Buildings scenario

C. Hydrogen Homes

In the scenario of implementing renewable energy sources and hydrogen storage for the buildings led to a total cost of \$69.2 million. The renewable system was made up of 7 MW of wind turbines and 13,020 kW of PV panels resulting in costs of \$17.5 million and \$20.6 million respectively. The largest financial cost was the fuel cell at \$26.3 million. The total emissions decreased from the base case down to 29,887 tonnes, with a large majority coming from embodied emissions in the installation of PV and wind renewable resources, taking 19,123 and 8,545 tonnes respectively. If the large, embodied emissions of the renewable energy sources were not considered, the total emissions of the system would be cut all the way down to 2,219 tonnes CO_2eq.

An alternative scenario where the grid supplied power to a hydrogen storage system was explored, but it was found that supplying the demand directly from the grid during on-peak hours was always more financially beneficial compared to charging the system due to fuel cell and electrolysis inefficiencies. This simply resulted in the original business-as-usual building scenario with no hydrogen infrastructure bought.

D. Hydrogen Fleet

The scenario replacing the diesel ICEV fleet with hydrogen FCEVs over time would result in a much more expensive cost at \$70.8 million. The scenario also boasted a surprising 36,497 tonnes CO_2eq emissions, a 37% increase from the base scenario. First, the system with 7 MW of wind turbines and 11,999 kW of PV panels plays a significant role of embodied emissions at 8,545 and 17,623 tonnes, respectively. Second, since only four ICEVs are replaced each year, the operating emissions from the remaining to-be-replaced ones adds 6,207 tonnes over the 25-year span. Along with the higher embodied emissions and price tag of FCEVs compared to ICEVs currently, this scenario is clearly not competitive economically or environmentally.

E. Hybridized System

Serving both the buildings and fleet with hydrogen results in a system cost \$124.1 million. The scenario is served by 12 MW of wind turbines and 19,177 kW of PV, lower than the sum of the two independent hydrogen scenarios. The total emission of the scenario is 53,224 tonnes CO_{2eq}. This system can save even more carbon emissions but at a higher cost due to the expensive fleet replacement.

Table 1 summarizes the cost and emissions of the scenarios studied. The listed values are the combined values of both sectors in each scenario.

TABLE I. SUMMARY OF SCENARIO COSTS AND EMISSIONS

Scenario	Cost ($)	Emissions (Tonnes)	Carbon Abatement ($/Tonne)
Business-as-usual	90,785,959	61,974	--
H_2 Homes implemented	93,226,107	56,492	445.1
H_2 Fleet implemented	137,656,252	71,886	No carbon abatement
Hybridized	124,133,977	53,224	3,811

The largest contributor to emissions in the hydrogen scenarios are the high embodied emissions of the renewable energy sources. Despite that, the hydrogen home scenario was able to reduce total emissions by shifting the supply to meet the demand with storage compared to using the more carbon intensive grid electricity.

In hydrogen fleet scenario, the emissions and costs were both drastically higher than the business-as-usual case. This scenario struggled with the high embodied emissions of not only the renewable energy sources but also the FCEVs, compared to ICEVs. Furthermore, the nearly quadruple starting price difference for FCEVs makes this scenario very difficult to be economically competitive at the current time. Either FCEVs will need to become much cheaper through government subsidies and systems, or the technology to reduce carbon emissions associated with them.

The hybridized system was able to reduce even more emissions due to its ability to lower the amount of renewable energy sources required. However, due to the poor potential of the fleet scenario, the cost of carbon abatement is much higher than the building power scenario.

V. CONCLUSION

This work examined two different sectors of residential power and heavy-duty fleets. Business-as-usual scenarios and individual or hybridized hydrogen scenarios are optimized separately with minimized costs and the emissions and costs of carbon abatement are analyzed. The hydrogen home scenario is found to be the most cost effective based on the carbon abatement costs. The hybridized hydrogen scenario has the largest reduction in emissions but with a much higher cost due to the expensive FCEV fleet replacement component.

It is found that the embodied emissions of renewable energy contribute significantly to the total hydrogen infrastructure emissions currently. Integrating renewable hydrogen with low carbon intensive grid electricity (e.g., off-peak) would be a vital future step in the study.

REFERENCES

[1] "U.S. Energy Information Administration - EIA - Independent Statistics and Analysis." *Where Greenhouse Gases Come from - U.S. Energy Information Administration (EIA)*

[2] Sen, Souvik, and Sourav Ganguly. "Opportunities, barriers and issues with renewable energy development – a discussion." *Renewable and Sustainable Energy Reviews*, vol. 69, Mar. 2017, pp. 1170–1181, https://doi.org/10.1016/j.rser.2016.09.137.

[3] Oliveira, Alexandra M, et al. "A green hydrogen economy for a renewable energy society." *Current Opinion in Chemical Engineering*, vol. 33, Sept. 2021, p. 100701, https://doi.org/10.1016/j.coche.2021.100701.

[4] "Ontario Electricity Emissions Factors and Guidelines." *The Atmospheric Fund*, taf.ca/custom/uploads/2024/06/TAF-Ontario-Emissions-Factors-2024.pdf.

[5] "Electricity Rates." *Electricity Rates | Ontario Energy Board*, www.oeb.ca/consumer-information-and-protection/electricity-rates.

[6] Pfenninger, Stefan, and Iain Staffell. "Long-term patterns of European PV output using 30 years of validated hourly reanalysis and Satellite Data." *Energy*, vol. 114, Nov. 2016, pp. 1251–1265, https://doi.org/10.1016/j.energy.2016.08.060.

[7] Staffell, Iain, and Stefan Pfenninger. "Using bias-corrected reanalysis to simulate current and future wind power output." *Energy*, vol. 114, Nov. 2016, pp. 1224–1239, https://doi.org/10.1016/j.energy.2016.08.068.

[8] "Technical Targets for Proton Exchange Membrane Electrolysis." *Energy.Gov*, U.S Department of Energy, www.energy.gov/eere/fuelcells/technical-targets-proton-exchange-membrane-electrolysis.

[9] Gerloff, Niklas. "Comparative life-cycle-assessment analysis of three major water electrolysis technologies while applying various energy scenarios for a greener hydrogen production." *Journal of Energy Storage*, vol. 43, Nov. 2021, p. 102759, https://doi.org/10.1016/j.est.2021.102759.

[10] Kubilay Karayel, G., et al. "A comprehensive assessment of energy storage options for green hydrogen." *Energy Conversion and Management*, vol. 291, Sept. 2023, p. 117311, https://doi.org/10.1016/j.enconman.2023.117311.

[11] Ciancio, Alessandro, et al. "Carbon abatement cost evolution in the forthcoming hydrogen valleys by following different hydrogen pathways." *International Journal of Hydrogen Energy*, vol. 64, Apr. 2024, pp. 80–97, https://doi.org/10.1016/j.ijhydene.2024.03.197.

[12] Wanniarachchi, S. T. (2022). Comparative Life Cycle Analysis of Heavy-Duty Vehicles (Class 7/8) Fueled by Renewable Diesel, Electricity, and Hydrogen.