SASTA OLIPHANT SCIENCE AWARDS

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Science Writing

Year 11-12

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Australian Government Department of Defence

Government of South Australia Department for Education

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The Applications and Limitations of PEM Hydrogen Fuel cells in the Electric Vehicle Industry

Introduction

According to the National Oceanic and Atmospheric Administration (NOAA), the year 2022 was the eleventh consecutive year carbon dioxide had increased by more than 2ppm, the highest sustained rate of increase in the 65 years since monitoring began (Figure 1) *(NOAA, 2023)*. This, in turn, has generated significant pressure on the transport sector to minimise its carbon emissions in order to maintain clean, sustainable transport systems. Therefore, a new technology is required to purify and potentially replace the used of the internal combustion engine, rectifying transportation of its greenhouse gas (GHG) emissions. Hydrogen fuel cells (HFCs) have the potential to meet these requirements, their high current density and carbon neutral characteristics allowing for more effective and sustainable power output. This investigation will discuss the practical applications and inherent limitations of HFC technology in the electric vehicle (EV) industry, considering the negative and positive impacts it has on society.

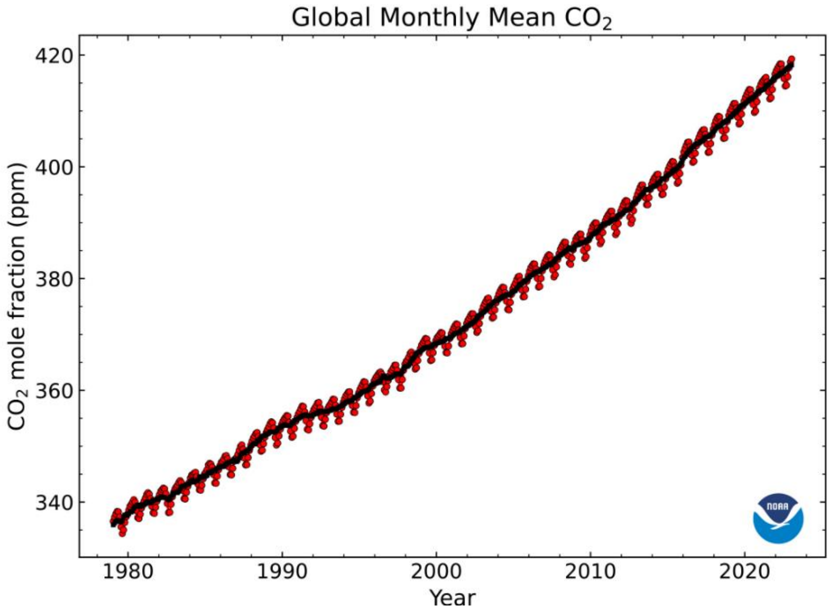

Figure 1: The average of monthly mean abundance of carbon dioxide (CO_2) over marine surface sites. The NOAA has measured carbon dioxide gases over the past several decades via a globally distributed network of air sampling sites *(NOAA, 2023)*. The graph shows a steady increase in the concentration of CO_2 gas since 1979, which has a strong correlation with global warming.

Chemical Background

Electrolysis is the process in which molecules are broken down into their individual chemical components via an electric current. There are three primary types of electrolysis, in which each can be distinguished according to the electrolyte they use: alkaline electrolysis, with a liquid electrolyte; high-temperature steam electrolysis, with a solid oxide electrolyte; and proton exchange membrane (PEM) electrolysis, with an acidic ionomer electrolyte. Although the underlying principles of all three are the same, proton exchange membrane electrolysis shows the greatest potential for EV applications *(Smolinka, 2009)*. PEM consists of the three main components: the membrane electrode assembly (composed of the membrane, cathode and anode); the gas diffusion layer; and the Bipolar (BP) plates (Figure 2). During the electrolysis process, water is electrochemically decomposed into hydrogen and oxygen. At the anode, the chemically broken-down substances undergo redox reactions, where oxygen molecules are reduced, and hydrogen molecules are oxidised *(Guo, 2023)*. An external circuit applying a potential difference is what drives the system, causing the diffusion of hydrogen ions (protons) towards the cathode via the proton exchange membrane. The PEM restricts the flow of negatively charged particles and oxygen molecules, thus the electrons exit from the anode through the external power circuit into the cathode. The oxygen molecules remain at the anode, where they can be collected for other uses. At the cathode, the electrons recombine with the protons to form hydrogen gas where it can then be used to fuel HFCs *(Giles, 2023)*.

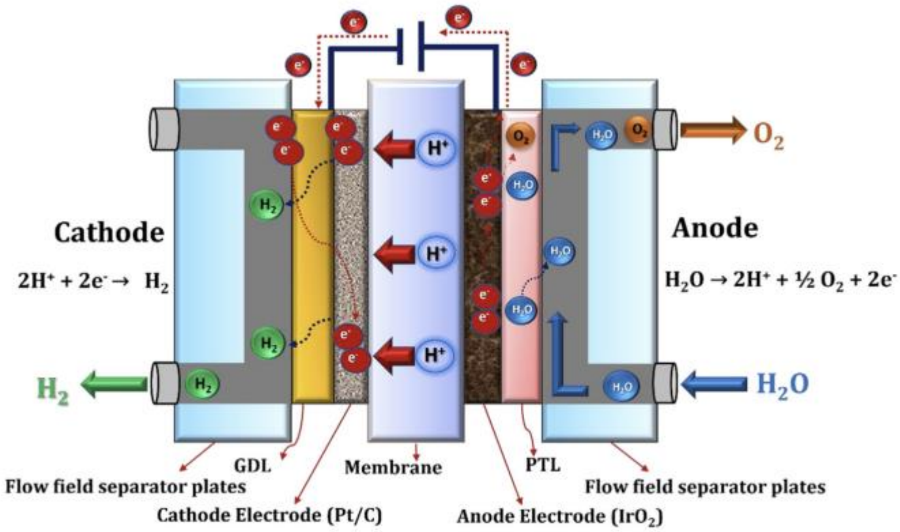

Figure 2: PEM electrolyser. The Porous Transport Layer (PTL) is an important component to the exchange membrane as it facilitates both the current distribution of electrons and mass transport for water molecules *(Brett, Iacoviello, 2018)*. Similarly, the bipolar plates (separator plates) ensure the proper distribution of the reactant particles and facilitate the flow of electrons. The Gas Diffusion Layer (GDL) is in direct contact with the hydrogen gas, acting as the channel for the gas to exit the electrolyser *(Hu, 2024; Du, Zhang, 2023)*.

PEM hydrogen fuel cells work in a very similar way to the PEM electrolyser, consisting primarily of an electrolyte membrane wedged in between the anode and cathode. During operation, the hydrogen fuel is fed to the anode, where it undergoes oxidation. This separates the electrons from the positively charged hydrogen nuclei, according to the half equation *(Barbir, 2005)*:

$$H_2 \rightarrow 2H^+ + 2e^-.$$

The PEM membrane, a typically thin, solid organic compound, only allows the positively charged protons to pass through, restricting the flow of negative charge. Thus, the electrons flow around the membrane through an external circuit forming an electrical current. At the cathode, the positively charged hydrogen ions undergo reduction according to the half equation:

$$2H^+ + 2e^- + \frac{1}{2}O_2 \rightarrow H_2O,$$

and goes on to combine with oxygen to form its only byproducts - water and heat (Figure 3) *(Barbir, 2005)*. Catalysts are used to facilitate the redox reactions at the cathode and anode and are typically composed of platinum particles uniformly supported on carbon particles to maximise its surface area. The electrodes are porous, allowing the molecules to pass through them via surface diffusion *(Office of Energy Efficiency & Renewable Energy, n.d.; Nishimura, 2001).*

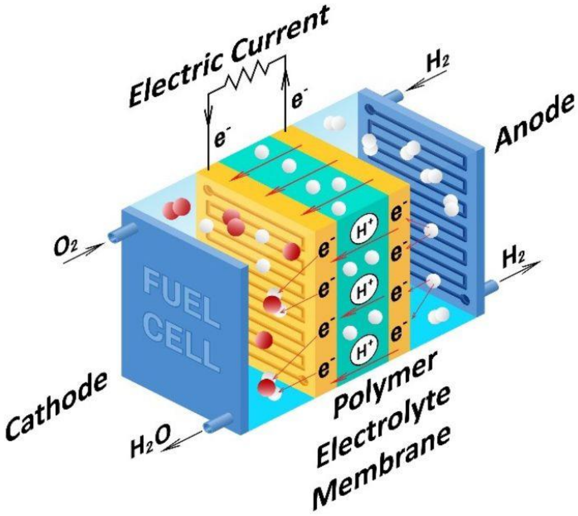

Figure 3: PEM hydrogen fuel cell. At the anode, as the hydrogen enters the fuel cell it decomposes into hydrogen ions and electrons. The ions pass through the proton conducting membrane whereas the electrons flow through an external circuit, producing an electric current. The oxygen molecules entering the cell via the cathode combines with the protons and electrons to generate heat and water (MathWorks, n.d.).

SHE: Applications and Limitations

The most successful deployment of hydrogen fuel cells is in the EV industry *(Wood, 2022)*. PEM HFCs provide several solutions to varying logistical challenges due to their wide operating temperatures that are easy to maintain, high current densities and great energy efficiencies *(Wang, Coa, et al, 2022)*. According to Enectiva, PEM cells possess an electrical system efficiency of 77% operating anywhere from 20 to 80 degrees Celsius, whereas alternative technologies such as alkaline electrolyser cells (AECs) (Figure 4) run up to 67% efficiency at operating temperatures ranging from 60 to 90 degrees. Thus, PEM offers greater fuel efficiencies that in turn allows EV's to travel farther with the same battery power *(unknown, n.d.)*.

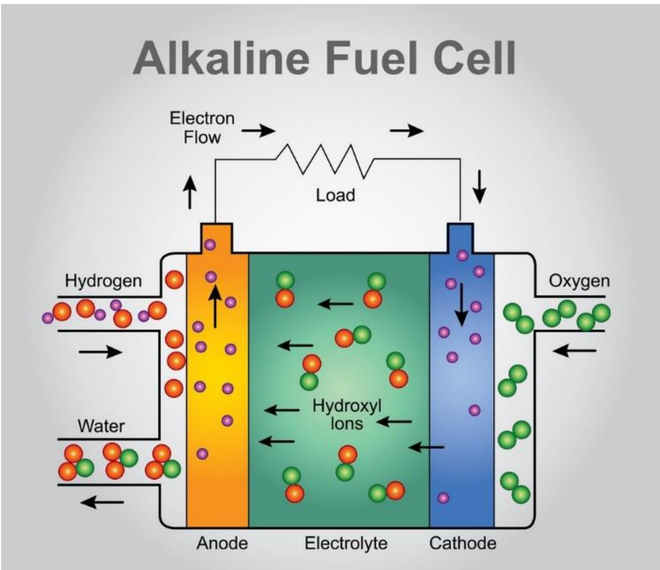

Figure 4: Alkaline Electrolyser Cell (AEC). AECs work very similar to PEM fuel cells, but instead of using a proton exchange membrane it utilises an aqueous solution of sodium hydroxide as the electrolyte. At the anode, the hydrogen undergoes oxidation, bonding with the hydroxyl ions in the electrolyte solution. Electrons are released and flow through the external circuit, generating an electric current (Tharad, 2024).

The robustness of PEM cells is further exemplified with its ability to generate a current density of $1A/cm^2$, 250% more than that of AECs *(Himabindu, Kumar 2019; Garra, 2023)*. This makes them suitable for high-power applications, which coupled with their small mass to volume ratios and suitable operating temperatures, have made PEM batteries the market leader in EV applications.

Since 1990, global carbon dioxide emissions from fossil fuels and industry have increased by over 60 percent. In 2022, it totalled 37.15 billion metric tons, of which 10 percent was credited towards vehicle emissions (Figure 5) *(Tiseo, 2024; Tiseo, 2023).* The increased concentration of carbon dioxide in the atmosphere disrupts the natural greenhouse effect, leading to rising global temperatures and contributing to global warming *(Lindsey, 2024)*. Therefore, through its implementation into the electric vehicle industry, HFCs play a critical role in reducing carbon emissions to develop a sustainable and carbon-neutral transport sector. It acts as the 'stepping stone' for the world to veer away from fossil fuels and lay more dependent on renewable energies, enhancing the resilience of vulnerable power grids (particularly in rural areas) and support economic development by providing more job opportunities *(Fletcher, 2024)*.

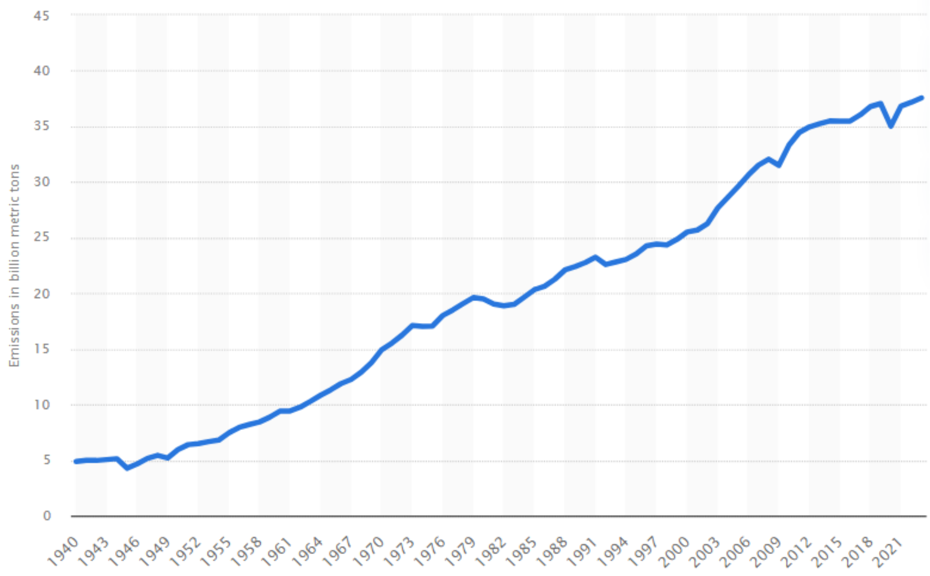

Figure 5: Annual carbon dioxide emissions worldwide from 1940 to 2023 *(Tiseo, I., 2024)*. The increase of carbon dioxide in the atmosphere (in billion metric tonnes) is the result of the burning of fossil fuels in both industrial and transport sectors *(NASA, n.d.)*.

According to the Union of Concerned Scientists (UCS), under California's renewable hydrogen requirements, hydrogen-powered fuel cell electric vehicles (FCEVs) have the potential to reduce over 50 percent of the fumes generated from existing gasoline vehicles *(Union of Concerned Scientists, 2014)*. A Life Cycle Assessment (LCA) of FCEVs were done to compare its energy and associated environmental impacts to conventional internal combustion engine vehicles (ICEVs). The assessment found that the energy consumption and GHG emissions during the fuel cycle of hydrogen were higher than that of the fuel cycle of gasoline, whereas during the vehicle cycle, the energy consumption and GHG emissions of the ICEV were significantly higher than that of the FCEVs. Nonetheless, it was concluded that the FCEVs overall life cycle energy consumption was roughly 2.3 times less than that of the ICEV and its overall greenhouse gas emissions 2.6 times lower *(Dincer, Hussain, 2010)*. The application of hydrogen fuel cells in the power generation systems of EV's may pave the way for an environmentally sustainable future, providing the opportunity to mitigate the effects of climate change by reducing GHG emissions.

Despite the potential for HFC technology to address several environmental challenges, the economic burdens associated with the production of hydrogen fuel stacks, specifically the electrodes and bipolar plates, require extensive considerations. The catalysts that coat the electrodes must be highly resistant to corrosion due to the strong acidic conditions within the cell, thus they consist of precious metals such as platinum, iridium and rutherfordium. In comparison to AECs, which utilise nickel-based water electrolysers, the exorbitant cost of these precious metals makes PEM electrolysis a significantly higher investment *(Wang, Coa, et al, 2022; Ang, 2024)*. Similarly, the titanium substrate and noble-metal coatings used to products the BPs are expensive, accounting for more than one-third of the electrolysis stack cost *(Hu, Liu, et al, 2024)*. This has significant implications on the production cost of hydrogen fuel, thus significantly reducing the succession of HFCs in its integration into the EV market as both consumers and manufacturers may opt out for better fuel and vehicles prices with alternative battery and/or combustion technology.

Currently, the lack of hydrogen infrastructure required to support FCEVs provides another major hurdle for further developments *(Dell, Rand, 2014)*. To support its commercial use in EVs, reliable, low-cost hydrogen distribution networks must be constructed. However, only limited pipeline networks exist in certain regions of the world, with most used to supply hydrogen to the refining industry *(Hu, 2024)*. Although the adaptation of these existing infrastructures to distribute the fuel could reduce this problem, the arrangement does not constitute a cohesive network for the supply of hydrogen gas. Additionally, the safe handling and long-term storage of hydrogen gas presents further obstacles. The metal cylinders used to store the hydrogen gas can deteriorate over time due to hydrogen embrittlement, leading to potential leaks. As hydrogen is a highly combustible gas, when mixed with the atmosphere it can ignite and explode, causing damage to surrounding structures and people *(Bhat, Meda, 2023)*.

While the environmental and energy prospects of HFCs may justify their application, it is crucial to conduct further scientific testing on catalysts to synthesis new compounds that minimise costs; and pool resources together to build and expand the hydrogen distribution networks for more efficient hydrogen storage and delivery as it continues to develop and become more commercially viable.

Conclusion

The application of hydrogen fuel technology in the EV industry is expanding globally as the need for environmentally friendly, robust, power generation systems remain. Scientific knowledge and understanding of electrolysis processes have enabled scientists to develop sustainable solutions, evaluating the economic and environmental impacts of HFCs to mitigate the effects of global warming and promote power efficiency. The limitations of hydrogen fuel cells, such as economic costs and lack of infrastructure, hinder its implementation into the EV market, but also provide opportunities for innovation and development of new electrochemical catalysts and fuel stack structures. Despite the challenges, hydrogen technology offers considerable improvements in robustness and sustainable power output, revolutionising the automotive industry and carrying a positive outlook for the future.

Word Count: 1583 (including in-text referencing)

References

Ang, C., 2024, *"Researchers develop a low-cost catalyst for green hydrogen production",* https://phys.org/news/2024-01-catalyst-green-hydrogen-production.html#:~:text=However%2C%20a%20challenge%20in%20advancing,rare%20and%20expensive%20in%20nature, accessed on: 11th Jun. 2024

Barbir, F., 2005, *"Fuel Cell Basic Chemistry and Thermodynamics",* https://www.sciencedirect.com/topics/engineering/fuel-cell-reaction#:~:text=The%20fuel%20cell%20reaction%20of,cell%20to%20drive%20a%20load, accessed on: 10th Jun. 2023

Bhat, N., Meda, U., Pandey, Raj, M., A., Subramanya, K., 2023, *"International Journal of Hydrogen Energy", Volume 48, pg. – 17894-17913,* https://www.sciencedirect.com/science/article/abs/pii/S036031992300530X#:~:text=Storing%20hydrogen%20in%20metal%20cylinders,is%20therefore%20a%20safety%20concern, accessed on: 12th Jun. 2024

Brett, D., Iacoviello, F., Majason, J., Shearing, P., 2018, *"Energy Procedia", pg. 111 – 119,* https://www.sciencedirect.com/science/article/pii/S1876610218305770#:~:text=The%20porous%20transport%20layer%20(PTL,current%20distribution%20and%20mass%20transport, accessed on: 13th Jun. 2024

Cao, X., Jiao, L., Wang, T., 2022, *"PEM Water electrolysis for hydrogen production: fundamentals, advances, and prospects",* https://link.springer.com/article/10.1007/s43979-022-00022-8, accessed on: 10th Jun. 2024

Dell, R., Rand, D., 2014, *"Hydrogen, Fuel Cells and Fuel Cells Vehicles",* https://www.sciencedirect.com/topics/engineering/hydrogen-infrastructure#:~:text=The%20lack%20of%20a%20hydrogen,that%20service%20present%2Dday%20automobiles, accessed on: 12th Jun. 2024

Dincer, I., Hussain, M., 2010, *"Electric and Hybrid Vehicles", pg. 275-286,* *https://www.sciencedirect.com/science/article/abs/pii/B9780444535658000117, accessed on: 11th Jun. 2024*

Du, X., Zhang, Z., 2023, *"A review of the Al-gas batteries and perspectives for a 'Real' Al-air battery",* https://www.sciencedirect.com/topics/engineering/gas-diffusion-layer, accessed on: 13th Jun. 2024

Fletcher, C., 2024, *"The Social Impact of Renewable Energy Initiatives", https://earth.org/the-social-impact-of-renewable-energy-initiatives/, accessed on: 26th Jun.2024*

Garra, B., 2023, *"Comparison of the various kinds of electrolyzers for hydrogen production",* https://www.enectiva.cz/en/blog/2023/08/comparison-of-the-various-kinds-of-electrolyzers-for-hydrogen-production/, accessed on: 10th Jun. 2024

Giles, T., 2023, *"Gaseous versus Liquid Hydrogen Storage",* https://powertorque.com.au/gaseous-versus-liquid-hydrogen-storage/#:~:text=Most%20hydrogen%20FCEVs%20operating%20today,pressures%2C%20namely%20H35%20and%20H70, accessed on: 10th Jun. 2024

Guo, Z., 2023, *"PEM (Proton Exchange Membrane) Water Electrolysis Membrane",* https://www.linkedin.com/pulse/pem-proton-exchange-membrane-water-electrolysis-technology-guo-3ifhe#:~:text=During%20the%20PEM%20water%20electrolysis,and%20electrons%20(e%E2%88%92), accessed on: 6th Jun. 2024

Himabindu, V., Kumar, S., 2019, *"Hydrogen Production by PEM water electrolysis – A review", pg. 442 -454,* https://www.sciencedirect.com/science/article/pii/S2589299119300035, accessed on: 6th Jun. 2023

Hu, L., 2024, *"How are the metallic bipolar plates used for PEM fuel cell stacks?", https://www.linkedin.com/pulse/how-metallic-bipolar-plates-used-pem-fuel-cell-stacks-lydia-hu-uzexc#:~:text=Bipolar%20plates%20for%20PEM%20fuel,electrons%20to%20generate%20electrical%20energy, accessed on: 25th Jun. 2024*

Hu, M., Liu, T., Shao, J., Tao, Y., Wang, Y., Zhang, Z., 2024, *"Fuel", Volume 368,* https://www.sciencedirect.com/science/article/abs/pii/S0016236124007580#:~:text=As%20one%20key%20component%2C%20the,the%20PEM%20electrolysis%20stack%20cost, accessed on: 11th Jun. 2024

Lindsey, R., 2024, *"Climate Change: Atmospheric Carbon Dioxide",* https://www.climate.gov/news-features/understanding-climate/climate-change-atmospheric-carbon-dioxide#:~:text=By%20adding%20more%20carbon%20dioxide,causing%20global%20temperature%20to%20rise, accessed on: 11th Jun. 2024

MathWorks, n.d., *"What Is A Fuel Cell Model?",* https://nl.mathworks.com/discovery/fuel-cell-model.html, accessed on: 13th Jun. 2024

National Aeronautics and Space Administration (NASA), n.d., *"Carbon Dioxide",* https://climate.nasa.gov/vital-signs/carbon-dioxide/?intent=121#:~:text=At%20a%20larger%20scale%2C%20the,primarily%20from%20burning%20fossil%20fuels, accessed on: 13th Jun. 2024

National Oceanic and Atmospheric Administration (NOAA), 2023, *"Greenhouse gases continued to increase rapidly in 2022",* https://www.noaa.gov/news-release/greenhouse-gases-continued-to-increase-rapidly-in-

2022#:~:text=The%20main%20driver%20of%20increasing,the%20Global%20Carbon%20Project%20%2C%20which, accessed on: 12th Jun. 2024

Nishimura, s., 2001," Handbook of Heterogeneous Catalytic Hydrogenation for Organic Synthesis", pp. 43-44, https://en.wikipedia.org/wiki/Platinum_on_carbon, accessed on: 10th Jun. 2024

Office of Energy Efficiency & Renewable Energy, n.d., *"Fuel Cell Animation (Text Version)",* https://www.energy.gov/eere/fuelcells/fuel-cell-animation-text-version, accessed on: 6th Jun. 2024

Smolinka, T., 2009, *"FUELS – HYDROGEN PRODUCTION | Water Electrolysis", https://www.sciencedirect.com/topics/engineering/water-electrolysis#:~:text=Three%20main%20technologies%20can%20be,used%20in%20the%20electrolysis%20cell%3A&text=alkaline%20electrolysis%2C%20with%20a%20liquid%20electrolyte%3B&text=polymer%20electrolyte%20membrane%20(PEM)%20electrolysis,solid%20polymer%20electrolysis%20(SPE)%3B, accessed on: 26th Jun. 2024*

Tiseo, I., 2023, *"Light-duty vehicle carbon dioxide emissions worldwide 2010-2022",* https://www.statista.com/statistics/1388092/carbon-dioxide-emissions-cars-vans-transport/#:~:text=Cars%20and%20vans%20account%20for%20around%2010%20percent%20of%20global%20CO%E2%82%82%20emissions,accessed on: 11th Jun. 2024

Tiseo, I., 2024, *"Annual global emissions of carbon dioxide 1940-2023",* https://www.statista.com/statistics/276629/global-co2-emissions/, accessed on: 10th Jun. 20244

Union of Concerned Scientists, 2014, *"How Clean Are Hydrogen Fuel Cell Electric Vehicles",* https://www.ucsusa.org/sites/default/files/attach/2014/10/How-Clean-Are-Hydrogen-Fuel-Cells-Fact-Sheet.pdf, 11th Jun. 2024

Tharad, V., 2024, *"HYDROGEN FUEL BASICS, DIFFERENT TYPES OF FUEL CELL FOR TRANSPORTATION, ELECTRIC VEHICLE APPLICATION AND ELECTRIC POWER GENERATION",* https://www.linkedin.com/pulse/hydrogen-fuel-basics-different-types-cell-electric-vehicle-tharad-kazvc, accessed on: 26th Jun. 2026

unknown, n.d., *"Understanding The Range & Efficiency Of Electric Vehicles",* https://www.recharged.com/understanding-range-and-efficiency/#:~:text=Efficiency%3A%20An%20EV's%20efficiency%2C%20or,%2C%20terrain%2C%20and%20driving%20habits, 10th Jun. 2024

Wood, J., 2022, *"Which countries could become the world's hydrogen superpowers?",* https://www.weforum.org/agenda/2022/02/clean-hydrogen-energy-low-carbon-superpowers/, accessed on: 10th Jun. 2024