Hydrogen Energy: Path Toward Decarbonizing the Transportation Sector

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Abstract

Over the last century, the world's dependence on fossil fuels caused significantly high greenhouse gas emissions, ultimately leading to global warming. The transportation sector has a critical impact on the increase in greenhouse gas levels in the atmosphere. Various technologies for decarbonization are investigated to mitigate global warming. For transportation, hydrogen is a promising sustainable energy option and has the potential to replace fossil fuels. As long as hydrogen production involves clean procedures, it can be classified as a low-carbon fuel. This paper aims to discover the role of hydrogen in the transition to a sustainable transport system. It explores hydrogen-powered vehicles and their ability to reduce fossil fuel consumption, particularly in the transportation sector. The paper discusses the advantages hydrogen has over fossil fuels but also acknowledges the possible drawbacks of the technology regarding the material requirement and cost. In addition, this paper explores different methods of producing energy using hydrogen and provides examples of real-life applications of the technology. Besides the technological aspect, this paper recognizes the sociopolitical aspects regarding the method and highlights the importance of making the right policies alongside technological advancements to maximize the potential of hydrogen energy.

1 Introduction

Global warming has been a major threat to life on Earth since the Industrial Revolution. Despite being a period of advancement and economic growth, the Industrial Revolution was at the expense of the environment and led to an "ever-expanding" system. [Sza20] As global energy demand increased with the development of various industries, the systems became dependent on fossil fuels for energy to power their work. Indeed, approximately 95% of the global energy demand is met by oil, coal, and natural gas. [ea20] Especially in the transportation sector, there is a high energy demand which is mostly satisfied by fossil

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fuels. Globally, about 80% of the energy is supplied by fossil fuels in transportation. Although their accessibility, efficiency, and low cost demonstrate them to be convenient sources of energy, fossil fuels have several disadvantages that indicate the need for a transition to renewable sources. Despite seeming abundant, fossil fuels have limited reserves and are not renewable, implying that they cannot be relied on. Moreover, the substantial volume of greenhouse gas emissions produced through their combustion has triggered human-induced climate change and remains a contributing factor to it.

Since the transportation sector accounts for a major part of the global energy demand, numerous innovations have emerged to decarbonize the industry, seeking alternatives to traditional fossil fuels. While oil has historically fueled the sector, there is a growing acknowledgment of the significance of transitioning to renewable energy and electrification. One of the solutions proposed is utilizing hydrogen energy to power vehicles. Being the most abundant element in the universe, hydrogen holds the potential to be an alternative to fossil fuels with its multiple advantages. Its high energy density makes it an efficient fuel and unlike conventional cars which rely on fossil fuels, hydrogen-powered vehicles do not have harmful emissions and their only byproduct is water. In addition, hydrogen provides energy security since it can be produced domestically, eliminating the dependence on importing fossil fuels for energy. [ea20]

Although its potential to assist a low-carbon energy system has been recognized very early on in history, it could not commercialize due to the challenges in its production. It is rarely found in its pure form in the environment and exists in compound forms; therefore, it needs to be separated from other substances before being ready for use. Currently, about 96% of hydrogen comes from the steam reforming method, which depends on using natural gas and has significant carbon dioxide emissions. [ea20] Thus, to be able to view hydrogen as a zero-carbon alternative, sustainable methods should be followed. Although different methods of sustainable production are being researched, many of them have not reached the stage of application besides electrolysis. [ea20] After production, hydrogen can be applied to the transportation sector in different ways. It can be used in internal combustion engines, which can be advantageous for the transition because it does not require extensive infrastructure. Another method of using hydrogen is through fuel cell electric vehicles. Fuel cell vehicles create the opportunity to use vehicles with zero harmful emissions. When they generate power, fuel cells only produce water. Furthermore, they have high efficiencies and can convert energy much more productively than a vehicle with a combustion engine. While multiple companies produce various hydrogen-powered vehicle models, the path to commercialization has proven to be elusive. The main impediments are associated with the high cost of hydrogen's production and the inadequacy of the required infrastructure. Therefore, it is crucial to enforce the right policies and regulations to support the development of technology and make it more accessible globally. Currently, in the energy industry, firms continue to prioritize profit over as shown with the recent earning reports of top fuel companies, in which their profit is shown to increase significantly over the course of last year. Yet, as the destructive impacts of global warming demonstrates, maintaining this system where profit is the priority is not sustainable. In literature, the policies and strategic plans of different nations regarding hydrogen technology have been reviewed. However, studies that discuss both the technical aspect and the role of the currently dominant economic model, capitalism, on its implementation are scarce. In the scope of this paper, hydrogen's potential to mitigate global warming by decarbonizing the transportation sector is investigated, particularly through fuel-cell vehicles. In addition, the impact of economic approaches on the effectiveness of hydrogen technology are briefly discussed. First, the potential of hydrogen as an element is introduced, including its advantageous features as well as its drawbacks. Then, the fuel cell technology is explained, which is followed by the comparison of different types of vehicles based on their energy source. After, examples of fuel cell vehicles are given from real-life companies and their applications are discussed. Finally, the role of policies and economic systems in the advancement of this technology is recognized.

2 Background Information

2.1 Production of Hydrogen

Hydrogen energy holds promise for the future of the sustainable transportation sector. Unlike fossil fuels, using hydrogen to power a vehicle only emits water as a by-product. This property of hydrogen makes it a great candidate for the net-zero carbon goal. However, hydrogen can be a clean energy source only if the procedures it goes through to be available for use are completed sustainably, similar to electricity. [AD20] These steps include production, storage, and delivery.

There are various ways of producing hydrogen from both renewable and nonrenewable sources. Although renewable technologies are progressively being developed and should be prioritized for decarbonization, more than 95% of hydrogen is provided from fossil fuels. With steam methane reforming, methane coming from natural gas and steam are reacted under really high temperatures to create hydrogen. Through this process, 10 kg of CO2 is emitted per kilo of hydrogen. [BL22] Yet, it is still favored by the industry due to its low cost, despite its dependence on limited and decreasing resources. In addition to natural gas, coal is utilized in the production of hydrogen. Through the method called coal gasification, coal is converted into syngas, which is composed of carbon monoxide and hydrogen. [ea20] To differentiate these greenhouse gas emitting methods, the hydrogen produced from fossil fuels is referred to as "grey hydrogen." [ea21d] To sustain the utilization of these production methods, it is crucial to mitigate their adverse environmental effects. To achieve this objective, they can be combined with various carbon capture and storage (CCS) techniques. When the process is decarbonized, the resulting hydrogen is labeled as "blue hydrogen." [BL22] Although it can be viewed as a solution in the short term, it is not viable for long-term application. [ea21d]

Therefore, technologies for producing hydrogen from renewable resources should be adopted to avoid any harmful emissions from the beginning and produce what is called ”green hydrogen.” Although there are multiple ways of generating green hydrogen, electrolysis is considered to be the most promising method among them. [ea21b] With electrolysis, water is broken down into its components, oxygen and hydrogen, with electricity. However, the source of electricity is critical to be able to label this technology sustainable. For the produced hydrogen to be ”green”, the electricity must be generated through renewable sources like solar and wind. [BL22] Yet, to rely on this method to replace nonrenewable techniques and be commercialized, its cost should be reduced. Fortunately, with the decrease in the cost of renewable electricity production and limited fossil fuel reserves, the cost is expected to get lower soon. [ea21d] Biomass gasification is also recognized to be an alternative solution to produce green hydrogen. In this process, biomass is reacted with steam and oxygen to form carbon monoxide, carbon dioxide, and hydrogen. With further research and development, biomass gasification can be a promising method in the future. There are various other technologies for green hydrogen production, from using photo-electrochemical cells to different biological methods, as included in Table 2. Yet, the majority of these are still in the stage of development and not ready to be commercialized. [ea20]

Method of Production	Explanation	Status of Technology
Steam Methane Reforming	Through the use of heated steam, hydrogen is extracted from natural gas.	Mature
Coal Gasification	Under high pressure, coal is reacted with hydrogen (H2), oxygen (O2) and steam, and a mixture of carbon monoxide and hydrogen is formed. The process is further followed by the reaction of the carbon monoxide and steam to produce additional hydrogen.	Mature
Electrolysis	With this endothermic process, electric energy is used for splitting water into its components, oxygen and hydrogen. The electricity can be provided from different resources, particularly from renewables to make the process sustainable.	Mature

Method of Production	Explanation	Status of Technology
Photo-electrochemical Decomposition	With a two-electrode setup where one is the anode producing oxygen and the other is the cathode producing hydrogen, water is split using sunlight.	Early R&D
Biomass Gasification	In a gasifier, biomass is chemically broken down with steam, heat and oxygen. Then, through a water gas shift reaction, the existing carbon monoxide (CO) is turned into carbon dioxide (CO2) and hydrogen (H2).	R&D
Pyrolysis	Under high temperatures in the absence of oxygen, biomass is transformed into bio-oil, various gases including hydrogen, and solid products.	Early R&D
Photo-electrolysis	Semiconductors in a photoelectrochemical cell are used as photocatalysts. The photocatalysts absorb the solar energy to induce an electric charge across the semiconductor and the electrolyte which is used for splitting water molecules.	Early R&D
Thermolysis	Heat is used to break down water molecules in a single step reaction under high temperatures.	Early R&D
Photofermentation	Photosynthetic bacteria's ability to produce hydrogen without oxygen inhibiting the process is utilized. Bacterias use organic waste as substrates to convert light energy into hydrogen through different processes.	Early R&D

Method of Production	Explanation	Status of Technology
Dark fermentation	Using anaerobic bacteria that is grown in the dark on carbohydrate-rich substrates, carbohydrates are fermented to produce hydrogen gas alongside acetic and butyric acids.	Early R&D

Table 1: Different Technologies Used for Hydrogen Production [ea20] [ea23b]

2.2 Challenges of Hydrogen Technology

2.2.1 Transportation

Besides production, there are other challenges to overcome before making hydrogen available for use in the transport sector. Many of the properties of hydrogen described as advantageous also have consequences to manage. Despite its high mass-based energy density, the low volumetric density of hydrogen makes it difficult to transport because it requires containers with large volumes to carry the same amount of energy as other fuel sources. The pressure and temperature conditions are also important to consider while choosing a method of transportation. [oE20] The transportation technologies differ according to the physical state hydrogen is in while being carried. [ea21b] The most suitable transportation method is selected according to various factors: the distance of travel, amount of hydrogen, size of refueling stations, the quantity of demand, etc. [BL22] To prevent inefficiencies and material losses resulting from physical and chemical features of hydrogen, the use of high-quality materials is vital to the process. [HB19] Using pipelines for long distances and trucks for short distances are the most commonly used methods. [ea21b] Considering railcars, barges, and ships are also suggested as an alternative to trucks to carry larger amounts. [oE20] Establishing suitable infrastructure for hydrogen delivery, alongside the implementation of varied transportation procedures, holds equal significance. [HB19] The existing infrastructure of networks and pipelines for transporting natural gas is also recognized to have the potential to be used for hydrogen transportation. [oE20] Yet, there are additional modifications required to enable hydrogen transportation. [BL22]

2.2.2 Storage

As mentioned, hydrogen's high mass-based energy density makes it an ideal alternative to fossil fuels. [ea21d] However, many aspects of creating a sustainable transportation sector by drifting away from fossil fuels rely on finding efficient and safe ways of storing hydrogen. [HB19] To make methods of storage commercially available, various pathways are being tested out. However, several characteristics of hydrogen keep the process of finding safe, durable, and efficient technologies challenging. [ea21b] Similar to its transportation, hydrogen can be stored in three different physical forms with various physical and chemical storage technologies. [ea22a] The physical storage includes compressing gaseous hydrogen into containers, using cryogenic systems with very low temperatures to store hydrogen in its liquid form, and using adsorption to store it within different materials. Storing hydrogen with a physical procedure also keeps it in a state ready for use. [HB19] For chemical storage, hydrogen can be chemically bonded with different hydrogen carriers like ammonia, methanol, or formic acid. [BL22] In addition, with chemisorption, it can be adsorbed. These processes require additional steps to reverse the reaction and release the hydrogen. [ea22a] Among the most common strategies is using cylinders and tanks for storing hydrogen in either gaseous or liquid form. [oE20] Although commercially used, both of them are relatively inefficient. [HB19] Due to its low energy density, gaseous hydrogen requires high pressures to be compressed or very low temperatures to be liquified with cryogenic systems. Both of these processes are significantly energy intensive and increase the costs of hydrogen storage due to energy and material demands. [ea22a] [ea21b] Additionally, the materials for the tank should be able to prevent leakage with strong bonds [ea22a] and allow hydrogen release with fast-release charge kinetics. Besides the technical challenges, the idea of using vehicles that contain high-pressure tanks is a potential concern in the eyes of the user. [HB19]

Metal hydrides are shown to have multiple advantages for storing hydrogen in a solid state and are most commonly used. With hydrogenation, hydrogen, and a metal can react to create metal hydrides. Their higher storage density, higher volume, and better safety make them a good candidate for use in fuel cell vehicles. [ea21b] Yet attention needs to be paid to the type of metal used to ensure that the hydrogenation is reversible. To keep this process efficient and cost-effective, hydrogenation should not have high energy demands for dehydrogenation. [BL22] Different types of porous nanomaterials are also investigated, as they allow easy and reversible adsorption and desorption of hydrogen. Unlike cryogenic systems, this procedure does not have intense energy requirements and can be carried out more efficiently. [oE20]

Geological storage is a favorable option for storing large amounts of hydrogen for long periods, and it can be achieved in multiple ways. "Salt caverns, saline aquifers, depleted natural gas or oil reservoirs, and engineered hard rock reservoirs" can be promising spots for hydrogen. [oE20] In addition, storing hydrogen underground makes it possible to store it in large volumes. Yet, it is also important to keep in mind that there are limited places available for this method, since not everywhere has the proper conditions for geological hydrogen storage. [BL22]

2.3 Application of Hydrogen for Transportation

The most common ways of using hydrogen in transportation is in internal combustion engines and fuel cell vehicles.

2.3.1 Hydrogen-Fueled Internal Combustion Engines (H2ICE)

Vehicles with internal combustion engines make up the majority of the current transportation industry. However, this method relies on liquid fossil fuels like diesel and gasoline for energy that cause high amounts of greenhouse gas emissions. [HB19] Hydrogen-fueled internal combustion engines can be an alternative to this fossil fuel-dependent technology, for one they have similar processes and structures as the engines of conventional vehicles. Therefore, they can be introduced to the market and spread easily. [ea22b] Unlike conventional vehicles, hydrogen-fueled combustion engines have low emissions, although not zero due to potential nitrogen oxide emission, and better efficiency. [St1] Several characteristics of hydrogen also make it advantageous for internal combustion engines. Compared to conventional vehicles, hydrogen-fueled internal combustion engines can be powered with lean mixtures of fuel. [HB19] In addition, Hydrogen's high auto-ignition temperature improves the efficiency of the engine. Also, since hydrogen can diffuse easier than natural gas and gasoline, it can both reduce the safety concern in case of leakage and allow a faster homogeneous fuel and air mixture formation. [AD20] The application of hydrogen-fueled internal combustion engines can be promising for increasing efficiency. [St1] However, various disadvantages come among these benefits. The risk of unwanted combustion, like pre-ignition, can decrease the engine's efficiency, although there are methods that can reduce this risk. [AD20] Additionally, larger volumes for storage are necessary for hydrogen-fueled internal combustion engine vehicles to achieve similar driving ranges to conventional vehicles. [HB19] To become widespread, hydrogen-fueled internal combustion engine vehicles require more research and development. [St1]

2.3.2 Hydrogen Fuel Cells (HFC)

Hydrogen fuel cells can have a significant role in the transition into clean energy in transportation. In brief, they are devices made of an anode, cathode, and an electrolyte membrane that can produce a flow of electricity from an electrochemical reaction, as illustrated in Figure 2. Vehicles with hydrogen fuel cells

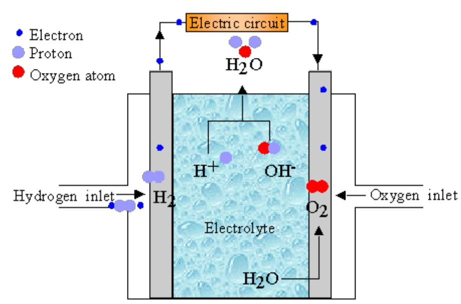

Figure 1: A schematic of the basic fuel cell components. [oC]

are powered by converting hydrogen's chemical energy into electricity and emit water only as the byproduct, making them a zero-emission technology. [ea22b] Still, they are capable of having similar driving ranges as conventional vehicles with internal combustion engines. [AH19] In terms of efficiency, Fuel cell vehicles (FCVs) exceed conventional vehicles and are among the most efficient vehicles. Similar to battery electric vehicles (BEVs), hydrogen fuel cell vehicles also use electricity to power the vehicle. However, FCVs exceed BEVs in many aspects. Firstly, fuel storage is more efficient and more convenient in terms of required space in FCVs, since they don't need a lithium-ion battery to store the energy. [ea22b] Besides, FCVs have a higher driving range, which makes them the better choice to travel for long distances. [ea18] Furthermore, refueling time for FCVs is much shorter than for BEVs, requiring only minutes instead of getting charged for hours. In terms of their environmental impact, BEVs can be disadvantageous due to the need to replace the battery every once in a while, despite the amount of usage. The batteries also become a waste source at the end of their life cycle. [ea22b] Despite their notable benefits that particularly become evident when assessed against other alternatives to conventional vehicles, FCVs are yet to be commercialized due to several reasons including the financial aspect, infrastructure need, and required policy framework. [AH19] The current cost of FCV production is quite high due to their advanced technology and expensive material demand. [ea18] Thus, they are unable to compete with the existing alternatives. [AH19] In addition, the infrastructure for FCV deployment is insufficient and requires investment.

3 Research Findings

3.1 Comparison of Different Vehicles Based on their Fuel Source

There are various parameters to consider when comparing vehicles with different sources of fuel. In this section of the paper, BEVs, FCVs, and ICEVs are compared to assess their overall application in the transportation sector and highlight the leading technology for creating a sustainable transportation sector. The parameters used for the vehicle comparison are their energy efficiency, performance and durability, ownership cost, and environmental impact.

3.1.1 Efficiency

The fuel type's efficiency varies according to the conditions of driving and the purpose the vehicle serves. For example, the advantage of powering a heavy-duty vehicle with a hydrogen fuel cell is not the same as a hydrogen fuel cell passenger car. In addition, to decide the leading vehicle type in efficiency, all aspects of the process need to be considered, including fuel production efficiency, energy conversions, and engine efficiency. This section aims to provide an overall sense of vehicle efficiency based on their fuel and operation technology. Therefore, multiple studies are combined to present a comprehensive evaluation. Overall, ICEVs have the poorest performance and are the least efficient option due to the energy lost while converting. [AD20] According to Wang et al, their thermal efficiency is found to be around 20%. [ea18] While operating, fuel cells have high efficiencies which is around 60% because they can benefit more from their fuel with their success in converting it. [ea21c] Yet when the whole process of using a hydrogen fuel cell is considered, including the production and transportation of hydrogen, the efficiency decreases. BEVs on the other hand are also found to be more efficient than ICEVs and they can be advantageous since they don't include the efficiency loss in HCVs during hydrogen's transportation. [ea22b] Yet, as mentioned earlier, the efficiency varies based on the type of vehicle, and there are multiple parameters to consider before concluding the decision.

3.1.2 Performance and Durability

A vehicle's performance is influenced by many of its properties. A lightweight vehicle is advantageous because it provides better fuel economy by decreasing the energy required throughout the vehicle's lifecycle. By being lighter and more compact than batteries, FCVs stand out compared to BEVs, especially for their use for heavier vehicles like trucks and buses. [ea21c] The size and weight of a BEV's battery can create concerns for their purchase since it will influence the car's operation. Another aspect to consider is the refueling time of the vehicle. Although BEVs can be advantageous in some ways, they require a long time to get refueled. In contrast, FCVs can be refueled in minutes, making them more suitable for urban use. [ea22b] Additionally, FCVs have a high driving range, especially compared to BEVs. Although some BEVs can exceed the usual standards of a BEV driving range, they are economically not feasible, and the majority of the affordable BEVs remain with shorter driving ranges. [Ü9] However, FCVs do not face this issue and can be the sustainable option for traveling long distances. According to the study of Acar and Dincer, 2020, between different types of vehicles including hybrid, biofuel, conventional, FCV, and H2ICE, electric vehicles have the poorest driving range, as demonstrated in Figure 2. [AD20] These advantages of FCVs enable them to compete with ICEVs in terms of performance where BEVs remain deficient.

3.1.3 Environmental Impact

The environmental impact of the overall transportation sector is one of the key drivers of developing sustainable alternatives. Conventional vehicles that rely on diesel and gasoline for fuel have long existed. However, among their alternatives, they have the highest negative environmental impact in terms of their greenhouse gas emissions. According to the studies of Onat et al. and Reichmuth et al., conventional vehicles release 21.40 kg of GHGs per 100 km. For BEVs, this number is 11.40 kg per 100 km, and for FCVs, it is 7.10 kg per 100 km. [AD20] Besides carbon dioxide, the emissions of internal combustion engines also cause other harmful gases to form like nitrogen and sulfur oxide. Unlike conventional vehicles, FCVs are considered zero-carbon vehicles when the hydrogen production process is done in sustainable ways as well. [ea21c] The resource demand of vehicles creates an additional burden on the environment. ICEVs are dependent on the limited fossil fuel reservoirs of the world. Although fossil fuels are easy to procure compared to other fuel sources, their increasing consumption makes them harder to reach. In other terms, what once was a "low-hanging fruit" becomes harder to obtain. Thus, intensive methods with high negative environmental impact become necessary. However, BEVs come across a similar problem as well in the production of the batteries. The batteries include environmentally harmful materials that can bring up problems especially when they need to be discarded after being used for a while. [ea21c] In addition, lithium, the main material of lithium-ion batteries, is also limited in its availability, which can cause issues as the use of BEVs increases. [Ü9] Among these fuels, hydrogen becomes the most advantageous one with its ability to provide high energy without being a burden on a limited reservoir. Sustainable technologies like electrolysis can enable hydrogen to generate energy from abundant resources. [ea21c]

3.1.4 Cost

The cost of the technology is one of the key barriers to the commercialization of FCVs. Several factors influence the total ownership cost of FCVs, including hydrogen production, the infancy of the technology, hydrogen refuel infrastructure, and initial purchase price. Currently, purchasing an ICEV car is cheaper than BEVs and FCVs mainly due to the existing and settled infrastructure. BEVs are also cheaper than FCVs because it is relatively older technology. FCVs are currently more expensive than their alternatives due to the high cost of producing green hydrogen and the required investment for infrastructure. [ea22b] Therefore, as a sustainable alternative to ICEVs, BEVs are preferred more than FCVs for having a proper infrastructure. However, similar to other emerging technological innovations, the price of HCVs is expected to decrease as further research is conducted and developments are achieved. [Ü9]

3.2 Real Life Applications of FCVs

As the investment in the sustainable transportation sector grows and the potential of hydrogen gets acknowledged, FCVs also start to become more available to users. There are leading car companies that dominate the hydrogen fuel cell automotive market. [ea23a] Toyota, Hyundai, and Honda were among the first companies to produce hydrogen-powered vehicles, which was later followed by other companies like Mercedes-Benz and Audi. Among these, Toyota Mirai has led the market, as it has been the first FCV that has been mass-produced and commercialised since its launch in 2014. [ea21a] It is also spread over different regions, including Japan, US, and Europe. In addition, in the US, the Environmental Protection Agency has qualified the Toyota Mirai as the most fuel-efficient hydrogen FCV. Another commercially available model of FCV is produced by Hyundai, which is named NEXO. The model was revealed as a part of Hyundai's Eco Series in 2018. [ea23a] Based on estimated values, it can be quite advantageous in terms of having a high range, which exceeds 600 km. [ea23a] Following Toyota and Hyundai is the company Honda. Along with Toyota, Honda produced one of the first cars that was certified by the Environmental Protection Agency in the US. [ea21e] The commercialized model of the brand is named "Clarity Fuel Cell" and it has been introduced to the industry much earlier than many of the other companies' vehicles. In the hydrogen FCV market, among the vehicle companies owned by Asian countries are the German companies Audi, BMW, and Mercedes-Benz. Audi has introduced a model named "h-tron Quattro", and Mercedes Benz has launched a plug-in hybrid FCV model that offers two options to the user for fuel. [ea23a] Overall, as seen in the examples of different car brands, fuel cell technology in the transportation sector is becoming more widespread and being adopted by different nations. Many of the national strategic plans for the future recognize the importance of hydrogen in the transition to a sustainable transportation industry. Indeed, hydrogen FCVs are being adopted by several countries as a part of their attempt to switch to the clean transportation sector. [ea23a] According to Fakhreddine et al., there were approximately 34,000 FCVs in use globally at the start of 2021. Japan has been prioritizing hydrogen FCVs to reach its aim of becoming a hydrogen society. [BL22] It has become one of the leading nations in the industry, as seen with the variety of hydrogen FCVs produced by the country. [ea23a] The US is one of the pioneers in the hydrogen sector. Indeed, in 2020, the government published the country's roadmap to adopt a hydrogen economy. [BL22] South Korea, the country to produce the first commercialized fuel cell vehicle, also has a lead in hydrogen energy. The government has several targets set for the future, such as having more than six million FCVs on the road within the next twenty years. In Germany, the transition to clean transportation with FCVs is supported by the government through different financial incentives. [ea23a] Large nations like Australia and Canada have also worked on including hydrogen energy in their national plans. In fact, in 2019, the Energy Council in Australia published a National Hydrogen Strategy. Similarly, Canadian authorities also released a Hydrogen Strategy in 2020. The European Union is also determined to keep hydrogen at the top of its priorities. Among their energy and climate policies, hydrogen energy has an important role. [BL22] Although not mentioned in this paper, many other countries from France to China to Morocco have their own sets of plans and strategies in terms of establishing a system for hydrogen energy, which validates the global effort to incorporate hydrogen into clean energy plans. Considering the major obstacles to creating a sustainable transportation system with hydrogen energy are mainly dependent on governments' incentives and decisions, it is promising to see many of them acting on the issue.

3.3 Shift to Sustainable Transportation and the Role of Economic Systems

The relationship between the global energy sector and economic systems are multifaceted and require comprehensive analysis to draw definite conclusions and develop action plans. Therefore, in this section of this paper, only one of the many aspects of this discussion is reviewed in detail. In essence, hydrogen technology itself has a significant contribution to the creation of a sustainable transportation industry. Yet, when it is not supported with the right practices, systems, and regulations, the sustainability of technological advancement cannot be achieved. Regardless of the advanced and impressive nature of technological innovation, its impact remains insufficient without fixing the exploitative behaviors of industries. Even though the initial catalyst behind utilizing hydrogen energy in vehicles is the aim to replace fossil fuels to achieve a sustainable transportation system, this intention can be corrupted and hydrogen is being exploited to "pave the way" for fossil fuel-based capitalism, the economic model relying on materialism and extensive consumption to drive economic activity. [Sza20] While hydrogen initially is suggested as a low-carbon substitute for existing energy sources, its commercial production does not align with this intention. Even though the implementation of a hydrogen-based transportation system can only be sustainable when the hydrogen is obtained through emission-free methods, the most common way for hydrogen production is through the use of natural gas for methane steam reforming, resulting in gray hydrogen, as discussed earlier. According to Szabó, one of the key reasons behind this discrepancy is resulting from the perspective of decision makers. The fossil fuel actors around the world view hydrogen energy as a strategy to keep the current fossil fuel capitalism that exploits natural resources by making it seem like a decarbonized version. [Sza20]

Another aspect of capitalism to consider is its influence on the consumption and growth levels of society. Although creating a green energy system is a part of the solution, it is not the only component that the capitalist system makes it seem like. Along with zero-emission energy sources, in the journey toward sustainable transportation, a significant alteration in consumption and production levels is imperative. This is necessary because many critical issues arise from the depletion of resources and the generation of substantial waste. The current dependency on fossil fuels is mainly caused by their ability to supply the current levels of energy consumption, and renewable energy sources like solar or wind are often pushed down because of their insufficiency in meeting the energy demand. However, the present climate crisis is mainly backed by extreme consumption levels and continuous growth resulting from a capitalist system. To achieve actual sustainability in the energy field and slow global warming, consumption habits must be altered so that renewable alternatives can suffice the need. Strategies to reduce extractivism and the commitment to growth should be considered for the adoption of sustainable alternatives to have an impact on mitigating climate change. Although there are other schemes like ecomodernism or green capitalism proposed to be sustainable pathways, they continue to support the current consumption behaviors. [DM22] Therefore, to enable renewable alternatives to have a beneficial effect, a systematic change should be achieved to quit the ever-expanding mode of production and consumption. [Sza20]

4 Discussion

Hydrogen energy plays a major role in building a sustainable future, particularly hydrogen FCVs in the transportation sector. However, keeping this initially sustainable alternative clean and emission-free is a challenge in various aspects. The challenge starts with the production of hydrogen. Among the different methods, natural gas-based production through steam methane reforming currently is prioritized due to its several advantages such as its low-cost and availability. Even though there are sustainable alternatives to this fossil fuel dependent process, their practical difficulties prevent them from getting commercialized. For instance, there are effective methods of producing hydrogen through utilizing certain characteristics of some microorganisms. Yet, due to lack of enough investment and recognition, they are still in the stage of RD. Therefore, to make green hydrogen production attainable, the attention in the energy industry should be directed towards sustainable and emission free procedures rather than cost-efficient ones. As they gain more attraction and receive the necessary investment, the carbon neutral methods can be commercialized and become financially feasible.

Along with production, commercial use of hydrogen for energy can only be achieved through facilitating its transportation and storage. In particular, when today's extensive fossil fuel infrastructure is considered, in order for hydrogen to take their place, it demands efficient and applicable methods to enable its use. Due to its natural characteristics, hydrogen requires advanced tools and circumstances for its transportation, which can depend on the physical state of the hydrogen. Storage of hydrogen is of equal importance as its transportation, and there are various techniques tested for its safe and efficient storage. Similar to its transportation, hydrogen can be stored in different physical states through appropriate technologies such as chemically storing it through adsorption, cryogenic systems for storing in liquid form, compression into containers as cylinders and tanks, geological storage techniques, etc. In the choice of technologies for both transportation and storage, it's important to pinpoint the method that is both efficient and feasible. Still, it holds equal significance to notice the potential of the emerging technologies in the process because the initial challenges they present are temporary and can prove beneficial in the long term.

Concerning the integration of hydrogen into transportation, there are predominantly two distinct approaches available. The first method is to use hydrogen to power internal combustion engines. Since the current industry is dominated by vehicles that perform with internal combustion engines, incorporating hydrogen as the sustainable alternative can be convenient. Furthermore, hydrogen's distinct features provide it with benefits in this approach. Although their use can offer a cleaner replacement to conventional vehicles, they do not fit into the aim of achieving a zero-carbon transportation sector because of the probable nitrogen oxide emission. There are ongoing efforts to enhance the suitability of this method, yet they are still in the stage of research. Therefore, hydrogen fuel cell vehicles emerge as the optimal choice for integrating hydrogen as a sustainable fuel in the transportation industry. In the fuel cells used inside the vehicles, water is broken down into its components using electricity and hydrogen is obtained without releasing harmful gasses. Besides being the carbon neutral choice, features of FCVs also exceed alternative vehicles like BEVs and hybrids with their high efficiency, convenient fuel storage, short refueling time, and high driving range. Yet, as with any other vehicle technology, they have particular material requirements that can create environmental damage during its extraction. Hence, alternative materials for fuel cells need to be discovered and improved to become available on a large scale. When considering the feasibility of the technology, the higher production cost of fuel cells might make them seem as an inconvenient technology to invest in. Nevertheless, hydrogen FCVs are manufactured by various automotive companies, indicating that their potential is recognized globally. Indeed, the world's most selling car company Toyota was one of the first brands to introduce FCVs. In the current scenario, numerous established automotive firms including Mercedes, Audi, and Hyundai are involved in crafting FCVs, reinforcing the perspective that hydrogen stands as the future of the transportation sector. In addition, governments around the world from Japan to Canada are taking hydrogen's potential to power the transportation industry into account and shaping their national strategic plans accordingly.

Taking these aspects, procedures, and applications of hydrogen into account, hydrogen is a promising fuel for meeting the goal of sustainable transportation. Although a new hydrogen-based system comes with its challenges, they should not be excuses to back down but rather should be focused on and improved to fulfill the potential of hydrogen. With the required investment in RD, hydrogen energy can be the key to zero-carbon transportation. Yet, when looking at the bigger picture, a successful hydrogen-based system is not sufficient to achieve the aim hydrogen energy is initially proposed for. The goal of creating sustainable systems for a decarbonized world is hard to achieve completely under a capitalist system that is meant to support continuous growth and consumption. Adopting an economic model that aligns with this primary aim is crucial for hydrogen-fueled transportation to be effective.

5 Conclusion

This research paper aimed to discover the potential of hydrogen energy as a sustainable alternative in the transportation sector. The current system of procuring and consuming energy is not sustainable and is the catalysis of various crises, global warming being the most evident one. As a solution, hydrogen can be used as a zero-emission fuel, particularly in the transportation sector which is a sector that has high contributions to global greenhouse gas emissions. In particular, hydrogen fuel cell vehicles hold great promise by being clean, efficient, and durable replacements for existing vehicles. Yet, the spread of this advantageous alternative is limited by its high cost. Since the necessary infrastructure for hydrogen-based transportation systems is not achieved, hydrogen cannot be commercialized with ease. This challenge indicates the urgent need to make the right policies to ease the process. Although there still are technical challenges regarding hydrogen fuel cell vehicles, they are not barriers to the commercialization of this process. What this transition requires is the proper investment and being prioritized. Governments around the world have already begun to include hydrogen in their roadmap plans, however, the decided aims must not stay on paper only. The production of hydrogen fuel cell vehicles by various firms indicates the technology's applicability when it receives the necessary attention. Many features of hydrogen make it a significant potential to reduce the negative impacts caused by fossil fuel-dependent systems. Regardless of the challenges that might come along with it, the power of hydrogen fuel should not be undermined and instead, be developed to make it the primary source in the transportation sector.

6 Recommendations

Though not discussed in this paper, there are several, but not many, studies in literature focusing on more sustainable materials to be used in the production of hydrogen fuel cells. Focusing on this area is crucial to maintain the sustainability of hydrogen in the future when the technology spreads out and demand increases. Additionally, the studies covering the technical aspect of the field should also include the impact of the present economic system. The applicability of hydrogen-based energy systems is not only restricted by the lack of technical advancements. If it is not favored and prioritized by the governments and the economic model lived under, it is difficult to create a space for it to develop and spread fast enough to have a significant impact. Although some examples in the literature focus on the impact of the capitalist regime on the deployment of hydrogen, not many directly focus on hydrogen fuels but rather mention the overall transition from fossil fuels to renewable sources.

References

[AD20] C. Acar and İ. Dinçer. The potential role of hydrogen as a sustainable transportation fuel to combat global warming. *International Journal of Hydrogen Energy*, 2020.

[AH19] A. Ajanovic and R. Haas. Economic and environmental prospects for battery electric- and fuel cell vehicles: a review. *Fuel Cells*, 2019.

[AH21] A. Ajanovic and R. Haas. Prospects and impediments for hydrogen and fuel cell vehicles in the transport sector. *International Journal of Hydrogen Energy*, 2021.

[BL22] B. Lamrani K. Benabdelaziz T. Kousksou B. Lebrouhi, J. Djoupo. Global hydrogen development - a technological and geopolitical overview. *International Journal of Hydrogen Energy*, 2022.

[DM22] A. Dunlap and D. Marin. Comparing coal and 'transition materials'? overlooking complexity, flattening reality and ignoring capitalism. *Energy Research Social Science*, 2022.

[ea18] J. Wang et al. Techno-economic challenges of fuel cell commercialization. *Engineering*, 2018.

[ea20] A. Pareek et al. Insights into renewable hydrogen energy: Recent advances and prospects. *Materials Science for Energy Technologies*, 2020.

[ea21a] A. Olabi et al. Fuel cell application in the automotive industry and future perspective. *Energy*, 2021.

[ea21b] L. Fan et al. Recent development of hydrogen and fuel cell technologies: A review. *Energy Reports*, 2021.

[ea21c] M. K. Singla1 et al. Hydrogen fuel and fuel cell technology for cleaner future: a review. *Environmental Science and Pollution Research*, 2021.

[ea21d] M. Yue et al. Hydrogen energy systems: A critical review of technologies, applications, trends and challenges. *Renewable Sustainable Energy Reviews*, 2021.

[ea21e] Y. Luo et al. Development and application of fuel cells in the automobile industry. *Journal of Energy Storage*, 2021.

[ea22a] S. Chakraborty et al. Hydrogen energy as future of sustainable mobility. *Frontiers in Energy Research*, 2022.

[ea22b] S. Dash et al. Hydrogen fuel for future mobility: challenges and future aspects. *Sustainability*, 2022.

[ea23a] Q. Hassan et al. Hydrogen fuel cell vehicles: opportunities and challenges. *Sustainability*, 2023.

[ea23b] R. Malik et al. Overview of hydrogen production technologies for fuel cell utilization. *Engineering Science and Technology*, 2023.

[HB19] S. Hosseini and B. Butler. An overview of development and challenges in hydrogen powered vehicles. *International Journal of Green Energy*, 2019.

[oC] University of Cambridge. A schematic of the basic fuel cell components. *University of Cambridge Department of Chemical Engineering and Biotechnology.*

[oE20] US Department of Energy. Hydrogen strategy: Enabling a low carbon economy. 2020.

[St1] Z. Stepień. A comprehensive overview of hydrogen-fueled internal combustion engines: Achievements and future challenges. *Energies*, 2021.

[Sza20] J. Szabó. Fossil capitalism's lock-ins: the natural gas-hydrogen nexus. *Capitalism Nature Socialism*, 2020.

[Ü9] D. Üçok. Hydrogen fuel cell vehicles. *Sabancı University International Center for Energy and Climate*, 2019.