Energy Transition and Environmental Benefit of Fuel Cell Electric Vehicles

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Abstract

Since the world is constantly generating electricity, we need a means to store any excess energy that we get, so as to not waste any of it. Surplus renewable energy can be stored in the form of hydrogen. This stored energy can be used in different applications like fuel cell electric vehicles, power generation, fertilizers and other chemical industries. Energy production as hydrogen through water electrolysis has been getting massive attention in the world as the excessive renewable entry on their energy grid. The aim of this paper is to provide information about the production of hydrogen and the countries which are shifting towards green hydrogen in the world, and to calculate the environmental benefits of fuel cell electric vehicles (FCEV) when they use the hydrogen that is being produced with the surplus renewable energy in Canada.

Keywords: *Fuel cell Electric Vehicle, hydrogen, renewable energy, proton exchange membrane fuel cell (PEM FC), Electric Vehicle*

1. Introduction

Hydrogen is an energy source that appeals to reducing climate change. Limiting global warming to below 2 degrees Celsius (°C) requires that CO2 emissions decline by around 25% by 2030, from 2010 levels, and reach net zero by around 2070 (IPCC, 2018). To stay below 1.5 °C of warming, which is a more feasible goal, global human-produced net CO2 emissions should be reduced by 45% by 2030, from 2010 levels, reaching net zero by around 2050 (IPCC, 2018). That being said, instead of decreasing, emissions have in fact increased (UNEP, 2018).

Of the world's GHG emissions, 66% come from energy-related sources, mainly CO2. An energy transition is needed now to break the link between economic growth and increased CO2 emission. The International Renewable Energy Agency (IRENA) developed a report to examine the possibilities of using hydrogen as a form of clean energy along with other types of fuels; the examinations were focused on preparing future strategies and long-term goals. This report was requested by G20 Karuizawa Innovation Action Plan on Energy Transitions and Global Environment for Sustainable Growth. On September 25, 2019, in Tokyo, Japan, this report was presented for the Hydrogen Energy Ministerial Meeting (IRENA, 2019)

The European Commission, the European Strategic Energy Technology Plan, and the European Community Research Program highlight goals to be completed regarding GHG emissions; 40% of new cars and vans to be zero- or close to zero- emissions by 2030 (European Commission), reduced GHG emissions by 2050 using hydrogen fuel cell technologies, and shifting priority to electricity-powered transportation respectively (European Parliament). The collaborative research and development (R&D) technological projects in Europe are funded by the European Commission (Larruscain et al., 2017); and sustainable transport is one of the priorities for transport research and innovation in Horizon 2020 (H2020) (European Commission). It is predicted that the annual sales for fuel-cell applications (like FCEVs) are 0.4 – 1.87 million units from 2020 to 2025 (Edwards et al., 2008).

Fuel cell technologies for transportation are mostly implemented in cars (E4tech, 2018). With a total stock of 11,200 FCEVs, around 4,000 of them were sold in 2018, which is a 56% increase over 2017 (AFC TCP, 2018), which is miniscule compared with the 2018 battery electric vehicle (BEV) stock of 5.1 million (IEA, 2019a) or the global car stock of more than 1 billion. In ranking order of most to least, the countries that account for the most registered FCEVs are the US (~50%), Japan (~25%), Germany and France (combined 11%), and Korea (8%). Of these FCEVs, Toyota, Honda, and Hyundai, with Mercedes-Benz starting to lease and sell Plug-in HEVs that implement a fuel cell, make most. Other vehicles that have begun using fuel cell technologies are Buses, trucks, and forklifts. Japan has built around 275,000 fuel cell co-generation systems running on natural gas.

Fuel cell costs have dropped 66% since 2015, and their durability is up to 10,000 hours, with stationary fuel cells running up to 80,000 hours (IEA, 2019b). As of now, due to very few options of refueling, FCEVs cannot be used by the masses. Hydrogen engines are refueled at special fuel pumps, which may be integrated into typical gas stations in the future. There are not many fueling stations available for use, with the US having around 40 FCEV refueling stations at the end of 2019, and Germany having around 80 (IEA, 2019b).

The purpose of this paper is to give information about the production of hydrogen and the countries which are shifting towards green hydrogen in the world. Furthermore, we aim to find the environmental benefits of fuel cell electric vehicles (FCEV) by seeing how the hydrogen produced by Canadian excess renewable energy functions. Information has been collected via a literature review. The remainder of the paper is organized as follows: Section 2 presents a literature review about fuel cells, types of fuel cells, proton exchange membrane fuel cells (PEMFC), the structure of PEMFCs, production of hydrogen .Section 3 addresses the Lifespan of EVs and FCEVs and calculates environmental benefits. Finally, the conclusion is presented.

2. Literature Review

Fuel Cell

A fuel cell (FC) is a galvanic cell that converts chemical energy to electrical energy, which has a direct application to an internal combustion engine (ICE). An ICE converts chemical energy to heat energy that is stored in the fuel supplied to the engine. It also produces rotational mechanical energy (Heywood, 1998). The mechanical energy generated will be used to drive the vehicle or generate electrical energy with a generator. A fuel cell works much the same way as an ICE, in that generates DC (direct current) from the electro-chemical reaction of chemical fuels. Single step process as chemical energy is changed over into electrical energy in the fuel cell, but instead with zero environment pollution and low operating temperature (Costilla et al., 2018; Chakraborty, 2019). However, fuel cells act as power sources if fuel is being provided to them (Giorgi and Leccese, 2013). For automotive options, hydrogen is one of the things to come. Hence, it is anticipated that the hydrogen fuel cell can overcome the weaknesses of BEVs.

Types of Fuel Cell

Depending upon different operating temperature, six types of fuel cells are being used presently. Alkaline fuel cells (AFCs), which have approximately 70 °C operating temperature, Direct methanol fuel cells (DMFCs) operating between 60 °C to130 °C, Molten carbon fuel cells (MFCs) that have temperature up to 650 °C, Phosphoric acid fuel cells (PAFCs) operating between 180 °C to 200 °C, solid oxide fuel cells (SOFCs), its operating temperatures is between 800 °C to1000 °C, and finally Proton exchange membrane fuel cells (PEMFCs), operating at low temperature of around 100 °C, but these can also work at temperatures of 150 °C to 200 °C (Appleby and Foulkes, 1989; Stefănescu, 2010)

Proton Exchange Membrane Fuel Cell (PEMFC)

Because of its low operating temperature of 50 °C to 100 °C, with their high power density 40% to 60%, and very low damage to the environment compared to conventional internal combustion engine vehicles, the proton exchange membrane fuel cell is the best choice for use in commercialized electric vehicles (Yi, 2003; Rajashekara and Rathore, 2015). The proton exchange membrane fuel cell is shown in figure 1.

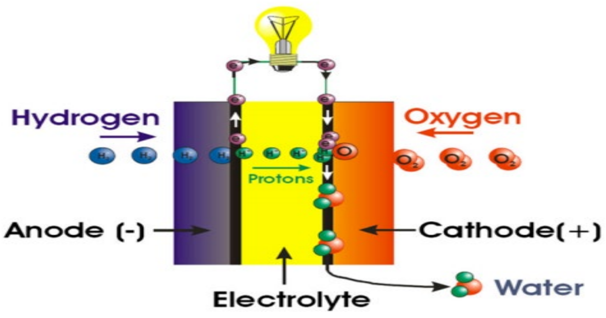

Figure 1: Schematic design of PEM fuel cell (Peighambardoust et al., 2010)

PEMFC Structure

Like all fuel cells, the three essential elements of a proton exchange membrane fuel cells (PEMFC) are an anode, a cathode and the membrane. In order to manufacture these three essential elements, separate sheets are used. In the next step, membrane electrode assembly (MEA) is created by connecting the electrode and electrolyte layer, by using hot pressing process (Haile, 2003; Larminie and Dicks, 2003; EG&G Services Inc, 2000). The membrane electrode assembly (MEA) consists of two catalyst layers, two gas diffusion layers and a proton exchange membrane, which are made individually and combined at medium temperature and pressure.

The Membrane

The most important and costly unit in a fuel cell is the membrane. Presently, different types of membranes are used. But due to the high proton exchange conductivity, good chemical stability and of a high mechanical durability the most commonly used is Nafion (DuPont) a sulphonated polymer with a Polytetrafluoroethylene (PTFE) backbone. The Nafion membrane is prepared by adding sulfonic acid groups into the large mixture of Teflon and thickness of the layers are between 50 and 175 µm. (Iwai et al.,2008; Rodgers et al., 2012; Hori et al., 2010). Some of the membranes that are being investigated are polymer-zeolite nanocomposite proton exchange membrane (Dashtimoghadam and Hasani-Sabrabadi, 2008), sulfonated polyphosphazene based membranes (Bose et al., 2011) and phosphoric acid-doped poly (bisbenzoxazole) and high temperature ion-conducting membrane (Asensio et al., 2010).

The Catalyst Layer

The catalyst layer which is known as the active layer is directly connected with the membrane and the gas diffusion layer. Application of the catalyst layer is either done on membrane or gas diffusion layer. The main purpose for applying this catalyst layer is to put catalyst nanoparticles (which are normally 5 to 15 nm platinum or platinum alloy like PtxRuy) within close vicinity of the membrane (Litster and McLean, 2003). The objective is to design a triple contact of gas/solid/membrane that allows the fuel cell to generate the electrochemical reaction.

The Gas Diffusion Layer

The gas diffusion layer is an electrical conductor, which transfers electrons to and from the catalyst layer. In a proton exchange membrane fuel cell, the porous gas diffusion layer permits that reactants successfully defuse to the catalyst layer. For the construction of a gas diffusion layer, generally porous carbon paper or carbon cloth with a thickness of 100 to 300 µm coated with a layer of micro porous carbon powder/PTFE is used. Inside the pore volume of the backing layer the polytetrafluoroethylene to stop water from collecting, thus allowing the gases to freely contact the catalyst sites. Moreover, it eases the product water deportation on the cathode as it generates a non-wetting surface inside the passages of the backing material. The gas diffusion layer also helps in managing the water by permitting the proper quantity of water to come and stay at the membrane for hydration. Furthermore, these layers are generally wet-proofed with a polytetrafluoroethylene (Teflon) diffusion coating to make sure that the layers pores do not become overcrowded with liquid water. (Litster and McLean, 2003). This arrangement helps the fuel cell process to begin, where at the anode the hydrogen is split into electrons and protons. The protons pass through the membrane to the cathode, producing water when it combines with oxygen and electron travels through the external circuit producing an electric current. For the hydration of proton exchange membrane (PEM), a high temperature is not required; it can run at 80 °C or lower.

Production of Hydrogen

According to an International Energy Agency, IEA, (2019b) report, 76% of hydrogen is produced by natural gas and 23% by coal, totalling 70 metric tonnes. In terms of percent usage, hydrogen produced every year takes up 6% of global natural gas use, and 2% of global coal use, which is around 205 billion cubic metres, and 107 metric tonnes, respectively. As a whole, global hydrogen production creates about 830 metric tonnes of CO2 every year. Only 2% of low-carbon hydrogen production is through electrolysis, but this figure has potential to be much larger. Excess electricity from variable renewables, although available for little time, is very cheap. This means that, as long as regions meet criteria, low-cost hydrogen production is feasible through dedicated, low-cost renewables. If all hydrogen production were through Electrolysis, the outcome would be a yearly electricity demand of 3,600 TWh. As for water, 617 million cubic metres would be required, which is about 1.3% of the water consumption of the global energy sector at present.

Depending on regional factors, like costs for different energy sources, hydrogen production costs can differ greatly from place to place. The most economic option for hydrogen production is natural gas without CCUS (carbon capture utilisation and storage), at the cost of USD 1 for every kg of hydrogen in the Middle East. For electrolysis to have competition against natural gas without CCUS, it would need prices to be in the range of USD 10 – 40 per MWh and full-load hours of 3,000 to 6,000 depending on local gas prices. If regions already use renewable resources or nuclear power plants and rely on high costs for natural gas imports, electrolysis-produced hydrogen is a good option for energy production.

Countries shifting towards production of green hydrogen

Water can be converted into hydrogen and oxygen using an electrolyser and electricity. Electrolysis plays a central role in the deployment of renewable hydrogen.

Canada

Air Liquide will build the largest Proton Exchange Membrane (PEM) electrolyser in the world with 20 MW capacity to produce low-carbon hydrogen using hydropower (Green Car Congress, 2019). Using renewable energy, like wind and hydropower, Renewable Hydrogen Canada (RH2C), based in Victoria, British Columbia, is planning to produce renewable hydrogen through water electrolysis. The utility has determined that hydrogen-enriched natural gas with up to 10% renewable hydrogen could be supplied utilizing existing infrastructure or, leaving no need for additional infrastructure, equipment modification or safety compromises (RH2C, n.d.).

The Netherlands

A 2 GW electrolyser system is being studied in Rotterdam Harbour (DI, 2019). Also, large-scale hydrogen deployment is planned in the province of Groningen (Delfzijl), the Netherlands; a 20 MW electrolyzer has been implemented since early 2020, and this may expand to 60 MW by the end of the year. The plant would supply hydrogen for methanol and synthetic aviation fuel production (Burridge, 2019).

Austria

Siemens is supplying a 6 MW Proton Exchange Membrane (PEM) electrolyser funded by the Fuel Cells and Hydrogen Joint Undertaking (FCH JU) in Linz (IWR, 2018).

Japan

Toshiba has ordered that a 10 MW electrolyser in Fukushima must power an annual 900 tonnes of hydrogen to be used for transportation, and this hydrogen is produced from a 20 MW solar photovoltaic, PV, project. The Yamanashi Fuel Cell Valley also includes a power-to-gas facility utilising a 1.5 MW PEM electrolysis coupled with a 21 MW solar PV system (Ohira, 2019).

China

Mainly Tianjin Mainland Hydrogen Equipment Co., Ltd. (THE) and Beijing CEI Technology Co., Ltd. have domestically produced the manufacturing capacity for electrolysers, in particular alkaline. THE is a world leading supplier of alkaline electrolysers and has delivered more than 400 production plants since 1994, with units of up to 1,000 cubic metres per hour (THE Co., Ltd., 2019). Suzhou JingLi Hydrogen Production Equipment Co., Ltd. also signed co-operation agreements in August 2018 with Dalian Institute of Chemical Physics for new hydrogen generation via water electrolysis technology research. The “863” and “973” national plans receive funding from the Ministry of Science and Technology and include several projects related to fuel cell technology development, which seems to be the main focus for hydrogen development in China (Holland Innovation Network China, 2019).

Australia

In Australia’s Pilbara region, 15 GW of solar and wind capacity is being developed to supply the local mining industry and to provide electricity for hydrogen commodity production through electrolysis (RN, 2019). A plan for a 50 MW wind and solar-fuelled electrolyser to be built by Neoen near Crystal Brook Australia has been made as part of a new Hydrogen Hub. Also, A 30 MW electrolyser along with an ammonia facility with a capacity of 50 tonnes daily is also planned in Port Lincoln, South Australia (Brown, 2018).

France

The Les Hauts de France project is a power-to-gas project that aims to build five hydrogen- electrolyser production units of 100 MW each over five years. The first of the five is planned to be built by the end of 2021, and HydrogenPro will supply turnkey electrolysers under the authority of H2V INDUSTRY, an integrator specialising in the engineering and development of large hydrogen production plants (GasWorld, 2018; Nel, 2017). The Port-Jérôme plant aims to desulphurise fuels and manufacture fertilisers using hydrogen supplied to the petrochemical industry (Exxon, Total, Yara, etc.). It is to be built next to the Exxon refinery. To decarbonise the natural gas used for heating, cooking and mobility, the project in Dunkirk wishes to integrate hydrogen into the natural gas distribution network (Energy Storage & P2G, 2018; Engie, 2019; Les Echos, 2019).

United Kingdom

Gigastack, a study funded by the UK Department for Business, Energy, and Industrial Strategy, will demonstrate the delivery of bulk, low-cost and zero-carbon hydrogen through gigawatt-scale Proton Exchange Membrane (PEM) electrolysis, manufactured in the UK. The project aims to reduce electrolytic hydrogen costs and material costs through a new 5 MW stack module design. A manufacturing facility with an electrolyser capacity of up to around 1 GW annually will be developed, with a goal to deliver large-scale (100 MW-plus) projects using multiple 5 MW units. The use of PEM electrolysers can be leveraged to exploit synergies with large, gigawatt-scale renewable energy deployments (ITM Power, 2019).

Germany

Projected for 2023, Amprion (a Transmission system operator) and OGE (a gas net operator) have presented a plan for a 100 MW electrolyser and dedicated hydrogen pipeline in the north-west of Germany, a EUR 150 million (USD 168 million) proposal (Amprion and Open Grid Europe, 2019). Furthermore, VNG, Uniper, Terrawatt and DBI, including 50 billion cubic metres of storage and a dedicated hydrogen pipeline, with potential expansion to 200 MW by 2030, plan a 40 MW wind park coupled with electrolysers near a chemical industry in Germany. Shell Wesseling refinery also plans to implement a 10 MW polymer electrolyte membrane (PEM) electrolyser in 2020, under a consortium with ITM Power from the UK (Energate, 2018). In Mainz, a 6-MW electrolyser has been operational since 2017 (BINE, 2018).

United States

The Office of Energy Efficiency and Renewable Energy has a dedicated workstream on hydrogen from renewables, with a focus on electrolysis that includes clear targets for cost and efficiency (US DOE, 2019).

3. Lifespan of EVs and FCEVs

Using various models, we have calculated and analyzed the approximate value an EV can run in terms of kilometers. To find this, we can look at the distance that is possible to be travelled in one complete cycle of charging and discharging. A report by Zhang et al. (2014) studied the best point before one should remanufacture a lithium-ion battery, LIB. They found that when a battery is charged and discharged repeatedly, two turning points of an LIB can be seen regarding the impedance. The first turning point presents a sharp increase in impedance due to the rapid solid electrolyte interphase formation. Then, the SEI layer formation slowed down for a period of time, which kept the battery in normal working conditions. Finally, the second turning point led to a further drastic increase in impedance due to severe damages in the internal circuitry of the battery. They concluded that the optimal point before a battery should be remanufactured is 500-550 cycles of charging and discharging to avoid irreversible damage in the LIB. For our calculation, we consider 550 cycles before a battery enters a remanufactured stage.

We have used conditional probabilities to find if the set condition is met by various EVs. As such, 200,000 km is being considered as the conditional probability A and S_1, S_2, S_3, S_4, S_5, S_6 are the individual occurrences.
A = 200,000 km
n = Electric Vehicle car brands
Tesla Model S 2019 (s_1): Range per cycle is 386 km (Lambert, 2018)
Total distance travelled in 550 cycle = 212,300 km
$p(S_1) = 1 \quad P(S_1|A)$ - Bayes' Rules
Nissan Leaf 2019 (s_2): Range per cycle is 360 km (Lambert, 2018)
Total distance travelled in 550 cycle = 198,000 km
$p(S_2) = 0.99\ P(S_2|A)$

Chevy Bolt 2019 (s_3): Range per cycle is 383 km (Chevrolet Pressroom, 2019)
Total distance traveled in 550 cycle = 210,650 km
$p(S_3) = 1$ $P(S_3|A)$
Kia Soul 2019 (s_4): Range per cycle is 448 km "New Kia Soul" (2019)
Total distance traveled in 550 cycle = 246,000 km
$p(S_4) = 1$ $P(S_4|A)$
Hyundai Kona 2020 (s_5): Range per cycle is 412 km (Hyundai Kona Electric, 2020)
Total distance traveled in 550 cycle = 226,000 km
$p(S_5) = 1$ $P(S_5|A)$
Jaguar I-Pace 2020 (s_6): Range per cycle is 374 km (Edmunds, 2020)
Total distance traveled in 550 cycle = 205,920 km
$p(S_6) = 1$ $P(S_6|A)$
We assume a uniform distribution for six equal occurrences.
$P(A) = (p(S_1) + p(S_2) + p(S_3) + p(S_4) + p(S_5) + p(S_6))/n = (1+0.99+1+1+1+1) = 5.99/6 = 0.998 \approx 100\%$

There is a chance close to 100% that the new battery will stay in this state (New) and will work until 200,000 km. California fuel cell partnership (CAFCP) reported that the distance an FCEV can run over its lifetime is 150,000 to 200,000 miles (240,000 to 320,000 km), since their fuel cell stacks are designed to last the entire lifetime. For the calculation of environmental benefits, we are taking 200,000 km for the end of life of an EVs and FCEVs.

Environmental Benefits

Robinius et al. (2018) reported the great benefits of hydrogen-powered fuel cell electric vehicles, with a carbon footprint of 2.7g CO2-eq/km when the hydrogen is produced from surplus renewable energy. On the other hand, the carbon footprint of an electric vehicle is 20.9g CO2-eq/km when BEVs are charged directly from the normal electricity grid without any specific liking for renewable energy. This was found by using the information from Transport Canada (2020) as shown in Figure 2 that projects the annual number of Zero Emission Vehicles (ZEVs) coming into the market. Our focus is to calculate the environmental benefits of fuel cell electric vehicle when using surplus renewable energy in Canada. Furthermore, if we take EVs and PHEVs entering the market in 2020, 2025, 2030, 2035, and 2040 as example years, we can calculate the environmental benefits of fuel cell electric vehicles. Table 1 shows the calculations for CO2-eq reduced when FCEVs use surplus renewable energy for the production of hydrogen and Figure 3 below graphs the data.

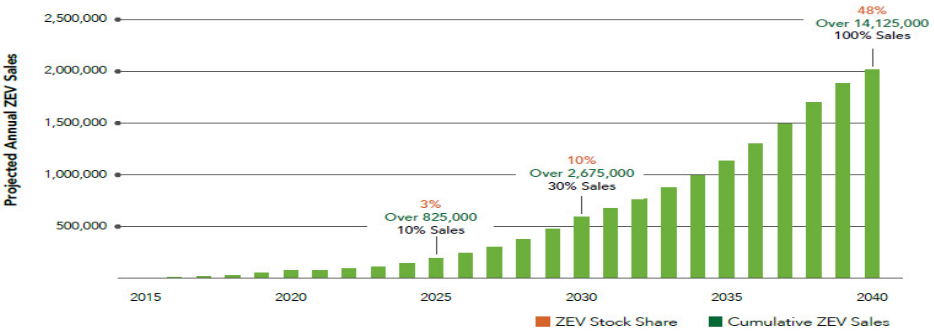

Figure 2: Projected Annual Zero-Emission Vehicle Sale in Canada
(Source Transport Canada 2020)

Table 1: Environmental Benefits of FCEV

Years	2020	2025	2030	2035	2040
Lifetime CO2-eq Emissions of EVs	522,500	1,045,000	2,633,400	4,598,000	8,360,000
Lifetime CO2-eq Emission of FCEVs	67,500	135,000	340,200	594,000	1,080,000
Saving CO2-eq Emission (EVs – FCEVs)	455,000	910,000	2,293,200	4,004,000	7,280,000

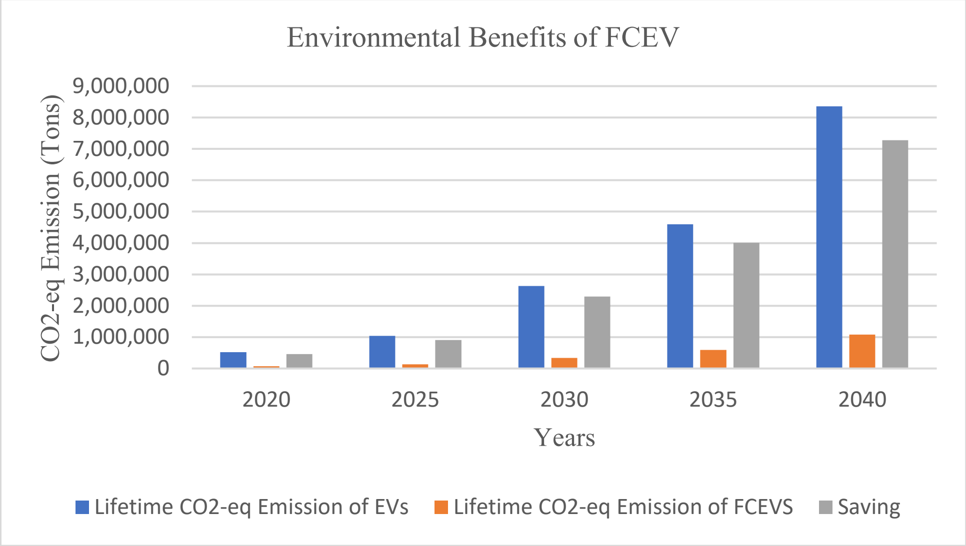

Figure 3: Environmental Benefits

4. Conclusion

Currently, the world is shifting towards becoming as emission-free as possible by finding any way to cut down on GHG emissions into the atmosphere. We have looked at various countries researching and developing their own renewable-energy generation facilities with the aim of having a greener society. One of the more recent findings is storing surplus energy in the form of hydrogen, which we can use for different applications. Our calculations have found that if we use the hydrogen generated in Canada by such means in Fuel Cell Electric Vehicles. The amount of CO2-eq emissions saved in tons as compared to typical Electric Vehicle being charged by conventional grids is 455, 500, 910,000, 2,293,200, 4,004,000, and 7,280,000 in the years 2020, 2025, 2030, 2035, and 2040, respectively. As such, by switching to FCEVs, we can reduce GHG emissions significantly; and thus, our move to a cleaner and safer environment becomes positively attainable.

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