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HYDROGEN FUEL CELL VEHICLES: A COMPREHENSIVE ANALYSIS OF SYSTEM ARCHITECTURE STRENGTHS AND CHALLENGES

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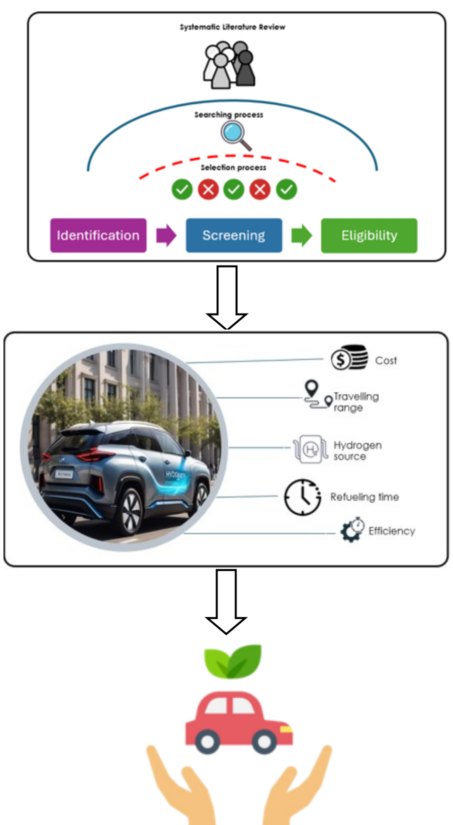
Graphical abstract



Abstract

Several countries are currently developing hydrogen-powered vehicle technology. However, this technological innovation has to be improved further. This is due to existing technology's limitations in terms of efficiency, cost, and infrastructure for hydrogen refueling systems. Therefore, this systematic review explores the current state of research on hydrogen-powered cars, focusing on technological advancements, environmental impacts, and future prospects. A comprehensive search of scholarly databases yielded a diverse range of studies published between 2019 and 2025. The analysis reveals a growing body of literature addressing key aspects of hydrogen car strengths and challenges. This study follows the PRISMA methodology, with literature collected from two databases, Scopus and ProQuest. After screening and eligibility assessment, 19 papers were included in the final analysis. The review synthesizes findings related to hydrogen fuel cell technology, addressing efficiency improvements, cost reductions, refueling time, traveling range, and the source of hydrogen. This assessment emphasizes the necessity of ongoing research and cooperation to address current obstacles and maximize the capabilities of hydrogen-fuelled vehicles as the world moves towards sustainable transportation options. The synthesis of diverse perspectives presented in this systematic review serves as a valuable resource for researchers, policymakers, and industry stakeholders interested in the ongoing evolution of hydrogen as a viable alternative in the automotive sector.

Keywords: Hydrogen car, fuel cell, sustainable transportation

Abstrak

Beberapa negara kini sedang membangunkan teknologi kenderaan berkuasa hidrogen. Walau bagaimanapun, inovasi teknologi ini perlu dipertingkatkan lagi. Ini disebabkan oleh batasan teknologi sedia ada dari segi kecekapan, kos dan infrastruktur untuk sistem pengisian bahan api hidrogen. Oleh itu, tinjauan sistematik ini meneroka keadaan penyelidikan semasa mengenai kereta berkuasa hidrogen, dengan memberi tumpuan kepada kemajuan teknologi, impak alam sekitar, dan prospek masa depan. Carian menyeluruh dalam pangkalan data ilmiah menemukan pelbagai kajian yang diterbitkan antara tahun 2019 dan 2024. Analisis ini mendedahkan semakin banyak hasil kajian yang membincangkan aspek utama berkaitan kekuatan dan cabaran kereta hidrogen. Tinjauan ini mensintesis dapatan berkaitan dengan teknologi sel bahan api hidrogen, merangkumi penambahbaikan kecekapan, pengurangan kos, masa pengisian semula, julat perjalanan, dan sumber hidrogen. Seiring dunia beralih kepada penyelesaian pengangkutan yang mampan, tinjauan ini menekankan kepentingan penyelidikan dan kerjasama berterusan untuk mengatasi cabaran sedia ada dan membuka potensi penuh penggunaan kereta hidrogen. Sintesis pelbagai pandangan yang dibentangkan dalam tinjauan sistematik ini berperanan sebagai sumber berharga bagi penyelidik, pembuat dasar, dan pemegang kepentingan industri yang berminat dalam perkembangan berterusan hidrogen sebagai alternatif yang boleh dilaksanakan dalam sektor automotif.

Kata kunci: Kereta hydrogen, sel bahan api, pengangkutan yang mampan

1.0 INTRODUCTION

Global warming is regarded as one of the most alarming natural threats. It transcends geographic boundaries, impacting ecosystems, weather patterns, and, most significantly, the delicate equilibrium that sustains life on Earth. Fundamentally, global warming denotes the incremental ascent in the temperature of the Earth's surface [1]. Due to human activities, particularly in the transportation sector [2], [3]. The burning of fossil fuels, such gasoline and diesel in vehicles such as cars, trucks, ships, and airplanes, releases substantial amounts of greenhouse gases, such as carbon dioxide, into the atmosphere. These gases trap heat, leading to a warming effect on Earth's climate.

The adverse impacts of global warming, such as extreme heat events, changing disease patterns, and compromised air and water quality, pose direct threats to human health and well-being [4]. The transportation sector is responsible for more than 25 % of the global greenhouse gases (GHG) emitted [5]. As the global demand for transportation continues to rise, so does the emission of these harmful gases. It is essential to address and modify our modes of transportation, adopting sustainable alternatives such as electric vehicles, hydrogen car and investing in cleaner energy sources, help lessen the effects of climate change brought on by humans by unlocking up opportunities to a greener and sustainable future.

A comparison of several energy cars for a sustainable future is shown in Table 1, which includes details on electric, solar, and hydrogen vehicle parameters. When evaluating these options based on driving range, notable differences emerge. Hydrogen vehicles can travel up to 300 miles [6] on a single refuel, offering a substantial range similar to conventional gasoline vehicles. Solar vehicles, however, have a more limited range, due to constraints of energy production which require between 124-186 Wh per kilometer and typically yielding daily energy production of only 2-3 kWh [7]. In comparison, electric vehicles have a driving range of 200 to 350 kilometers per charge[8]. However, studies indicate that increasing battery capacity can significantly extend the travelling range. For example, ones study reports that with a net battery capacity of 90 kWh and an energy demand of 0.224 kWh per kilometer, it can achieve approximately 402 km [9].

These distinctions represent each vehicle type's specific strengths and restrictions, determining its usefulness for particular driving needs and conditions. When evaluating refueling and recharging times for different vehicle types, hydrogen vehicles offer the fastest turnaround, with refueling taking just 5-10 minutes. In contrast, solar vehicles experience long recharging times, which can vary significantly depending on sunlight availability and the vehicle's energy storage capacity. Electric vehicles fall in between, with recharging times that range from moderate to long, depending on the type of charging station and battery capacity. This variation in refueling and recharging times impacts the overall convenience and usability of each vehicle type.

When considering the infrastructure needs of different types of vehicles, hydrogen and electric vehicles both have flexible charging options. Hydrogen and electric vehicles can be serviced by both grid-tied or off-grid charging stations, offering versatility in various settings. In contrast, solar vehicles do not require conventional charging stations as they rely on solar energy for operation. This distinction highlights both infrastructure flexibility of hydrogen and electric vehicles [10]. Electric vehicles in particular can utilize battery-swap systems that allow rapid replacement of depleted batteries, so that it can reduce the reliance of long recharging time [11].

When comparing hydrogen and electric vehicles in terms of environmental impact and safety, several distinctions become apparent. Both types are known for their low emissions, making them environmentally friendly options. However, their safety considerations are far apart. Hydrogen vehicles have inherent risks related to hydrogen storage, which requires stringent measures to prevent leaks and potential explosions. Electric vehicles offer low emissions, but face safety concerns related to battery fires and handling of hazardous materials. These factors underscore the importance of continuous improvement in safety and regulations to support the secure and sustainable use of these alternative transportation. Table 1 shows the comparison of both energy vehicles.

Table 1 Comparison of energy vehicle

Parameter	Hydrogen vehicles	Electric vehicles
Driving Range	483 km	200 to 350 km
Refueling/ Recharging time	Short (5-10 minutes)	Moderate to long
Charging Station	Grid-tied or off-grid	Grid-tied or off-grid
Environmental impact	Low emissions	Low emission
Safety	Hydrogen storage risks	Battery safety risks

Currently, the development of hydrogen cars represents a notable stride towards sustainable transportation. As we all know, the target of hydrogen cars is to reduce emissions [12], which can help to decrease global environmental issues. The widespread use of hydrogen cars has the potential to greatly reduce air pollution, hence improving public health and safety.

Hydrogen cars utilize fuel cell technology, which converts hydrogen gas into electricity to power electric motors, emitting only water vapor as a byproduct. Despite facing challenges such as limited infrastructure and high production costs, significant advancements have been made in recent years. Major automotive manufacturers, including but not limited to Toyota, Honda, and Hyundai, have introduced hydrogen fuel cell vehicles to the market. Such as the Toyota Mirai and Hyundai Nexo. Continued innovation and research are essential to address the existing limitations and support a more sustainable, environmentally friendly transportation landscape.

One promising direction for future development involves integrating the electrolysis process with fuel cell vehicles, complemented by thin-film solar panels. This approach could enable on-board hydrogen production using solar energy, reducing reliance on external refueling infrastructure and overcoming a key barrier to widespread hydrogen vehicle adoption. By harnessing solar-driven electrolysis, hydrogen vehicles could achieve greater energy independence, improved efficiency, and enhanced technological viability.

2.0 HYDROGEN CAR SYSTEM ARCHITECTURE

Hydrogen cars operate using fuel cells that generate electricity through a chemical reaction between hydrogen and oxygen, producing only water vapor as a byproduct [13]. Unlike traditional gasoline-powered vehicles that emit harmful pollutants like carbon dioxide and nitrogen oxides, hydrogen cars offer a cleaner and more environmental friendly alternative. Figure 1 shows a hydrogen fuel cell vehicle with on-board storage of compressed gas.

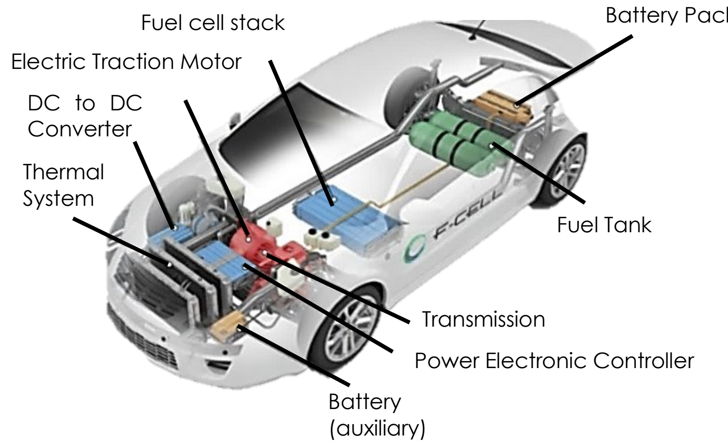


Figure 1 Fuel cell vehicle with on-board storage [14]

A fuel cell vehicle (FCV) is an advanced type of electric vehicle that uses hydrogen gas as a fuel source to generate electricity through a chemical reaction within a fuel cell. In a fuel cell, hydrogen reacts with oxygen from the air to produce electricity, water, and heat. This electricity then powers the vehicle's electric motor, providing propulsion. One of the key advantages of FCVs is their environmentally friendly operation [15], as they emit only water vapor and heat as byproducts, making them a zero-emission vehicle [16], [17].

Three components are needed for a fuel cell system an electrolyte, a cathode, and an anode [18]. Fuel cells are categorized according to the type of electrolyte material that is utilized. Even though a fuel cell may have hundreds of individual cells, they all have three basic components. The electrolyte is located between the cathode and anode. Figure 2 shows an operational diagram for a polymer electrolyte fuel cell (PEMFC). By transitioning to hydrogen cars on a larger scale it can mitigate the negative consequences of vehicle emissions on the global climate. This shift not only addresses the pressing issue of climate change but also has direct implications for public health. Reduced air pollution would mean a decrease in respiratory and cardiovascular diseases, ultimately saving lives.

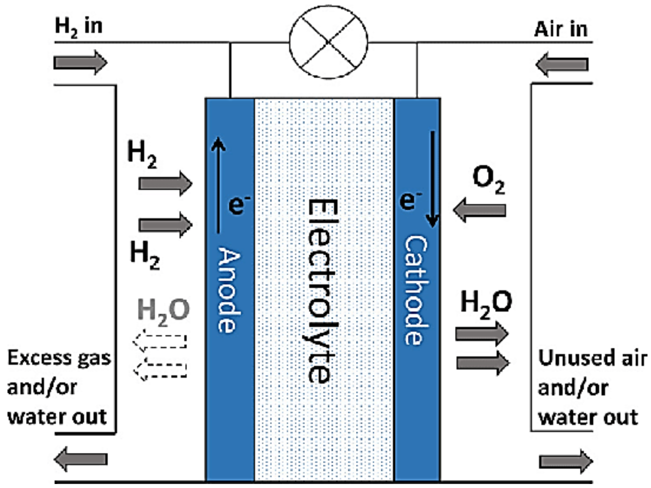


Figure 2 Fuel cell operation diagram [19]

Hydrogen FCV presents a promising technology for clean energy, but their widespread adoption faces significant challenges, particularly around infrastructure [20], [21], [22]. The infrastructure for hydrogen refueling stations is heavily dependent on the efficient and safe transportation of hydrogen, whether as a compressed gas or a cryogenic liquid. It involves substantial energy losses [23] at each stage, from electrolysis production to compression and cooling, which require considerable amounts of electricity and reduce the overall efficiency of hydrogen as a fuel. Currently, hydrogen transport relies primarily on tanker trucks to move hydrogen from production facilities to refueling stations, despite the consideration of pipelines for future use. This method is constrained by the capacity of trucks, limiting the amount of liquid hydrogen they can carry [24]. Additionally, the cost of hydrogen production facilities is directly proportional to the demand for hydrogen [25]. Overcoming these challenges is crucial in realizing the full potential of hydrogen as a clean and sustainable energy source for transportation.

A systematic literature review is a formal method that systematically identifies and consolidates relevant research, employing structured, transparent, and reproducible procedures at every stage of the process [26]. This research proposes a comprehensive review of the literature using mixed methodologies, quantitative, qualitative, and explicit integrative review analysis. Despite the extensive literature available on hydrogen cars, there is limited initiative to systematically examine these studies, discern patterns, and establish potential themes. Critically, the procedures involved in the review, such as identification, screening, and eligibility; have not received sufficient attention. Conventional literature review practices face various challenges concerning transparency and potential bias, as many authors tend to select articles that align with their research preferences [26]. Certainly, such a system would present a significant obstacle for future researchers aiming to reproduce the research, confirm the interpretations, or assess the study's thoroughness.

Considering the existing research gap, the present study seeks to perform a systematic literature review with a specific emphasis on the strengths and challenges faced by the development of hydrogen cars. This method allows the authors to substantiate empirical evidence, pinpoint gaps in knowledge, and provide a roadmap for future research in this domain. The primary research question guiding this review is: 'What is the efficacy of hydrogen cars in reducing gas emissions?' Furthermore, this paper places a central emphasis on hydrogen cars, recognizing their significance in addressing both gas emissions and associated health risks.

This research aims to pave the way for a more sustainable and eco-friendly future in the realm of transportation. Nonetheless, these vehicles come with their own set of challenges, such as lower energy density when compared to liquid hydrocarbon fuels [20], elevated expenses [22] associated with transportation, storage, and distribution in compressed or liquefied states, along with the absence of a widespread infrastructure [20], [21], [22]. Additionally, hydrogen encounters typical hurdles associated with emerging technologies, including limited vehicle options [20], limited public awareness, aversion to risk [22], and the necessity to establish a suitable institutional framework [25].

3.0 METHODOLOGY

3.1 PRISMA

The review was conducted under the PRISMA Statement (Preferred Reporting Items for Systematic Reviews and Meta-Analyses), a standard method commonly used in environmental management research. This approach guides the authors to record every searching strategy for all databases [27]. It helps to facilitate a clear and systematic process in identifying, screening and selecting relevant literature. A detailed search of hydrogen vehicle-based terms can be done with PRISMA method and provides a solid way to track the developments in hydrogen vehicle area.

3.2 Resources

Derived from the established research inquiries, three primary keywords were pinpointed: hydrogen, and car. Enhancements to these keywords include synonyms, related terms, and variations found using an online thesaurus such as thesaurus.com. References to the keywords used in previous research, suggestions from Scopus and ProQuest, and guidance from experts have all been studied. Based on this process, several keywords similar to hydrogen cars, including hydrogen, automobile, vehicle, convertible were checked. As indicated in Table 2, the combinations of these terms were processed in Scopus and ProQuest utilizing search methods like field code functions, phrase searching, wildcards, truncation, and Boolean operators. Additionally, the searching process was based on a manual searching technique. Although a hydrogen car is one way to mitigate the problem of electric vehicle, regrettably, it comes with its own drawbacks, particularly in managing the handling of hydrogen. Based on the search efforts, a total of 25,174 potential articles were identified from the selected databases.

Table 2 Search string in selected database

Database	String
Scopus	"Hydrogen vehicle" OR "hydrogen mobility" AND "fuel cell vehicle"
Proquest	"Hydrogen car" OR "hydrogen vehicle" OR "hydrogen cars" OR "hydrogen vehicles"

During the screening phase, papers were reviewed and either included or excluded based on specific criteria indicated in Table 3, using the database or manual assessment by the authors. Considering the concept of "research field maturity" as emphasized by Shaffril *et al.* [26] this evaluation restricted the screening procedure to publications released in the years 2019 to 2023. The timeline was selected on the fact that there was enough published research to allow a representative review. Because empirical research papers have first-hand data, the authors decided to look them over.

Notably, only works written in English were taken into consideration to avoid confusion. Selecting engineering research studies as one of the criteria was thought to boost the likelihood of finding more papers about hydrogen cars, since the systematic review target was related to them. The author also limits the keyword in Scopus, which is hydrogen powered vehicles, hydrogen fuel cell vehicles, hydrogen fuel cell, hydrogen fuel, hydrogen car, hydrogen vehicles and hydrogen fuels only in the finding. A total of 24,963 articles were excluded from the review during this stage since they were not in line with the inclusion requirement. 24,963 items were eliminated from the review because they did not meet the inclusion criteria. Throughout this round of the review, a total of 24,963 items were disqualified for inclusion because they did not meet the rules. As an outcome, 211 articles were left over for review in the next phase.

3.3 Eligibility and exclusion criteria

Table 3 Research conducted according to a particular set of standards

Criterion	Inclusion	Exclusion
Timeline	2019-2023	2018 and earlier
Document type	Articles	Review article, book and conference proceedings
Language	English	Non-English
Subject area	Engineering	Non-engineering studies

In order to determine if the remaining publications met the predetermined inclusion criteria, the authors manually reviewed each one, searching over the abstract, title, and body of the work. One hundred and twenty articles were excluded during the title screening state, and during the abstract screening stage, 45 articles were removed. One hundred and twenty articles were eliminated at the title screening stage, while forty-five articles were eliminated at the abstract screening stage. Twenty further publications were removed following the authors' review of the selected articles. In total, 185 articles were removed in this stage since they did not focus on hydrogen cars.

3.4 Systematic Review Process

Four stages were involved in the systematic review process. The review process was performed in October 2023. The first phase identified keywords used for the search process. Relying on previous studies and thesaurus, keywords similar and related to hydrogen vehicle were used (Table 2). At this stage, after careful screening, a total of 24,963 items were disqualified. The second stage was screening. One duplicated article was removed. At this stage, out of 210 articles eligible to be reviewed, a total of 185 articles were removed. The third stage is eligibility, where the full articles were accessed. After careful examination, a total of six articles were excluded as some did not focus on hydrogen vehicles. The last stage of review resulted in a total of 19 articles that were used for the analysis as shown in Figure 3.

3.5 Data Abstraction and Analysis

The remaining articles were assessed and analysed. Efforts were concentrated on specific studies that responded to the formulated questions. The review of the abstracts was intended to provide a basic overview of what each paper contained and begin with data abstraction. In this process, the authors aimed to ensure that the selected studies aligned closely with their research objectives. By starting with the abstracts, they could quickly filter out irrelevant articles, allowing them to concentrate their efforts on those most pertinent to their inquiries. The subsequent in-depth reading of the full articles enabled a comprehensive exploration of the themes, providing a solid foundation for the conclusions drawn from the research.

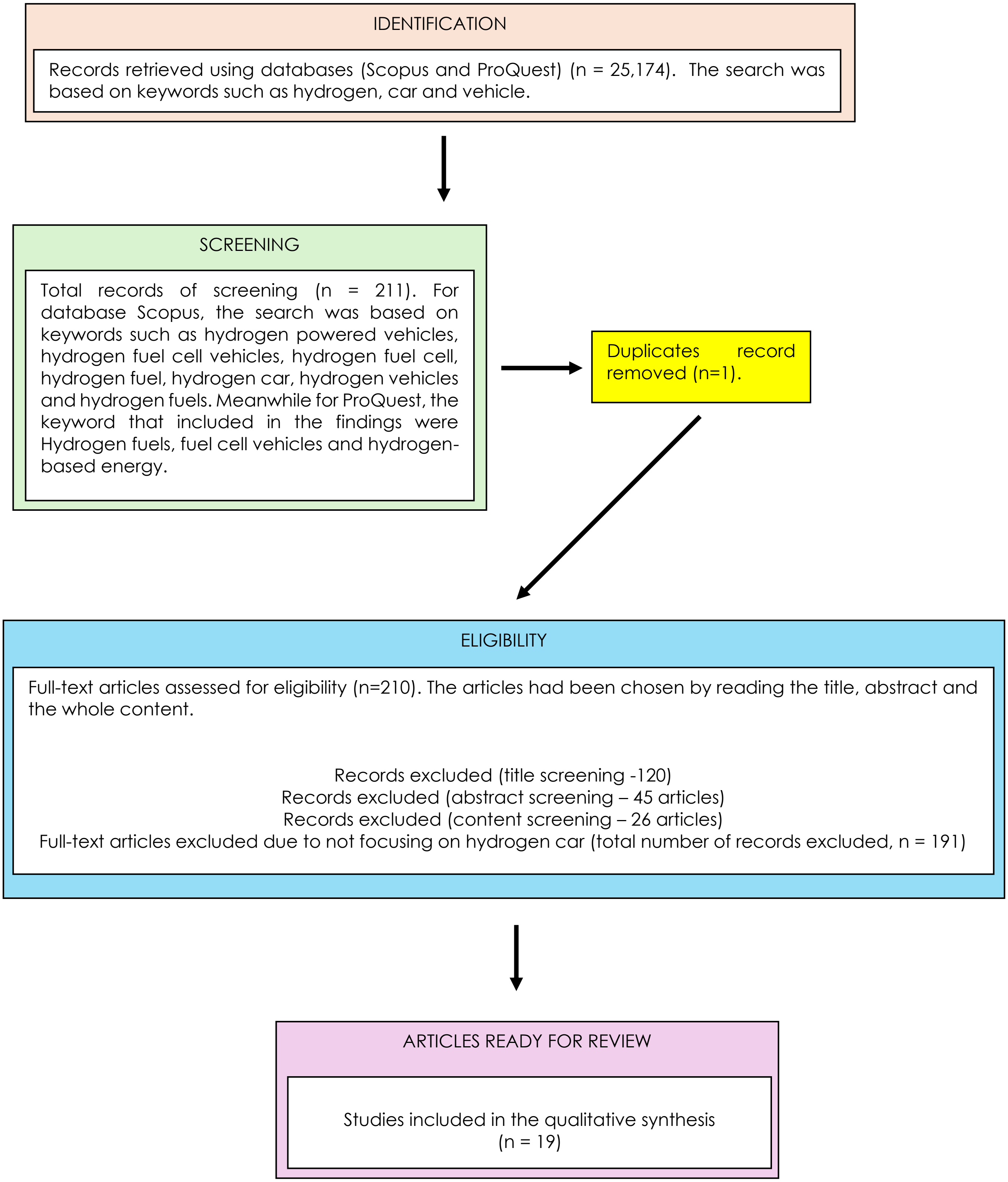


Figure 3 The flow diagram of the searching process

Table 4 The findings

Authors	Parameters							
	E	**R**		**C**	**H**		**D**	
		≥3 min	**<3 min**		**External**	**Internal**	**>100km**	**<100km**
A. Akac *et al.* [25]	/	/		/	/		/	
N. Wang *et al.* [26]	/			/	/		/	
M. P. Alves *et al.* [27]				/	/			
M. S. HAbIb *et al.* [28]	/			/	/			
M. T. Ahad *et al.* [29]				/	/			
O. Fakhreddine *et al.* [30]	/			/	/		/	
P. Wiśniowski *et al.* [31]				/	/			
L.-I. Dulău [32]		/		/	/		/	
M. Yazdi *et al.* [33]					/			
A. Szałek *et al.* [34]	/	/		/	/		/	
O. Bethoux [35]					/		/	
N. A. Baharuddin *et al.* [36]	/			/	/			
K. Wróbe *et al.* [37]	/			/	/			/
J.-E. Shin [38]	/				/			
E. Y. C. Wong *et al.* [39]	/	/	/		/		/	
N. Hoque *et al.* [40]				/	/			
Z. Xiaoxin *et al.* [41]	/			/	/			
A. N. Mancino *et al.* [42]	/			/			/	
D. D. Wolf *et al.* [43]		/		/	/		/	

E - Efficiency R – Refueling time C - Cost H – Hydrogen production D – Distance travelling

4.0 RESULTS

The review resulted in five main themes related to hydrogen vehicles. The five main themes are efficiency, refueling time, cost, hydrogen sources and distance travelling. The refueling time will be evaluated based on whether it takes less than 3 minutes or exceeds 3 minutes. The hydrogen source will be assessed to determine if it is produced internally within the vehicle's system or sourced externally. For the distance traveled, the evaluation will consider whether the vehicle can cover less than 100 km or travel a greater distance. The results provided a comprehensive analysis of the current hydrogen vehicles.

4.1 Efficiency

In recent studies, A. Akac *et al.* [28] has emphasized the hydrogen itself is very efficient in their findings. On the other hand, N. Wang *et al.* [29] focused on environmental efficiency effect. Z. Xiaoxin *et al.* [30], E. Y. C. Wong *et al.* [31] and O. Fakhreddine *et al.* [32] directed their attention towards energy conversion efficiency. Based on the articles, the energy efficiency is about 85%, 70-80% and 63% respectively. J.-E. Shin [33] highlighted the production of hydrogen technology efficiency in Korea which is still in development.

Many different businesses, including Vaillant, which uses Combined Heat and Power (CHP), are part of the German fuel cell and hydrogen market. CHP decreases the amount of energy lost by almost half, and the device can supply power with an efficiency of more than 90% while dramatically reducing emissions per kWh generated [34]. A. Szałek *et al.* [35] reported a current energy efficiency of approximately 75% in hydrogen production by electrolysis. The efficiency of the propulsion system is about 45-55% [36]. The efficiency based on A. N. Mancino *et al.* [37] more than 60% which is more than internal combustion engines (ICE) powered vehicles. Two comparisons of the fuel cell type efficiency had been compared in [38]. The proton exchange fuel has 40-60% while the alkaline fuel cell has 60% efficiency. In summary, recent research has illuminated different facets of hydrogen efficiency, focusing on its inherent, environmental, and energy conversion aspects. Overall, these studies highlight the diverse nature of hydrogen efficiency, indicating that ongoing technological advancements and methodological developments are shaping its significance within sustainable energy frameworks.

4.2 Refueling Time

Charging electric cars, particularly electric vehicles (EVs), can be a time-consuming process. In contrast, hydrogen-powered vehicles, as exemplified by the Toyota Mirai, present an attractive solution. Refueling the Mirai takes only 3 minutes [35] [39]. A. Akac *et al.* [28] state that it takes 3-8 minutes. L.-I. Dulău [40] mentioned that both the Toyota Mirai and Hyundai Nexo only require 5 minutes for refueling. Two types of hydrogen fuel cell vehicles were looked at in detail [31]. These were the compressed gaseous hydrogen tank-based vehicle (HFCV1) and the solid-state hydrogen storage fuel cell vehicles (HFCV2). HFCV1 needs 3-5 minutes to refuel, while HFCV2 needs less than 1 minute to refuel.

4.3 Cost

The cost of hydrogen in various countries has been documented according to [28], as illustrated in Table 5. [29] conducted a cost evaluation of new energy vehicles (NEVs) through a life cycle analysis (LCA). The existing market prices of these vehicles lack competitiveness, and obstacles such as the limited availability of a widespread network of hydrogen refuelling stations hinder the broad commercial adoption of fuel cell (FC) vehicles [41]. According to Habib, hydrogen fuel cell (HFC) vehicles still face cost challenges. On a positive note, the water electrolysis method is gaining increased attention, driven by the declining costs of renewable power for green hydrogen production.

Table 5 Cost of hydrogen

Country	Levelized cost of hydrogen
Bolzano, Italy	14.6€/kg
Pau city, France	12€/kg
Groningen city, Netherlands	16-19€/kg

O. Fakhreddine *et al*. [32] discussed about the cost of using hydrogen fuel cell (HFC) technology in the transportation industry. It highlights the initial expenses, maintenance costs, and operational costs of HFC systems in various modes of transportation, emphasizing the need to consider these factors when evaluating the viability of hydrogen fuel cells in transportation. Additionally, the document addresses the cost optimization and efforts to reduce maintenance costs associated with HFC technology. It also discusses the potential lower operational and maintenance costs of HFCs compared to internal combustion engines, contributing to the overall viability of hydrogen fuel cells in transportation.

P. Wiśniowski *et al*. [42] discussed various costs related to the production and use of vehicles, particularly in the context of automotive development. It includes the cost projection of state-of-the-art lithium-ion batteries for electric vehicles up to 2030, the unit costs of fuel cells, hydrogen tanks, and electric batteries, as well as the production costs of a passenger car with a hydrogen drive in the USA from 2015 to 2050. L.-I. Dulău [40] mentioned the total cost of ownership of hydrogen vehicles, as well as the analysis of the total cost for different types of fuel cell vehicles. Additionally, the document discusses the development and possible challenges regarding adopting hydrogen vehicles, such as infrastructure and ownership cost. Z. Xiaoxin *et al.* [30] extensively discusses various costs related to the optimization of integrated energy systems. This includes the fuel cost of thermal generation units, operating costs of energy storage systems, costs of abandoning wind and light energy, costs of electric vehicles (EVs) charging/discharging, costs of hydrogen fuel cell vehicles (HFCVs), and overall operating costs of the system under different optimization models.

D. D. Wolf *et al*. [39] discussed the purchase cost, cost of use, and total cost of the two alternative propulsion modes, namely battery electric vehicles (BEVs) and fuel cell electric vehicles (FCEVs). They compared the infrastructure costs for hydrogen distribution networks and electricity grids. It also highlights the importance of including production costs of hydrogen and electricity in the research to compare the total costs for both propulsion modes. Additionally, the study mentioned the cost comparison of the two alternatives (BEV and FCEV) in Germany, showing that infrastructure costs are essentially the same at low market penetration level, but vary as vehicle penetration increases.

N. Hoque *et al*. [43] note that the costs associated with their research are relatively high, contingent upon the materials used. The costs of their research are relatively considerable, depending on the materials employed. Hydrogen fuel cells were once considered an exclusive and expensive technology, mostly used in high-end applications like NASA spacecraft, and constrained by the lack of hydrogen fuelling facilities [34]. According to A. Szałek *et al.* [35], a growth in hydrogen demand could result in a substantial cost reduction (up to 70%) for hydrogen supply in the next ten years. They also emphasize the positive influence of investment expenses on the design and scale of refuelling stations. To conclude, although there are still obstacles to overcome, constant endeavours to minimize expenses and improve techniques for producing and distributing hydrogen present encouraging opportunities for the increased integration of hydrogen fuel cell vehicles in the transportation industry.

4.4 Distance Travelling

According to A. Akac *et al.* [28], there is mention of a long fuel range of approximately 500-700 km. C. Shao *et al*. [44] report that the 100-kWh battery of the Tesla Model S, with a driving range of 160,000 km, can maintain more than 93% of the factory capacity without requiring battery replacement. In contrast, the 40-kWh battery of the Nissan Leaf can only maintain approximately 62%. [32] suggests that Fuel Cell Electric Vehicles (FCEVs) outperform Battery Electric Vehicles (BEVs) for vehicle ranges over 160 km. L.-I. Dulău [40] mentioned that the Hyundai Nexo has a traveling range of 756 km, while the Toyota Mirai has a range of 650 km. Szałek, Pielecha, and Cieslik (2021) state that FCEVs can reach a range of 600 km. E. Y. C. Wong *et al*. [31] claimed that the Toyota Mirai has a range of 500 km. O. Bethoux *et al*. [45] mentions that the Hyundai Nexo can cover 666 km based on the WLTC cycle. A. N. Mancino *et al*. [37] suggests a range of over 400 km. Finally, K. Wróbe *et al*. [45] and D. D. Wolf *et al*. [39] conducted a comparison of various car models as shown in Table 6 and 7.

Table 6 Comparison of various car models [39]

Car Model	Travelling range
Toyota Mirai	500 km
Honda Clarity	650 km
Hyundai ix 35	500 km

Table 7 Comparison of various car models [36]

Car Model	Travelling range
BMW Hydrogen 7	200 km (hydrogen) + 480 km (gasoline)
Ford P2000	100 km
Mazda RX-8 Hydrogen RE	100 km (hydrogen) + 500 km (gasoline)
ETEC Chevrolet Silverado	230-260 km
Toyota Quantum Prius	100-130 km
Volkswagen Polo-converted	~400 km

4.5 Hydrogen Production

According to the information presented in Table 4, majority of sources indicate that the hydrogen needed for cars is manufactured at industrial facilities and subsequently transported to fuel stations. This underscores the production of hydrogen is external to the car itself. Table 4 outlines all the processes involved in hydrogen production, revealing that these processes are conducted on a large scale, primarily within industrial settings. Interestingly, O. Bethoux [45], N. A. Baharuddin *et al.* [34] and J.-E. Shin [33] did not specify the processes involved in hydrogen production. However, they did mention refueling stations, indicating that the hydrogen used is produced externally.

Table 8 represents a comprehensive overview of various hydrogen production processes, including Electrolysis, Steam Reforming of Methane, Partial Oxidation of Hydrocarbons, Gasification of Biomass, and Coal Gasification. Electrolysis, a lab-based process, utilizes electrical energy to induce a non-naturally occurring reaction. However, it grapples with significant limitations such as high costs, low system efficiency, integration challenges, restricted freshwater access, and the expense of catalysts. Steam Reforming of Methane, not specified as lab-based, involves reacting natural gas with steam to yield hydrogen and carbon dioxide, but it raises concerns about greenhouse gas emissions and increased demand for depletable natural gas reserves. Similarly, Partial Oxidation of Hydrocarbons, not lab-based, results in synthesis gas but releases carbon dioxide.

Table 8 Hydrogen production process

Process	Concept	Lab Based		Limitation
		Yes	No	
Electrolysis [28], [29], [38], [46], [40], [47], [35], [43], [30], [39].	An electrical current is used to start a chemical reaction that would not happen naturally.	both		• High cost • Low system efficiency • System integration • Access of freshwater • Expensive catalyst
Steam reforming of methane [46], [40], [39]	The natural gas reacted with steam to produce hydrogen and carbon dioxide.	/		• Release Carbon dioxide as greenhouse gases • the increased demand for natural gas to produce hydrogen would deplete natural gas reserves.
Partial oxidation of hydrocarbons [29], [46], [39].	A controlled combustion process using a hydrocarbon feedstock, often methane or other hydrocarbons, in limited oxygen or air conditions. Partial oxidation results in the production of syngas, which is a mixture of hydrogen (H_2) and carbon monoxide (CO).	/		Release Carbon dioxide as greenhouse gases
Gasification of biomass [46], [40]	The process involves turning biomass, like organic materials from plants or garbage, into a gaseous mixture that includes hydrogen.	/		• Release Carbon dioxide as greenhouse gases • Need H2 separation process from mixture gas • Variable results depend on the catalysts • High capital cost
Coal gasification [46], [35]	Coal gasification is a process that transforms coal into a gas mixture consisting mainly of hydrogen and carbon monoxide.	/		• Release Carbon dioxide as greenhouse gases • Feedstock impurities • High reactor cost

Gasification of Biomass, another non-lab-based process, converts biomass into a hydrogen-containing gaseous mixture, but encounters challenges like carbon dioxide emissions, the need for hydrogen separation, variable outcomes dependent on catalysts, and high capital costs. Lastly, Coal Gasification, not specified as lab-based, transforms coal into a hydrogen-carbon monoxide gas mixture, but faces issues such as carbon dioxide emissions, feedstock impurities, and high reactor costs. These comparisons of hydrogen production processes show that the electrolysis process is the only method that produces green hydrogen, making it the most efficient way to generate hydrogen with zero emissions.

Electrolysis produces hydrogen without emitting greenhouse gases [48] if powered by renewable energy sources like solar, wind, or hydro, making it a cleaner alternative [49] [50] [51] to traditional methods such as steam methane reforming (SMR), which emit significant amounts of CO^2. Additionally, hydrogen can act as an energy storage medium, allowing excess electricity from renewable sources to be stored and used when supplied is low or high demand. The versatility of hydrogen produced through electrolysis enables its use in various applications, including fuel cells for vehicles, industrial processes, and residential energy needs.

5.0 DISCUSSION

5.1 Strength of the Hydrogen Car

Hydrogen fuel-cell electric vehicles (HFCEVs) present a compelling alternative within the realm of low-carbon transportation, boasting various advantages over alternative technologies. Firstly, they contribute to enhanced public health by circumventing air pollutants, thereby improving air quality. Notably, these vehicles yield a zero-carbon footprint, as they produce no tailpipe emissions, positioning them as an environmentally conscious option compared to traditional internal combustion engine vehicles [52] [53]. The high efficiency of FCEV further solidifies their status as a sustainable mode of transportation. Moreover, their minimal noise emissions contribute to quieter urban environments, promoting a more peaceful coexistence. With their potential for niche applications, particularly in public transportation, freight transport, and industrial settings where extended driving ranges and swift refueling times are paramount, hydrogen fuel-cell vehicles emerge as versatile solutions.

The strength of hydrogen cars lies in their potential for long driving ranges, quick refueling times, and the ability to provide high traction power. Hydrogen cars utilize high-pressure hydrogen tanks, which can be strategically placed to optimize vehicle space and passenger comfort [45]. The use of fuel cell systems (FCS) allows for efficient storage of reactants and rapid refueling, making them suitable for intensive use in applications such as taxis, buses, and long-distance heavy-duty vehicles. Additionally, hydrogen cars offer a viable alternative to battery electric vehicles (BEVs) and internal combustion engine vehicles (ICEVs) by providing long driving ranges, low emissions, and fast refueling times. These factors contribute to the strength of hydrogen cars as a potential solution for sustainable road transportation.

Additionally, hydrogen's ability to be produced from renewable sources such as solar and wind energy allows for the storage of excess energy, providing a solution for load balancing and reducing greenhouse gas emissions [53], [46] and [39], stated that green hydrogen is attained through the electrolysis process powered by renewable energies such as wind or solar. Electrolysis processes extend beyond the confines of industrial environments, finding diverse applications in non-industrial settings. The versatility of electrolysis allows for practical implementation in a range of contexts beyond conventional industrial sectors. Individuals and small-scale operations can harness electrolysis for purposes such as home hydrogen production, utilizing renewable energy sources like solar or wind to generate clean and sustainable hydrogen fuel.

The strength of hydrogen cars lies in their high efficiency and low energy density as a fuel [54], which translates to the highest energy density per kilogram [32]. This property is beneficial for hydrogen fuel, but it may pose challenges when storing it onboard. One solution to this challenge is storing hydrogen as a compressed gas at extremely high pressure. Additionally, hydrogen fuel cell vehicles have the potential to significantly reduce greenhouse gas emissions and offer extended driving ranges. However, challenges such as onboard hydrogen storage, cost, and infrastructure development need to be addressed for widespread adoption. Furthermore, hydrogen-powered trains demonstrate a range roughly ten times greater than the battery-powered electric trains, and hydrogen fuel cell technology has the potential to reduce the climate impact of the aviation industry by approximately 75% to 90%.

5.2 Challenges and Issues

Concerning infrastructure, the establishment of an extensive hydrogen distribution network is paramount to meet the increasing demand for hydrogen vehicles. Addressing the challenges of Norway's sparse population requires decentralized production methods like electrolysis, coupled with the integration of high CO^2 taxation to enhance the competitive cost of hydrogen. Strategic investments in production methods and infrastructure can position hydrogen cars as strong contenders in the shift towards sustainable transportation systems. However, significant obstacles persist, notably the high cost of hydrogen passenger cars compared to their battery electric counterparts, hindering widespread adoption. Infrastructure remains a challenge, with the absence of a dedicated pipeline network for hydrogen transportation, and energy losses along the hydrogen value chain raise efficiency concerns. Despite the hurdles, addressing these challenges is vital for the successful development of a hydrogen economy and the widespread adoption of hydrogen cars.

Transitioning away from fossil fuel vehicles in European cities poses challenges for both battery electric vehicles (BEVs) and fuel cell electric vehicles (FCEVs). Infrastructure demands for distributing alternative energies, such as hydrogen for FCEVs and electricity for BEVs, present a major hurdle. Autonomy concerns, varying ranges, and charging requirements differ between BEVs and FCEVs, impacting users with specific needs or longer commutes. While FCEVs offer longer ranges and quick refueling times, they come with higher purchase costs. Carbon emissions and safety considerations also differ, with BEVs potentially having lower CO^2 emissions but facing safety challenges related to battery fires. Efficiently locating charging stations is crucial for both types of vehicles, addressing user concerns about charging availability.

Overcoming challenges in infrastructure development, range limitations, costs, emissions, safety, and optimizing charging infrastructure is essential for the successful adoption of alternative propulsion in the transition towards sustainable transportation. Continued research and investment in both electric vehicle technologies are crucial for navigating these obstacles and maximizing the benefits of alternative propulsion.

5.3 Research gaps and Opportunities

In analyzing the research landscape regarding hydrogen mobility applications in small to medium-sized European cities and regions, the article recognizes several noteworthy elements. It offers a thorough overview of ongoing hydrogen initiatives, illuminating associated challenges, barriers, and opportunities. Particularly, the article underscores a research gap concerning best practices in multi-sector coupling, specifically overlooking the integration of hydrogen for both transportation and energy storage purposes. This oversight implies a potential avenue for exploration into the broader applications of hydrogen across diverse economic sectors beyond transportation. Additionally, the article acknowledges a limited discussion on the potential environmental and social impacts of hydrogen production and utilization, indicating a necessity for further investigation in this crucial area.

Shifting the focus to the extensive integration of electric vehicles (EVs), a separate document conducts an in-depth examination of various studies to investigate both the environmental and economic consequences of this transition. Encompassing a wide array of subjects including life cycle assessment (LCA), greenhouse gas emissions, energy consumption, and the influence of subsidy policies, the document provides insights into the intricacies and difficulties associated with the widespread adoption of EVs. Moreover, it explores the environmental and economic aspects related to the operation of equipment for EVs, such as charging infrastructure and smart grids, presenting a comprehensive perspective on the challenges and opportunities within this dynamic landscape.

Finally, the examination extends to the realm of hydrogen fuel cell systems (FCS) designed for road vehicles, with a specific focus on challenges associated with reducing costs, ensuring compactness, and extending the lifespan of fuel cell vehicles (FCVs). In identifying prospects for research and development, the article underscores the imperative of cost reduction in FCS, achieving compact design enhancements without compromising vehicle functionality, and prolonging the longevity of FCVs. The challenges outlined, particularly in terms of sourcing cost-effective materials, achieving a compact yet durable design, present opportunities for inventive solutions. Additionally, the document highlights the potential of FCVs in long-distance heavy-duty vehicles and various market segments, envisioning a shift from niche markets to a more widespread market for hydrogen. This transformative process demands a comprehensive grasp of business models and supply chain strategies, addressing environmental and economic considerations throughout the entire value chain. Essentially, the research gap lies in overcoming hurdles related to cost, compactness, and lifespan, while the opportunities emerge from exploring the diverse potential applications of FCVs and formulating appropriate business models and supply chain strategies.

6.0 CONCLUSION

In summary, the advancement and integration of hydrogen fuel cell technology in automotive applications shows immense potential for a sustainable and environmentally friendly future. The research outlined in this journal highlights progress in hydrogen car technology, emphasizing its capacity to transform the transportation sector. Hydrogen fuel cells, known for their efficiency and eco-friendly attributes, present a compelling alternative to conventional fossil fuel-powered vehicles. The studies discussed demonstrate notable advancements in performance, range, and infrastructure support for hydrogen cars. Despite the positive strides, challenges such as cost, infrastructure development, and public acceptance persist. Nonetheless, the encouraging developments suggest a promising future for hydrogen-powered vehicles.

Looking ahead, it is imperative to intensify research and development efforts to overcome the challenges and unlock the potential of hydrogen cars. Future initiatives should prioritize key areas, starting with a thorough exploration of strategies to significantly reduce the manufacturing and operational costs associated with hydrogen fuel cell vehicles. Collaborative efforts with stakeholders are crucial to expedite the establishment of a robust hydrogen refueling infrastructure, providing the necessary support for widespread adoption. Technological innovations must be pursued, delving into advancements in fuel cell technology, materials, and energy storage to enhance the overall efficiency and performance of hydrogen cars. Furthermore, there is a need for comprehensive public awareness campaigns to educate and inform the public about the numerous benefits of hydrogen cars while dispelling any misconceptions. Advocacy for supportive policies that incentivize the adoption of hydrogen fuel cell vehicles and foster a conducive regulatory environment is equally important. By concentrating on these critical areas in future research and development endeavors, the realization of a sustainable and mainstream hydrogen-powered automotive sector becomes feasible.

More research should investigate the electrolysis process in conjunction with fuel cell vehicles, with the use of thin-film solar panels to improve the present hydrogen vehicle technology. This innovative approach could enable on-board hydrogen production using solar energy, thereby reducing reliance on external hydrogen refueling infrastructure and addressing one of the primary challenges in hydrogen vehicle adoption. By harnessing solar power to generate hydrogen through electrolysis, vehicles could achieve greater energy independence and efficiency. Research should focus on optimizing the efficiency of thin-film solar panels, enhancing the integration of these panels with the electrolysis and fuel cell systems, and ensuring the overall feasibility and performance of this integrated solution under various environmental conditions. Additionally, studies should evaluate economic viability, environmental impact, and practical implementation of this technology, paving the way for more sustainable and self-sufficient hydrogen-powered transportation.

The hydrogen that is produced from this electrolysis process will serve as a clean and renewable energy source for EV. This proposed technique also eliminates the need of external refueling infrastructure for hydrogen vehicles (eg; hydrogen car). This self-contained system exemplifies the concept of portable green hydrogen, as the vehicle becomes a mobile hydrogen production unit. By integrating renewable energy, electrolysis, and hydrogen storage directly into the vehicle, it will contribute to the advancement of eco-friendly transportation solutions, reducing carbon emissions and fostering a more sustainable future. Figure 4 shows the conceptual of proposed technique mentioned below.

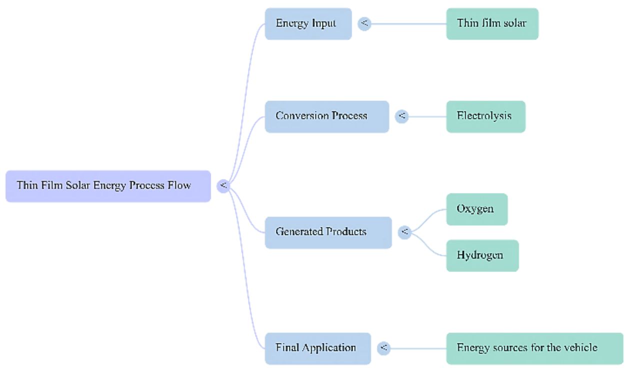


Figure 4 Block diagram of the proposed technique

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Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

References

[1] Mikhaylov, A., N. Moiseev, K. Aleshin, and T. Burkhardt. 2020. Global Climate Change and Greenhouse Effect. *Entrepreneurship and Sustainability*. 7(4): 2897.

[2] Dhar, S., M. Pathak, and P. R. Shukla. 2018. Transformation of India's Transport Sector under Global Warming of 2°C and 1.5°C Scenario. *Journal of Cleaner Production*. 172: 417–427.

[3] Hannappel, R. 2017. The Impact of Global Warming on the Automotive Industry. In *AIP Conference Proceedings*. 1871(1).

[4] QiaoHong, S., M. ChiYuan, M. Hanel, A. G. L. Borthwick, D. QingYun, J. DuoYing, and L. Hu. 2019. Global Heat Stress on Health, Wildfires, and Agricultural Crops under Different Levels of Climate Warming. *Environment International*. 128: 125–136.

[5] Ahmed, A. A., M. A. Nazzal, B. M. Darras, and I. M. Deiab. 2023. Global Warming Potential, Water Footprint, and Energy Demand of Shared Autonomous Electric Vehicles Incorporating Circular Economy Practices. *Sustainable Production and Consumption*. 36: 449–462.

[6] Albatayneh, A., A. Juaidi, M. Jaradat, and F. Manzano-Agugliaro. 2023. Future of Electric and Hydrogen Cars and Trucks: An Overview. *Energies*. 16(7): 3230.

[7] Oluwalana, O. J., and K. Grzesik. 2025. Solar-Powered Electric Vehicles: Comprehensive Review of Technology Advancements, Challenges, and Future Prospects. *Energies*. 18(14): 3650.

[8] Sanguesa, J. A., V. Torres-Sanz, P. Garrido, F. J. Martinez, and J. M. Marquez-Barja. 2021. A Review on Electric Vehicles: Technologies and Challenges. *Smart Cities*. 4: 372–404.

[9] Boström, T., B. Babar, J. B. Hansen, and C. Good. 2021. The Pure PV-EV Energy System—A Conceptual Study of a Nationwide Energy System Based Solely on Photovoltaics and Electric Vehicles. *Smart Energy*. 1: 100001.

[10] Mehrjerdi, H. 2019. Off-Grid Solar Powered Charging Station for Electric and Hydrogen Vehicles Including Fuel Cell and Hydrogen Storage. *International Journal of Hydrogen Energy*. 44: 11574–11583.

[11] Alhazmi, Y. A. 2025. Electric Vehicle Battery Swap Stations: An Overview and Critical Review. *Journal of Umm Al-Qura University for Engineering and Architecture*. 1–14

[12] Berggren, C., and T. Magnusson. 2012. "Reducing Automotive Emissions—The Potentials of Combustion Engine Technologies and the Power of Policy. *Energy Policy*. 41: 636–643.

[13] Sery, J., and P. Leduc. 2022. Fuel Cell Behavior and Energy Balance on Board a Hyundai Nexo. *International Journal of Engine Research*. 23(5): 709–720.

[14] Borawake, O. K., Y. Khandarkar, T. Alam, and D. Kore. 2023. A Comprehensive Review of Hydrogen Automobiles Future Prospects. *International Research Journal of Engineering and Technology (IRJET)*. 10(7): 1232–1238.

[15] Shao, C., C. Feng, M. Shahidehpour, Q. Zhou, X. Wang, and X. Wang. 2021. Optimal Stochastic Operation of Integrated Electric Power and Renewable Energy with Vehicle-Based Hydrogen Energy System. *IEEE Transactions on Power Systems*. 36(5): 4310–4321.

[16] Fayaz, H., R. Saidur, N. Razali, F. S. Anuar, A. R. Saleman, and M. R. Islam. 2012. An Overview of Hydrogen as a Vehicle Fuel." *Renewable and Sustainable Energy Reviews*. 16(8): 5511–5528.

[17] Sun, Y., M. Anwar, N. M. S. Hassan, M. Spiryagin, and C. Cole. 2021. A Review of Hydrogen Technologies and Engineering Solutions for Railway Vehicle Design and Operations. *Railway Engineering Science*. 29: 212–232.

[18] Varga, Á. 2007. "Introduction to Fuel Cell Technology. In *Introduction to Fuel Cell Technology*. 1–32. Boston, MA: Springer.

[19] Yue, M., H. Lambert, E. Pahon, R. Roche, S. Jemei, and D. Hissel. 2021. Hydrogen Energy Systems: A Critical Review of Technologies, Applications, Trends and Challenges. *Renewable and Sustainable Energy Reviews*. 146: 111180.

[20] Wong, E. Y. C., D. C. K. Ho, S. So, C.-W. Tsang, and E. M. H. Chan. 2021. Life Cycle Assessment of Electric Vehicles and Hydrogen Fuel Cell Vehicles Using the GREET Model—A Comparative Study. *Sustainability*. 13(9): 4872.

[21] Kolbe, Karin, S. Lechtenböhmer, and M. Fischedick. 2020. Hydrogen Derived from Algae and Cyanobacteria as a Decentralized Fueling Option for Hydrogen Powered Cars: Size, Space, and Cost Characteristics of Potential Bioreactors. *International Journal of Sustainable Transportation*. 14(5): 325–334.

[22] Ewelina, P., N. Łukasik, I. Wysocka, A. Rogala, and J. Gębicki. 2022. Recent Progress on Hydrogen Storage and Production Using Chemical Hydrogen Carriers. *Energies*. 15(14): 4964.

[23] Hren, R., A. Vujanović, Y. V. Fan, J. J. Klemeš, D. Krajnc, and L. Čuček. 2023. Hydrogen Production, Storage and Transport for Renewable Energy and Chemicals: An Environmental Footprint Assessment. *Renewable and Sustainable Energy Reviews*. 173: 113113.

[24] Lane, B., B. Shaffer, and S. Samuelsen. 2020. A Comparison of Alternative Vehicle Fueling Infrastructure Scenarios. *Applied Energy*. 259: 114128.

[25] Greene, D. L., J. M. Ogden, and Z. Lin. 2020. Challenges in the Designing, Planning and Deployment of Hydrogen Refueling Infrastructure for Fuel Cell Electric Vehicles. *eTransportation*. 6: 100086.

[26] Shaffril, H. A. M., A. A. Samah, and S. Kamarudin. 2021. Speaking of the Devil: A Systematic Literature Review on Community Preparedness for Earthquakes. *Natural Hazards.* 108(3): 2393–2419.

[27] Sarkis-Onofre, R., F. Catalá-López, E. Aromataris, and C. Lockwood. 2021. How to Properly Use the PRISMA Statement. *Systematic Reviews.* 10(1): 117.

[28] Akac, A., K. Tsiatsiou, and A. Angelakakis. 2022. A Review on Best Practices Using Hydrogen Fuel-Cell Electric Vehicles in Public Transport. *IOP Conference Series: Earth and Environmental Science*. 1123: 012055.

[29] Wang, N., and G. Tang. 2022. A Review on Environmental Efficiency Evaluation of New Energy Vehicles Using Life Cycle Analysis. *Sustainability*. 14(6): 3371.

[30] Xiaoxin, Z., C. Qigong, and G. Yuan. 2023. Optimal Scheduling of Integrated Energy Systems Including Hydrogen Electrolyzers, HFCVs, and Electric Vehicles. *Energy Science & Engineering*. 11(1): 347–356.

[31] Wong, E. Y. C., D. C. K. Ho, S. So, C.-W. Tsang, and E. M. H. Chan. 2021. Life Cycle Assessment of Electric Vehicles and Hydrogen Fuel Cell Vehicles Using the GREET Model—A Comparative Study. *Sustainability.* 13(9): 4872.

[32] Fakhreddine, O., Y. Gharbia, J. F. Derakhshandeh, and A. M. Amer. 2023. Challenges and Solutions of Hydrogen Fuel Cells in Transportation Systems: A Review and Prospects. *World Electric Vehicle Journal.* 14(6): 156.

[33] Shin, J.-E. 2022. Hydrogen Technology Development and Policy Status by Value Chain in South Korea. *Energies.* 15(23): 8983.

[34] Baharuddin, N. A., W. W. Yusoff, A. J. A. Aziz, and N. M. Tahir. 2021. Hydrogen Fuel Cells for Sustainable Energy: Development and Progress in Selected Developed Countries. *IOP Conference Series: Materials Science and Engineering.* 1078(1): 012011.

[35] Szałek, A., I. Pielecha, and W. Cieslik. 2021. Fuel Cell Electric Vehicle (FCEV) Energy Flow Analysis in Real Driving Conditions (RDC). *Energies.* 14(16): 5018.

[36] Wróbel, K., J. W. W. Tokarz, J. Lach, K. Podsadni, and A. Czerwiński. 2022. Hydrogen Internal Combustion Engine Vehicles: A Review. *Energies.* 15(23): 8937.

[37] Mancino, A. N., C. Menale, F. Vellucci, M. Pasquali, and R. Bubbico. 2023. PEM Fuel Cell Applications in Road Transport. *Energies.* 16(17): 6129.

[38] Habib, M. S., P. Arefin, and R. Situmeang. 2022. Adoption of Hydrogen Fuel Cell Vehicles and Its Prospects for the Future. *Oriental Journal of Chemistry*. 38(6): 12995–13005.

[39] Wolf, D. D., and Y. Smeers. 2023."Comparison of Battery Electric Vehicles and Fuel Cell Vehicles. *World Electric Vehicle Journal*.14(9): 262.

[40] Dulău, L.-I. 2023. CO_2 Emissions of Battery Electric Vehicles and Hydrogen Fuel Cell Vehicles. *Clean Technologies.* 5(2): 696–712.

[41] Alves, M. P., W. Gul, C. A. C. Junior, and S. K. Ha. 2022. A Review on Industrial Perspectives and Challenges on Material, Manufacturing, Design and Development of Compressed Hydrogen Storage Tanks for the Transportation Sector. *Energies.* 15(14): 5152.

[42] Wiśniowski, P., A. Borucka, M. Menes, and A. Świderski. 2022. CO Emission Costs Due to the Production and Use of Vehicles in the Context of Automotive Development. *Transport and Telecommunication Journal*. 23(4): 311–319.

[43] Hoque, N., W. Biswas, I. Mazhar, and I. Howard. 2020. Life Cycle Sustainability Assessment of Alternative Energy Sources for the Western Australian Transport Sector. *Sustainability.* 12(14): 5565.

[44] Shao, C., C. Feng, M. Shahidehpour, Q. Zhou, X. Wang, and X. Wang. 2021. Optimal Stochastic Operation of Integrated Electric Power and Renewable Energy with Vehicle-Based Hydrogen Energy System. *IEEE Transactions on Power Systems.* 36(5): 4310–4321.

[45] Bethoux, O. 2020. Hydrogen Fuel Cell Road Vehicles: State of the Art and Perspectives. *Energies.* 13(21): 5843.

[46] Ahad, M. T., M. M. H. Bhuiyan, A. N. Sakib, A. B. Corral, and Z. Siddique. 2023. An Overview of Challenges for the Future of Hydrogen. *Materials.* 16(20): 6680.

[47] Yazdi, M., R. Moradi, R. G. Pirbalouti, E. Zarei, and H. Li. 2023. Enabling Safe and Sustainable Hydrogen Mobility: Circular Economy-Driven Management of Hydrogen Vehicle Safety. *Processes.* 11(9): 2730.

[48] Kumar, S. S., and V. Himabindu. 2019. Hydrogen Production by PEM Water Electrolysis—A Review. *Materials Science for Energy Technologies.* 2(3): 442–454.

[49] Ozturk, M., and I. Dincer. 2021. A Comprehensive Review on Power-to-Gas with Hydrogen Options for Cleaner Applications. *International Journal of Hydrogen Energy.* 46 62: 31511–31522.

[50] Nnabuife, S. G., A. K. Hamzat, J. Whidborne, B. Kuang, and K. W. Jenkins. 2024. Integration of Renewable Energy Sources in Tandem with Electrolysis: A Technology Review for Green Hydrogen Production. *International Journal of Hydrogen Energy*.

[51] Ishaq, H., I. Dincer, and C. Crawford. 2022. A Review on Hydrogen Production and Utilization: Challenges and Opportunities. *International Journal of Hydrogen Energy.* 47(62): 26238–26264.

[52] Yao, Z., W. Qi, J. Wang, Z. Ding, X. Jiang, Y. Hong, and Y. Li. 2023. Safety Risk and Strategy Analysis of On-Board Hydrogen System of Hydrogen Fuel Cell Vehicles in China. *Energies.* 16(23): 7727.

[53] Albatayneh, A., A. Juaidi, M. Jaradat, and F. Manzano-Agugliaro. 2023. Future of Electric and Hydrogen Cars and Trucks: An Overview. *Energies.* 16(7): 3230.

[54] Rajalakshmi, N., R. Balaji, and S. Ramakrishnan. 2021. Recent Developments in Hydrogen Fuel Cells: Strengths and Weaknesses. In *Sustainable Fuel Technologies Handbook*, 431–456. Academic Press.