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Hydrogen fuel cell heavy-duty trucks: review of main research topics

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ABSTRACT

Road transportation is a significant source of CO_2 emissions and energy demand. Consequently, initiatives are being promoted to decrease the sector's emissions and comply with the Paris agreement. This article synthesizes the available information about heavy-duty fuel cell trucks as their deployment needs to be considered a complementary solution to decreasing CO_2 emissions alongside battery electric vehicles. A thorough evaluation of 95 relevant documents determines that the main research topics in the past ten years converge on public policies, hydrogen supply chain, environmental impact, drivetrain technology, fuel cell, and storage tank applications. The identified research gaps relate to expanding collaboration between institutions and governments in developing joint green macro policies focused on hydrogen heavy-duty trucks, scarce research about hydrogen production energy sources, low interest in documenting hydrogen pilot projects, and minimal involvement of logistic companies, which need to plan their diesel freight's conversion as soon as possible.

1. Introduction

Transport consumes 28% of total energy demand and is a significant source of CO_2 emissions, growing as much as 10.3 Gt CO_2/year globally by 2040 [1]. This sector is among the most 'hard-to-abate', and the difficulty of decarbonizing it comes from the high vehicle dependency, rapid adoption of vehicles in developed countries, mature and inexpensive combustion-based engine technologies, low petroleum costs, and limited alternatives to petroleum-based fuels [1].

Additionally, the transport sector worldwide consumes less than 3.4% of renewable energies, heavily depends on oil and petroleum products, and road transport is the most energy demanding sub-sector [2]. As a result, it is critical to implement short and medium-term solutions for decarbonizing this segment and contribute to upfront the CO_2 emission crisis and temperature rising that is developing worldwide.

One way of decarbonizing the road transport sector is by using battery electric vehicles (BEVs) and fuel cell electric vehicles (FCEVs). These vehicles include different types and sizes, ranging from light-duty passenger vehicles to heavy-duty trucks, trains, boats, and planes.

BEVs and FCEVs have many advantages over their diesel counterparts. First, BEVs electric powertrain has higher energy efficiency than internal combustion engines since they have less heat loss [3]. They also have power reversibility associated with a charge-discharge efficiency of the Li-Ion batteries, which reduce the overall energy consumption by recovering braking energy. However, intensive use and long distances require high energy storage, which increases battery mass, reduces available cargo volume in the vehicle, and boosts costs and energy consumption [4]. Therefore, BEVs are proven to be more suitable for passengers and light-duty applications.

FCEVs commonly use hydrogen gas as a power source, generated with different energy sources. Although there is no universal agreement on hydrogen name colors, “green” hydrogen is called when it is produced from water by electrolysis using electricity from renewable resources [5], most commonly solar or wind power energy. Nevertheless, the cheapest hydrogen production is “grey” hydrogen, obtained via steam reforming of natural gas. If this process is combined with carbon capture technology, CO_2 emissions are mitigated, and “blue” hydrogen is obtained [5,6].

FCEVs are more suitable for replacing heavy-duty internal combustion vehicles because this energy vector has a high specific energy density, and fuel cells have good energy efficiency. Hence FCEVs have faster charging times and greater autonomy compared to BEVs [7].

Furthermore, hydrogen tanks take up less space and are lighter than batteries, so more load can be transported in the trailer. The challenge is finding efficient, safe, compact, and cost-effective hydrogen storage solutions by improving materials’ development [8]. This would lead to optimal spatial packing within the vehicle and efficient thermal management for delivering the required vehicle capability and performance [9]. For providing a safe hydrogen delivery to the vehicle, several details must be considered during charging time, e.g., the state of charge, the vehicle tank temperature, the hydrogen flow rate, the amount of hydrogen gas accumulated in the vehicle’s tank, and the high-pressure storage vessels’ conditions [10]. Another aspect worth highlighting about FCEVs safety is that an explosion hazard exists associated with the use of hydrogen gas, so in case of leakage, an appropriate fire extinguisher and ventilation systems are required [11].

Hybrid vehicles combine both technologies: a battery and a fuel cell. The challenge in this case, is finding optimum energy management by maximizing hydrogen economy and sustaining the battery charge [12–17]. Additionally, if done correctly, this hybridization could bring interesting benefits once it overcomes some barriers, such as cost, durability, and hydrogen refueling infrastructure. If an optimum size of fuel cells and battery modules could be achieved, hydrogen consumption and vehicle cost could be minimized [18].

From the environmental point of view, BEVs and FCEVs do not produce emissions other than those related to evaporation (e.g., paint) and wear (e.g., tires and brakes) [3], and FCEVs only emit water at the tailpipe. However, energy consumption and emissions must be considered during electricity production and the hydrogen supply chain, especially if grey or blue hydrogen is used. BEVs generally entail the lowest emissions when certain conditions such as sector coupling, seasonal energy storage, or demand management can be implemented. Otherwise, FCEVs that use hydrogen produced through solar energy or curtailment of excess electricity have even lower emissions than BEVs [19]. Another possibility to reduce emissions is using vehicles with a mix of hydrogen and natural gas or gasoline. This represents a good opportunity to encourage the use of hydrogen in the short term as well [20].

From the user’s point of view, drivers’ decision about considering a zero-emission vehicle in their next car purchase is not that obvious. FCEVs would have great potential if users received government support because their main barriers seem economical and related to purchase price and fuel availability [21]. Other detected barriers would be the driving range, fuel costs, and vehicle type. Less significant barriers would be the charging infrastructure, the CO_2 vehicle's emissions, and a CO_2 tax [22]. Furthermore, in some cases, barriers are due to information deficit, and a "chicken and egg" problem arises. Users do not choose BEVs or FCEVs due to their high prices and sometimes limited available infrastructure compared to diesel vehicles because they do not know about the benefits of these vehicles or their environmental impacts, and they lack encouragement to accept and use them [23]. Furthermore, the development of charging stations could be inclined toward a general trend of innovation that starts with early adopters, and is not only based on finding the appropriate cities ready to adopt the technology [24].

Because of the benefits that FCEVs present compared to BEVs in the heavy-duty road transport sector, numerous countries are considering deploying FCEVs in their environmental pathway toward a more sustainable economy, supported, among other things, by transport models that forecast the impact of these net-zero strategies [25].

This research aims to synthesize and analyze the available information in the literature regarding hydrogen heavy-duty fuel cell trucks (HFCTs), find research gaps, and suggest a call to action to implement these net-zero vehicles' strategies. Scientific articles indexed in well-known databases are used to guarantee quality results from high-impact journals.

Since this study focuses on heavy-duty trucks, other vehicles like cars, trains, trams, forklifts, buses, or garbage trucks are excluded. Additionally, only hydrogen technology is evaluated as a primary and only mobility energy source, so other technologies like catenary vehicles, battery-extended vehicles, battery electric vehicles, hybrid vehicles, or hydrogen production methods unrelated to transport applications are also excluded.

The following methodology is implemented to collect and analyze the available information: after gathering papers related to the subject, articles are filtered, classified, and evaluated using primary data collection techniques regarding authors, affiliation, and other attributes. Afterward, common topics are extracted to summarize findings and identify research gaps. From this procedure, six general research categories are obtained and analyzed.

2. Methodology

Available information on the subject is consulted using a systematic review approach. As this is a relatively new topic that has been recently developed and studied, documents published in Scopus and Web of Science databases in the last ten years (2011 to 2021) are selected. The following string is used to gather the specific information about hydrogen fuel cell trucks/heavy-duty and their application in the transport system:

TOPIC: (hydrogen) AND TOPIC: ("fuel cell") AND TOPIC: (truck* OR "heavy-duty" OR "transport* system")*

The search focuses on any type of English article related to the aforementioned topics. After comparing titles and authors, duplicates between both consulted databases are excluded, resulting in 369 documents retrieved from the search.

A general check is done over the search results. Even though a filter language was initially made in the database research, four documents were found with an abstract written in English and the core article written in another language, so they were eliminated.

After that, the duplicated documents regarding the same conference paper and article were also eliminated, maintaining only the journal article in the list.

The resulting documents are thoroughly examined to check if they fulfill the selected research criteria and scope. Abstracts, keywords, and introductions are considered in this stage. Several documents are disregarded because they relate to other types of vehicles that are not part of the study scope or have no resemblance to the mobility topic.

In summary, 95 documents are selected for further analysis, as seen in Figure 1.

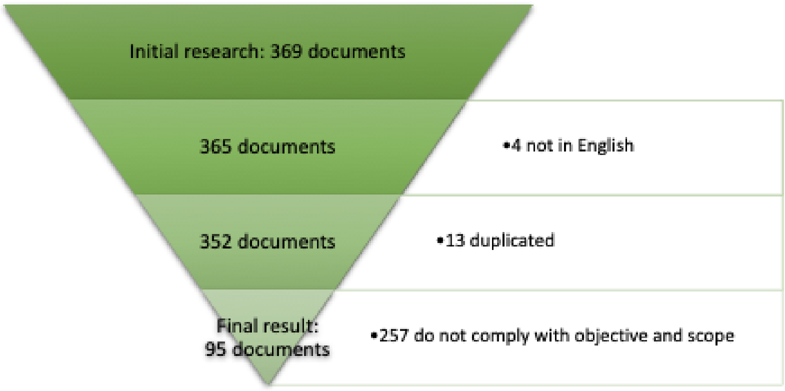


Figure 1: steps of the systematic review implemented in this research.

The resulting 95 documents are classified using a bibliometric analysis according to type (article, conference paper, or review article), year published, country, affiliation, journal (in case of articles and reviews), and authors.

In order to have a general understanding of the research approach and the topics covered in each selected document, a methodology based on the principles of systematic mapping (or evidence mapping) and narrative review is used [26]. After reading the papers, notes are taken to describe the main topics discussed. Afterward, results are analyzed, and six common topics emerge as recurrent in the bibliography. They are presented as follows:

- **Public policies:** includes recommendations addressed to a government to develop or accelerate a hydrogen mobility decarbonization strategy involving the deployment of HFCTs. These recommendations include several topics ranging from emissions regulations to commercialization strategies, or vehicle and refueling stations deployment strategies.
- **Hydrogen supply chain:** analyzes hydrogen production, storage, distribution, and/or commercialization, and its implementation for direct use in HFCTs. This topic also includes studies of business models, different hydrogen production options, and various configurations of refueling stations. The last topic appears as predominant and considers hydrogen demand, hydrogen distribution, and optimization of location and size of the hydrogen infrastructure.
- **Environmental impact:** evaluates greenhouse gas (GHG) emissions or other environmental impacts, e.g., particulate matter, when considering the use of HFCTs. These studies also focus on hydrogen's life cycle environmental footprint, considering emissions of hydrogen production methods. Reducing emissions in the hydrogen supply chain generally means decarbonizing the energy production matrix.
- **Drivetrain technology:** evaluates and/or compares different vehicle powertrain technologies for HFCTs. Most articles explore the differences between diesel, battery,

fuel cell, and other energy source drivetrains from various points of view, and even expand the study to vehicle freights. Others, focus their approach on general descriptions and analysis of HFCTs.

- **Fuel cell application:** investigates technology applications on a specific part of the vehicle: the fuel cell. This relatively new topic within HFCTs focuses on studies about different types of fuel cells, including materials' compositions, fuel cell components, and methods for improving the cell's efficiency.
- **Storage tank system application:** explores technology applications on a specific part of the vehicle: the hydrogen storage system. Vessels containing gas or liquid hydrogen for HFCTs are studied, including their design, location within the truck, and safety.

These topics encompass different pathways. Some focus on the vehicle itself and its technology, such as drivetrain technology, fuel cell, and storage tank application research areas. In contrast, others focus on general aspects that impact the use and commercialization of HFCTs and hydrogen for mobility. This is the case for the hydrogen supply chain, public policies, and environmental impact topics.

An additional categorization of the content of the articles is performed, resulting in a practical o theoretical approach. A "practical" classification is used when a laboratory analysis, strategy implementation, or evaluation result from previous research is conducted. On the other hand, a "theoretical" category is used when articles perform analysis, investigation, or suggestions that do not entail real-life applications.

3. Bibliometric analysis

After applying the aforementioned methodology, 95 filtered documents are analyzed. 76% correspond to journal articles, 18% are conference papers, and 6% are reviews. The evolution in the number of documents published about HFCTs over the past ten years can be seen in Figure 2.

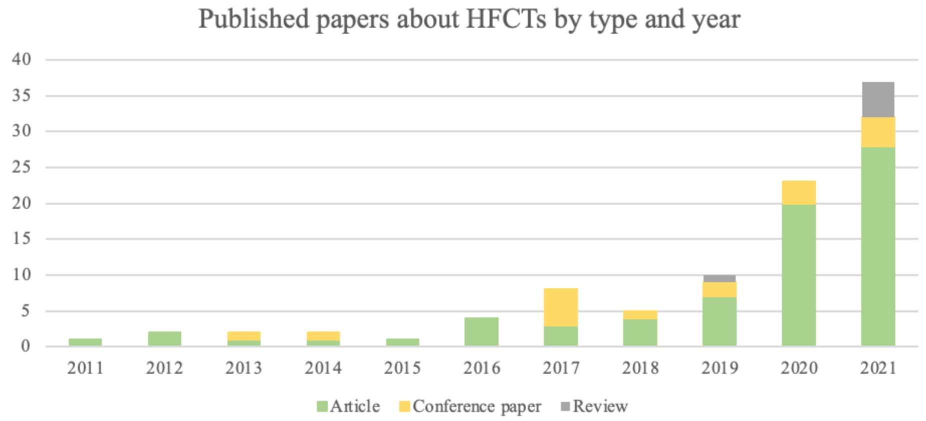


Figure 2: published papers about HFCTs in the last ten years.

At the beginning of the analyzed period, document production was scarce, but in 2020 the numbers started to increase significantly. This 'explosion' was prominent regarding journal articles mainly, and document indexation increased 270% from 2019 to 2021 in the consulted databases, reflecting the recent relevance FCEVs have acquired as a decarbonization strategy.

When studying the most influential countries regarding significant document contribution to HFCTs topics, the United States comes first with 27 published documents, followed by Germany (17), the United Kingdom (14), China (11), and Canada (11), along with 13 other countries which made an independent contribution. Moreover, there has been a strong collaboration between two or more countries, resulting in 22 joint publications. Figure 3 shows a collaboration map between the countries analyzed. The bigger the node, the greater amount of publications the country has in terms of research in HFCTs in the last ten years. Additionally, the thicker the edge, the greater number of joint publications the countries have.

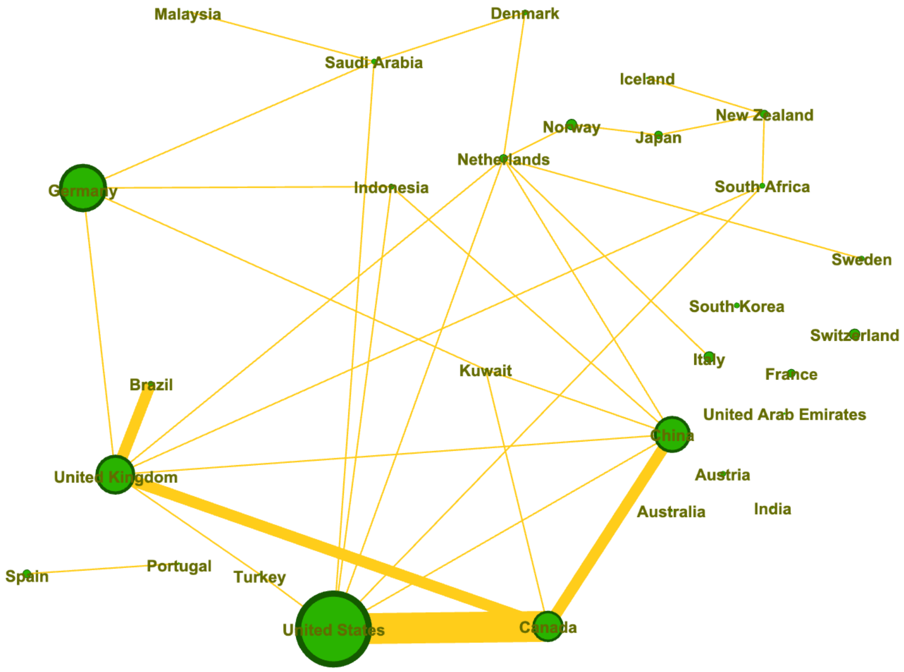


Figure 3: HFCTs published papers by country and collaboration between countries in the last ten years.

The information shown in Figure 3 indicates which countries are leaders in researching on HFCTs, and exposes that South America and Africa are the least represented continents. From South America, only one study was found about the city of Sao Paulo in Brazil [27], and from Africa, one study was found as well, focused on South Africa's future road transport system [28]. Both were made in collaboration with the United Kingdom.

Regarding affiliation, Figure 4 shows that 73% of the documents are written by universities and research institutes, whereas companies and governments have a lower publishing rate of 7 and 6%, respectively. Additionally, bilateral associations between institutes are not predominant even though companies work with academia in 8% of the papers.

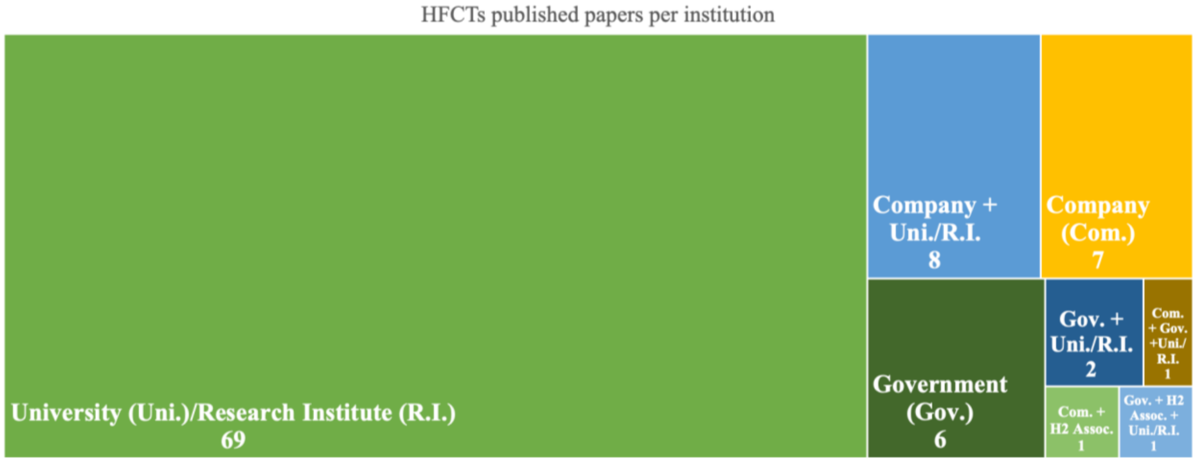
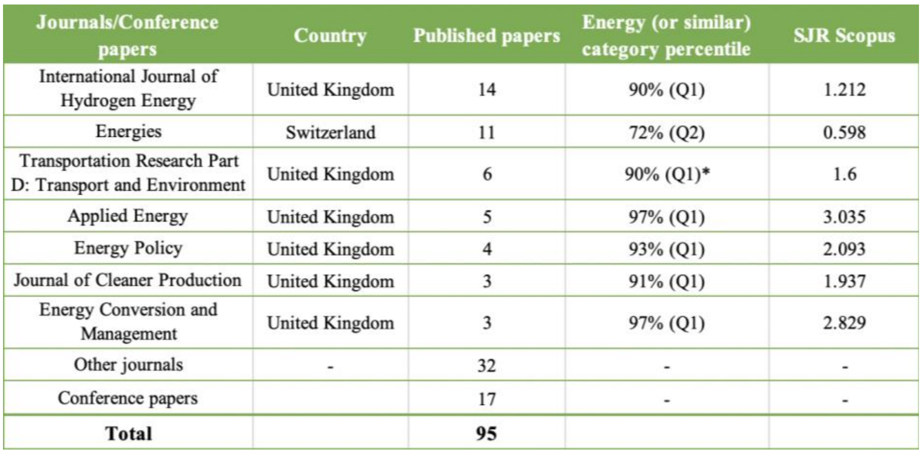


Figure 4: HFCTs published papers per institution in the last ten years.

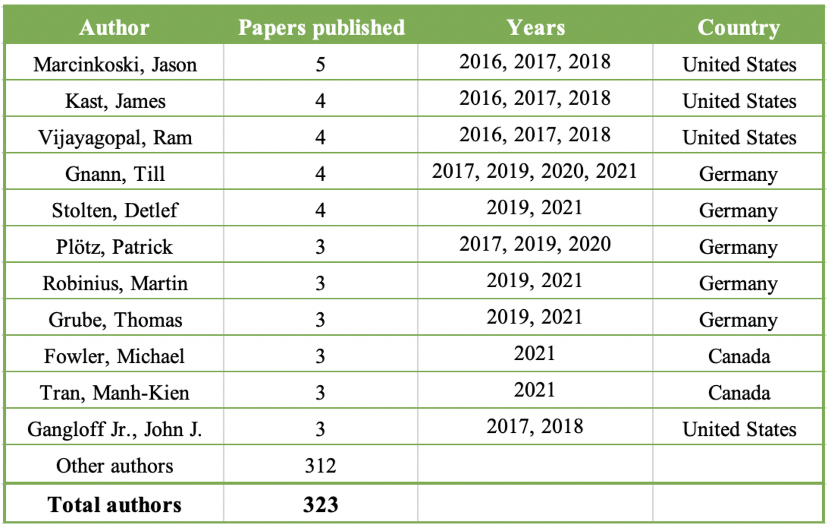
When examining the most popular journals to publish research about HFCTs, the “International Journal of Hydrogen Energy” ranks first with 15% of the published papers. Other journals with a significant publishing percentage are “Energies” (12%) and “Transportation Research Part D: Transport and Environment” (6%). Table 1 shows the number of articles published in each journal, together with its impact metrics. The category percentiles [29], the quartile rankings, and the SCImago Journal Rank (SJR) [30] numbers are associated with the Scopus database and Scopus journal ranking. Most of the journals mentioned belong to the Q1 quartile and have a cite score rank in the energy category (or similar) of more than 90%.



Journals/Conference papers	Country	Published papers	Energy (or similar) category percentile	SJR Scopus
International Journal of Hydrogen Energy	United Kingdom	14	90% (Q1)	1.212
Energies	Switzerland	11	72% (Q2)	0.598
Transportation Research Part D: Transport and Environment	United Kingdom	6	90% (Q1)*	1.6
Applied Energy	United Kingdom	5	97% (Q1)	3.035
Energy Policy	United Kingdom	4	93% (Q1)	2.093
Journal of Cleaner Production	United Kingdom	3	91% (Q1)	1.937
Energy Conversion and Management	United Kingdom	3	97% (Q1)	2.829
Other journals	-	32	-	-
Conference papers		17	-	-
Total		**95**		

Table 1: most popular journals with published topics about HFCTs in the last ten years.
* “Transportation” category used.

Related to the authors, 323 contributed to this research topic. Jason Marcinkoski from the Department of Energy (United States) stands out with five contributions. At the same time, his colleagues James Kast from the Department of Energy (United States) and Ram Vijayagopal from Argonne National Laboratory (United States) appear with four papers each. Other thriving authors are Till Gnann from the Fraunhofer Institute for Systems and Innovation Research (Germany), and Detlef Stolten from the Institute of Energy and Climate Research from Forschungszentrum Jülich (Germany), also with four articles each. Only five out of 34 researchers with more than two publications are women. This indicates that the participation and education of women in this topic should be further promoted to achieve equal opportunities in this work field. Table 2 shows the most prolific authors with additional information about their published papers.



Author	Papers published	Years	Country
Marcinkoski, Jason	5	2016, 2017, 2018	United States
Kast, James	4	2016, 2017, 2018	United States
Vijayagopal, Ram	4	2016, 2017, 2018	United States
Gnann, Till	4	2017, 2019, 2020, 2021	Germany
Stolten, Detlef	4	2019, 2021	Germany
Plötz, Patrick	3	2017, 2019, 2020	Germany
Robinius, Martin	3	2019, 2021	Germany
Grube, Thomas	3	2019, 2021	Germany
Fowler, Michael	3	2021	Canada
Tran, Manh-Kien	3	2021	Canada
Gangloff Jr., John J.	3	2017, 2018	United States
Other authors	312		
Total authors	**323**		

Table 2: HFCTs most contributing authors, publications, and years.

As mentioned before, six research categories represent the main topics scholars investigate and write about in their papers. A summary of this classification together with a practical and theoretical approach classification distributed by affiliation, is presented in Table 3.

Topic	Application	Uni./R.I.	Com.+ Uni./R.I.	Com.	Gov.	Gov.+ Uni./R.I.	Gov.+H2 Assoc.+ Uni./R.I.	Com.+Gov. +Uni./R.I.	Com.+ H2 Assoc.	Total
Public policies	Practical implementation	0	0	1	0	0	0	0	0	11
	Theoretical analysis	8	0	0	0	1	0	0	1	
Hydrogen supply chain	Practical implementation	2	0	0	0	0	0	0	0	25
	Theoretical analysis	18	1	2	1	0	0	1	0	
Environmental impact	Practical implementation	0	0	0	0	0	0	0	0	24
	Theoretical analysis	19	2	1	1	1	0	0	0	
Drivetrain technology	Practical implementation	2	1	1	0	0	0	0	0	20
	Theoretical analysis	13	1	1	1	0	0	0	0	
Fuel cell application	Practical implementation	1	1	0	0	0	0	0	0	10
	Theoretical analysis	5	2	0	0	0	1	0	0	
Storage system application	Practical implementation	1	0	1	0	0	0	0	0	5
	Theoretical analysis	0	0	0	3	0	0	0	0	
Total		**69**	**8**	**7**	**6**	**2**	**1**	**1**	**1**	**95**

Table 3: Summary of HFCTs papers classified according to research topic, application approach, and affiliation.
Uni: University; R.I.: Research Institute; Com.: Company; Gov.: Government; H2 Assoc.: Hydrogen Association.

Only 12% of the papers analyzed (11 documents) have a practical research approach. This can give an idea of the general state of the art of HFCTs because, even though the hydrogen technology is mature as it has been used in the industry for more than 30 years, HFCTs are still in an initial commercial phase, and few vehicles are operating on the streets.

Among the research areas analyzed, hydrogen supply chain, environmental impact, and drivetrain technology are the most prominent topics given the number of documents included in each category, representing 74% of all the published papers. This suggests that scientists prioritize research on broader topics, such as transport alternatives to decrease fuel consumption and greenhouse gas emissions, hydrogen production, and refueling networks for the vehicle’s daily operations. Additional observations regarding each research area are: governments have limited participation in both public policies and hydrogen supply chain topics, and most of the documents are produced by universities; companies have scarce article production about the environmental impact of HFCTs, and no automobile manufacturers were detected to have contributed to these studies about their trucks; companies show low involvement with the study of different trucks’ technologies, however, they write almost half of the research articles about fuel cells; governments seem more involved in storage system applications, and is the only topic where they collaborate more than universities and research institutes.

No other state-of-the-art review about HFCTs was found among the papers scrutinized. As a result, this article could be one of the first to gather all the available research information regarding this topic over the last ten years.

A table containing detailed information regarding all the selected documents can be seen in Appendix A.

4. Topics covered in the literature

In order to understand research gaps and suggest actions for implementing HFCTs strategies, the documents collected in each research category are analyzed in depth next.

4.1. Public policies

Effective policies should meet multiple objectives, such as balancing different solutions of powertrains, providing fuel supply security, and defining a sustainable and consistent transport policy for economic growth and efficient environmental protection, among others [31]. When examining the documents related to HFCTs and their connection to public policies, only one article focuses on the "big picture", while the others are based on case studies. However, they share the exploration of key barriers and long-term recommendations and policies that governments should pursue to adopt HFCTs and decarbonize the transport sector in developed and non-developed countries.

On the one hand, Ajanovic and Haas [32] analyze key barriers hindering the use of hydrogen and FCEVs, focusing on their economic performance as a crucial point for future development. The authors state that, for achieving full benefits for the transport sector by the year 2030, it is imperative to provide stable and long-term policy framework conditions and coordinate actions between regions to take advantage of economies of scale.

On the other hand, and related to case studies, Ruf et al. [33] present the only practical approach to public policies. The research introduces the H2ME project, a five-year plan started in 2015 expected to deploy 1,400 hydrogen fuel cell cars, vans, and trucks alongside 49 hydrogen refueling stations across 8 European countries. At that time, it was the world's largest hydrogen mobility network. This and other projects under the HyFIVE association contributed to analysis and recommendations for governments on topics such as commercialization strategies, customer attitudes towards the technology, and the hydrogen role in the transport sector. A similar paper is based on the Hydrogen Mobility France coalition. Stewart et al. [34] present the low-cost and low-risk strategy this coalition has developed to deploy vehicle and refueling stations based on captive fleets, low-cost stations, and several vehicle types, from cars to buses and trucks. This strategy also shows the transition to full hydrogen mobility for passenger cars France would need to pursue in the medium term.

A general European situation review on accelerating the decarbonization of road freight transport is analyzed in three articles. On the one hand, Noll et al. [35] study the total cost of ownership of different types of drivetrain technologies and suggest critical parameters that should be targeted to increase the adoption of low-carbon emissions vehicles for the year 2050. In their findings, BEVs sound promising in the light and medium-duty sector, and in the heavy-duty sector might be viable only in countries that have implemented policy measures. Additionally, policymakers are suggested to target operational costs before investment costs and implement a mix of policy interventions. On the other hand, Borbujo et al. [36] review the current European legislation and standardization for hydrogen and battery electric buses and heavy-duty trucks. They additionally present areas that would need to be standardized, like higher capacity and flow charging rates for FCEVs to help achieve a 55% GHG reduction by the year 2030. Finally, Van der Zwaan et al. [37] pose that the decarbonization process for the transport sector would come after the decarbonization of the power sector, since reducing emissions for electricity production is usually cheaper than for transportation. Therefore, spending limited financial resources on the power sector would make more sense. Furthermore, they state that investments would not be optimally spent by establishing an extensive hydrogen distribution network, and electric cars would be a better option for the next one or two decades. However, electric transportation seems to be the most expensive alternative from a long-term perspective unless electric car costs drop substantially.

One of the public policies suggested by researchers is the construction of electric roads with continuous electricity transmission. They are characterized by high economies of scale with high investment costs and low marginal costs, and economies of scope where the benefit per kilometer depends on the size of the network. Börjesson et al. [38] evaluate the social benefits of electric roads in Sweden using a cost-benefit analysis. The authors find it relevant to consider investing in electric roads making the cost-benefit analysis a key decision point. Modeling techniques determine the optimal shipment sizes and transport freight, including mode and vehicle type. Their findings show that if the intention is to optimize social welfare by setting the user charge, the revenue will not cover the investment cost of the road. By connecting the three most important cities in Sweden with an electric road, emissions are expected to be reduced by one-third of the overall emissions of heavy-duty trucks in the country by the year 2030. However, they also present an argument against electric roads: investment and maintenance costs are uncertain, and electric vehicles (battery and fuel cells) can reduce the benefits of these roads in the future.

A similar approach is studied in Iceland by Shafiei et al. [39]. By modeling the country's energy sector focused on road transport energy demand for the year 2050, possible transition pathways towards a low-carbon transport sector are proposed. Additionally, fuel demand, GHG emissions, and costs are modeled in different scenarios considering oil price, carbon tax, fuel supply, government initiatives, and the consumer sector. Results show that there could be feasible transition paths to decarbonization through travel demand, vehicle technologies, fuel types, and efficiency improvements. Investment in supply infrastructure for alternative fuels is needed to provide long-term economic benefits by saving fuel costs and mitigating GHG emissions.

The oldest paper in this bibliographical research of HFCTs is from Takeshita [40]. The author studies GHG emissions from road transport through the year 2050, considering the impact of implementing air pollutant emissions regulations in developing countries and global CO_2 mitigation policies. He states that light and heavy-duty trucks would significantly contribute to increasing global GHG emissions. Therefore, to decrease them, it is important that non-developed countries adopt the same vehicle emission standards as developed countries within a 30-year lag. Moreover, the timing of implementation of air pollutants emissions regulations in developing countries has a more significant impact on future GHG emissions than global CO_2 mitigation policies.

Finally, two studies cover hydrogen public policies implementations in Asia. One is presented by Li and Kimura [41]. The authors explore if the Association of Southeast Asian Nations (ASAN) should follow up the long-term plans and targets leading countries are implementing for the hydrogen sector, and if FCEVs (cars, buses, and trucks) could be economically justified. They calculate energy consumption, carbon emissions, and vehicle costs, and estimate future developments for hydrogen and FCEVs in terms of costs and reduction of carbon emissions for each ASAN member country by the year 2030. Their findings include the regions where FCEVs could become competitive and therefore targeted and prioritized, and the critical policies for developing this alternative technology. The other article is presented by Havertz [42] and centers the discussion on South Korea's recently launched hydrogen economy program, which promotes the use of hydrogen in the industrial, residential, and transport sectors for the years 2022, 2030, and 2040. This program could reduce GHG emissions in the long-term by building a nationwide network of hydrogen refueling stations, reducing the price of hydrogen by more than 50%, and promoting FCEVs' purchases. All these actions are evaluated by the author discussing if this is a case of ecological modernization, one of the principles of environmental policies.

4.2. Hydrogen supply chain

It is essential to develop the necessary hydrogen ecosystem for deploying FCEVs in the streets. Consequently, the hydrogen supply chain category has a key role and is identified as one of the baselines for expanding the operation of FCEVs. Since a hydrogen transportation system brings more social benefits than social costs, the introduction and deployment of FCEVs and their hydrogen infrastructure can be justified socially and nationally [43]. Furthermore, installing refueling stations implies, in the beginning, high investments and low utilization, so defining and modeling the optimal network before the construction has elevated research value [44]. Research on hydrogen infrastructure almost monopolizes the discussion on this topic, while some articles investigate hydrogen production.

After studying the use of electric vehicles in the transport sector, a broad discussion about CO_2 emissions generation is presented by Jamerson [45]. According to the author, to strike back these emissions, the pathway to sustainable carbon-free energy production is nuclear power, and the appropriate technology to use in the transport sector is FCEVs. Some reasons for promoting nuclear power would be reliability, long-lasting operations, availability of the energy source, safety, and sustainability. The author also states that trucks would be the first vehicles to adopt hydrogen technology because costs would eventually become competitive.

Bethoux [46] likewise, asserts that long-distance heavy-duty vehicle conversion to fuel cells will play an essential role in decarbonizing the sector in the next one or two decades. Therefore, his research focuses on the advances needed to move from a niche to a mainstream consumer product, specifically addressing green hydrogen production, storage, and distribution. The greener the hydrogen is, the more competitive and environmentally friendly FCEVs become compared to BEVs.

When it comes to refueling stations, three articles stand out. First, El-Taweel et al. [47] present analytical methodologies to estimate the size of electric and hydrogen-based refueling stations. Additionally, Peters et al. [48] pose that, to use synthetic fuels made from CO_2 and sustainably produced hydrogen, the existing refueling infrastructure could be used, and this strategy could reach vehicle fleets in the medium term. To achieve this, it is necessary to expand the renewable electricity capacity generation. Finally, Mayer et al. [49] study hydrogen refueling stations that dispatch liquid and gaseous hydrogen from the technical requirements and cost viewpoints. To do this, they consider ambient temperature and station capacity and utilization. The authors state that investment costs, energy consumption, and specific costs of dispatching liquid hydrogen would be lower than gaseous hydrogen. However, liquid hydrogen would have higher energy consumption when considering the entire hydrogen supply chain (conditioning and transportation to the station).

Most of the papers in this research category are based on case studies, and seven of them focus on Germany. A heavy-duty truck driving database is used to obtain the country's potential vehicle and electric demand, fuel consumption forecast, and a prospective refueling network up to the year 2050. As a result, the impact of the electricity surplus with the introduction of HFCTs would be nearly 9% of the country's total electricity demand, per year, by 2050 [50]. In another article, infrastructure development and distribution costs are studied for the transport and chemical industry sectors by 2050 [51]. For the initial phase, low-cost storage and better utilization of existing refueling stations are recommended, and the authors additionally suggest using public transport and captive fleets in this stage. Moreover, they state that carbon taxes will impact hydrogen costs positively for transport, and CO_2 taxes would be required to provide a cost-competitive scenario for green hydrogen [51].

Four approaches are presented for developing refueling infrastructure scenarios in Germany. Rose and Neumann [52] study hydrogen refueling stations with local production vs. an infrastructure location connected to a power system. The levelized cost of hydrogen is calculated for each alternative, and projections are made for the year 2050. The outcome suggests optimizing the energy sectors and exploiting synergies. Nugroho et al. [53] focus on green hydrogen production for heavy-duty vehicles and estimate the costs for an existing refueling network design of 137 refueling stations based on German traffic data for the year 2050. For this network, the investment for a centralized scenario with pipeline distribution would imply a reduction of 13% of the costs compared to on-site production. This also infers a decrease in the levelized cost of hydrogen for the pipeline alternative. Reuß et al. [54] bring a more complex infrastructure study. For a network of 9,683 refueling stations, 15 production locations, and three different storage modes (compressed gaseous hydrogen, liquid hydrogen, and liquid organic hydrogen carriers) by the year 2050, the authors explore the optimization of the hydrogen supply chain and calculate its costs. They conclude that compressed gaseous hydrogen would be more convenient when there are small distances between the production location and the station. In contrast, liquid hydrogen could be more suitable for distances greater than 130 km. Nugroho et al. [44] additionally consider the location capacity restrictions for the existing charging station models used for heavy-duty vehicles. The location capacity limit seems to significantly impact the number of stations required, station utilization, and station variety.

Wanapinit and Thomsen [55] present the only article focused on an industrial plant. The authors explore flexible electricity production with photovoltaic energy and batteries to propel HFCTs in a German gravel plant. They claim that the total cost of electricity production is lower, and emissions are reduced by 70% compared to the business-as-usual system by the year 2030. Despite the photovoltaic generation, the flexibility in hydrogen production, and the help of an energy system optimization model, the authors claim that HFCTs are not as competitive as diesel trucks due to high investment costs and fuel prices, with costs increasing by 8% unless hydrogen is produced with the plant's surplus electricity generation.

Another European case study is presented by Çabukoglu et al. [56] by studying Swiss heavy-duty truck operations. The authors allege that if every truck in this country turns to hydrogen, the energy consumption would be equivalent to 13% of the total energy consumed by the country. Also, in terms of GHG emissions, there would be almost no reduction because hydrogen production would not use renewable resources, so significant investments should be made to change this. The opposite case occurs in Norway, where almost 100% of the electric power is hydroelectric, therefore, green hydrogen could be easily produced. For this situation, Ulleberg and Hancke [57] calculate the levelized cost of hydrogen in two possible scenarios: one with a small-scale hydroelectric power plant and the other with a small network of hydrogen refueling stations. The authors suggest that the optimal alternative is having a fleet of HFCTs with a refueling station with nearly 100% capacity utilization. Meanwhile, Bansal et al. [58] study a one-stop charging station for BEVs and FCEVs in Denmark. Considering a lifespan of 25 years, the supposed optimal solution in terms of costs and less environmental impact is grid-connected hydrogen production using a wind energy source and hydrogen delivery with a tube trailer. One of the oldest papers that emerged during the research is related to hydrogen supply and studying the evolution and success of the Dutch hydrogen economy. A complete framework is analyzed to introduce hydrogen in the transport sector, resulting in a production facility based in Rotterdam with hydrogen supplied by trucks, for a 25% FCEV market penetration by the year 2050. Other hydrogen production options are evaluated, e.g., coal for coal gasification demands to be cheaper and technologically competitive than natural gas for methane reforming [59]. Oldenbroek et al. [60] study how balancing 100% renewable electricity, heating, cooling, and transport systems in Denmark, Germany, Great Britain, France, and Spain would be achieved using grid-connected FCEVs. These systems are modeled for the year 2050 with a mixture of BEVs and FCEVs, and FCEVs would always balance the energy systems guaranteeing energy supply. Additionally, seasonal hydrogen storage using underground salt caverns is studied. Although the study is focused on light-duty vehicles, a special mention of heavy-duty trucks is made.

Five articles analyze different North American case studies. One is based in Canada and focuses on the optimal sizes and locations needed for developing a hydrogen infrastructure in an early-stage transition (when the conversion from diesel to FCEVs begins) in a highway corridor [61]. If the FCEV market share grows from 0.1 to 1%, hydrogen production and its delivery costs would fall 21%, and 37,000 tons of CO_2 would be avoided every year. Three other articles are based on case studies in the Western US. On the one hand, Zhang et al. [1] simulate hydrogen demand for light, medium, and heavy-duty vehicles in a distributed system across the Western area. By increasing hydrogen production flexibility by oversizing electrolyzers, hydrogen and electricity generation costs, and CO_2 emissions seem to decrease. On the other hand, Vijayakumar et al. [62] focus on California in the year 2050 projecting two scenarios for FCEVs adoption and determining the amount of hydrogen production sites and refueling stations required. By 2030, the authors prove an exponential increase in the set-up of the number of production plants and refueling stations, so they claim that rapid increases in infrastructure investments are needed from now on. Additionally, transporting hydrogen using pipelines is apparently proven to carry cost savings, a similar conclusion to which Nugroho et al. [53] arrive at when analyzing the German case study. Finally, Hernández et al. [63] evaluate the number and location of each refueling station in the Western US using a mathematical model based on operation distances and the best hydrogen production for supporting HFCTs charging. Green hydrogen production is allegedly proven viable through solar energy in several cases. The last North American case study analyzed is proposed by Liu et al. [64] for a national hydrogen refueling infrastructure along major interstate highway corridors. The objective is to deploy HFCTs for the national long-haul trucking fleet by 2025. Locations and capacities of hydrogen refueling stations are modeled, and fuel demand is estimated, alongside an economic feasibility analysis calculating the total ownership cost. With a HFCTs penetration of 10%, these vehicles would become more competitive in fuel and other costs, so they could be economically viable if vehicle and hydrogen liquefaction costs are reduced. On the other hand, the stations depend on regional factors and demand, which determines the capacity of each station. As a result, a strategy suggested for station deployment is to have early investments in target regions where station costs are expected to be relatively low, e.g., in the Pacific and West South Central regions.

The last case study investigated is an article published by Kotze et al. [65], which focuses on New Zealand's path to decarbonizing the heavy-duty transport sector with green hydrogen. Hydrogen production capacity investments and electricity supply are estimated to turn 71 to 90% of heavy-duty vehicle fleets into HFCTs by 2050. The cost ranges are broad due to the uncertainties in the development of hydrogen technology. The authors also recommend policies for this decarbonization path and suggest deepening the study and comparing the results to the investments required to use other vehicle technologies.

In the past ten years, practical research has also focused on the hydrogen supply chain, considering production, distribution, and dispensing of hydrogen into the vehicle. However, hydrogen can be supplied in different forms, and cryo-compressed hydrogen is an alternative studied by Xu et al. [66], who also found a way to reuse the waste energy from the fuel cell to heat the cool hydrogen. Besides the hydrogen supply chain, another essential factor of success for the commercialization and operation of FCEVs is the business model used by the vehicle company to get to the market. This is the case of Nikola Motors Co., which used a bundled business model to commercialize its hydrogen power technology and partner with other companies to create a hydrogen ecosystem that enables them to compete with established contenders [67].

4.3. Environmental impact

Reducing GHG emissions is one of the most relevant topics related to FCEVs when comparing the benefits over internal diesel combustion engines. It also contributes to meeting the world's global challenges for the year 2050 reflected in the Paris agreement and helps fight the temperature rising the Earth is experimenting with global warming. The distinctiveness of this research area is that all the documents are theoretical, and no practical studies were retrieved. As with the other research topics, some papers in this category cover general information about emissions, while others focus on countries’ case studies. Furthermore, two approaches are usually considered when evaluating HFCTs’ environmental impact. Some authors perform a well-to-wheel analysis (WtW), which considers all the transformations from the primary sources that lead to the fuel, and the consumption of useful energy in the vehicle and its emissions [68], while others implement a life cycle assessment (LCA) that evaluates the energy consumption and emissions incurred during fuel exploitation, transport, injection, and utilization [69].

There are numerous studies to consider when it comes to general information about how hydrogen reduces greenhouse gas emissions. The oldest paper is from Perham [70] who proposes that hydrogen can replace fossil fuels, especially in cars, buses, and trucks. However, combining this energy source with vehicle monitoring and computer-generated maps could significantly reduce carbon emissions produced by combustion engines, mainly trucks. A modern approach is presented by Machado et al. [71], by considering LCA studies regarding fuel consumption and GHG emissions for heavy-duty trucks. The study shows that biogas trucks or HFCTs would be better for reducing GHG emissions, while natural gas trucks or HFCTs would be better for reducing particulate matter and NOx emissions. These last two would also be more economically viable. They additionally observe that the scientific community is less interested in air pollutants literature than in GHG emissions.

The paper by Guandalini and Campanari [68] is one of the first documents exploring and comparing a WtW analysis between BEVs and FCEVs for road freight transportation. For a driving cycle simulation, the authors conclude that both electric vehicles (BEVs and FCEVs) could be competitive with diesel vehicles because they show less energy consumption and emissions. Lee et al. [3] also perform a WtW analysis between HFCTs and their diesel counterparts. Using steam methane reforming, the FCEVs seem to reduce WtW petroleum energy use by more than 98% compared to diesel engine vehicles. This would imply a reduction in GHG emissions ranging from 20 to 45% (depending on the air pollutant) for different classes of trucks. A relevant point is that considering the American average electricity generation mix, HFCTs would increase sulfur oxide emissions because of the upstream emissions related to electricity use for hydrogen compression or liquefaction [3]. Additionally, they state that vehicles that use liquid hydrogen would have fewer emissions reductions compared to the ones that use hydrogen gas. Another technology comparison in terms of environmental impact is studied by Wolff et al. [72]. With simulations and an LCA, the results show that battery electric trucks seem to be more cost-competitive than diesel-powered engines. Still, the environmental impact of these electric vehicles is 313% higher than diesel. On the other hand, with renewable energy sources, battery vehicles have a -65% of environmental impact. If FCEVs are used, the environmental impact would decrease 27% more [72].

When considering the hydrogen production point of view, Antonini et al. [73] investigate the technical performance of passenger cars and trucks and their life cycle environmental footprint with dry biomass used as an energy source. As expected, this hydrogen production's life cycle carbon footprint is slightly positive without carbon capture and storage, and negative with carbon capture. Furthermore, the authors pose that FCEVs using hydrogen from biomass with carbon capture and storage would be the most environmentally friendly option. Nevertheless, limited biomass resources and alternative uses of this energy source should be considered. Haugen et al. [74] study hydrogen production using natural gas as a primary energy source, since they state that decarbonization in road transport also implies CO_2 reduction goals in the energy source and in energy use. Energy efficiency and CO_2 emissions are calculated with a tank-to-wheel analysis for BEVs and FCEVs. CO_2 intensity seems lower for light-duty BEVs with a decarbonized primary energy source, and they claim to be 65% more efficient than FCEVs when using grid energy. This conclusion is extrapolated to heavy-duty vehicles, but with the use of conventional battery systems, where they present a 55% carbon reduction. The only case they show where both types of technologies have similar carbon intensities is when using trailers for hydrogen distribution.

Among the published case studies, six focus on Europe using different perspectives. Through an LCA, Tahir and Hussain [75] propose that, with the current German energy matrix, BEVs seem to present more advantages with fewer emissions and a better user driving experience when compared with FCEVs. However, a significant impact in the transport sector needs to happen to reduce the upcoming emissions in the future. Therefore, the authors pose the importance of FCEVs offering the same driving experience as BEVs, and hydrogen production using renewable resources. Breuer et al. [76] consider investments and operating costs of the associated German infrastructure and compare different types of electric engine vehicles. The authors conclude that it would be more beneficial from an environmental point of view if all trucks convert to fuel cells. Nevertheless, it is not the best solution from an economical point of view, as other alternatives perform better in terms of costs and infrastructure modification. Booto et al. [77] base their discussion in Norway with an ample focus on the life cycle environmental impact for different heavy-duty vehicles considering the entire supply chain of the energy used. These authors claim that HFCTs would reduce GHG emissions by 48% compared to a Euro VI truck of the same category and under the same operating conditions. A further comparison between different drivetrains of medium and heavy-duty trucks is performed by Sacchi et al. [78]. Using an LCA, the authors estimate that, by 2040, battery and HFCTs would be promising options to reduce GHG emissions in long-distance segments in Europe, but this requires several conditions, such as improvements at an energy storage level, and GHG emissions reductions in electricity production. Additionally, these electric options have a competitive advantage within urban and regional applications. However, they will have to compete against mature combustion-based technologies with lower efficiencies expected to diminish their emissions by hybridization, engine improvements, or the use of better fuels.

Navas-Anguita et al. [79] focus their study on an LCA about the environmental performance of hydrogen production for transport use in Spain. By modeling energy systems with carbon footprint restrictions, steam methane reforming of natural gas seems to maintain a high relevance in the short term, while water electrolysis could be the leading technology used in the medium and long-term. In scenarios with highly restrictive carbon footprint limits, biomass gasification is apparently an interesting hydrogen production technology in the long-term. This study is subsequently deepened later when the authors study the implementation of alternative fuels (including hydrogen) and vehicles in Spain. They review the production technologies of these fuels up to the year 2050 from a techno-economic and life cycle carbon footprint perspective. The scholars concluded that road transport would use biofuels, hydrogen, and electricity, and that the electricity surplus needed for electric vehicles would be mainly produced using renewable resources. These fuels would imply a GHG emissions reduction of 86% from the year 2020 to 2050 [80].

Other case studies focus on China because of the number of diesel vehicles operating in the country, the associated emissions, and the energy sources used. If heavy-duty FCEVs could replace the total stock of heavy-duty diesel vehicles, GHG emissions could be reduced by one-third in an urban area studied by Lao et al. [69]. On the other hand, considering the Chinese heavy-duty truck fleet and contrasting different scenarios of FCEV penetration forecasts, GHG emissions generated by this fleet would decrease by nearly one-fifth in an optimistic FCEV penetration scenario according to Liu et al. [81] through a WtW analysis. Two years later, the same authors expanded this research and estimated, through an LCA, the GHG emissions from different hydrogen production pathways for the year 2050. The results show that GHG emissions of heavy-duty truck fleets would increase and, if all the diesel vehicles convert to HFCTs, emissions would be reduced by 63% by 2050. Additional reductions could be achieved if the source of hydrogen production is shifted to water electrolysis [82].

Four North American case studies are retrieved from the database research. In the first one, Mac Kinnon et al. [83] focus on California in the year 2055 and review the impacts of reducing heavy-duty vehicle emissions. The authors consider that adopting FCEVs to replace light-duty vehicles in early adoption countries would reduce emissions when the market share reaches 50 to 100% penetration. Additionally, FCEVs in the heavy-duty sector could achieve comparable or enhanced air quality benefits. Talebian et al. [84] calculate the WtW GHG emissions from road transportation in a province in Canada, where more than half of the emissions are due to road freight transport. To achieve a 64% GHG emissions reduction by 2040, more than 65% of the freight trucks would have to change to an electric powertrain, meaning a penetration of 100% of BEVs as early as 2025. Hence, regulations on fuel efficiency would probably fail to achieve the desired reductions. Additionally, every 1% of GHG emissions reduction from road freight transport would require 1.5 to 3.8% additional hydroelectric generation by the year 2040. Specifically, this surpasses the largest hydroelectric project in the province, so new policies should be implemented to support renewable electricity generation as well. Another case study focused on Canada is brought by Keller et al. [85]. In their article, they allege that a reduction in emissions depends on the carbon intensity of the electricity system, alternative fuels for vehicles, and vehicle charging profiles. Here they compare alternative pathways for decarbonizing the electricity sector and the heavy-duty transport sector by the year 2060. Adopting alternative fuel vehicles in the absence of carbon taxes suggests a cumulative emissions reduction of 3% in the best scenario, compared to a reference scenario that uses natural gas as fuel. When increasing the CO_2 tax, the adoption of FCEVs increases, and a significant emission decline could be achieved, obtaining a 43% cumulative reduction. Lastly, through a WtW analysis, Shamsi et al. [86] estimate the healthcare expenses due to diesel vehicles on a Canadian highway. The results show that it would be necessary to integrate BEVs and FCEVs to decrease GHG emissions, and that the health cost of air pollution is higher than the cost of carbon tax due to this pollution.

A case study in Japan presented by Watabe et al. [87] estimates with an LCA, the GHG emissions reduction when internal combustion vehicles and hybrid vehicles are banned from 2035 onwards. These vehicle bans combined with a consumer choice model, would promote BEVs for mini-sized vehicles and FCEVs for light and heavy-duty applications.

When considering Oceania's research about HFCTs, a single case LCA study from Australia emerges. Ally et al. [88] study heavy-duty vehicles' energy use and emissions. The authors pose that these are growing at a greater rate compared to energy use and emissions for light-duty vehicles, and they explore which sustainable energy technology can compete with diesel engines for the heavy-duty market. FCEVs seem to have attractive characteristics for heavy-duty transport, and they need to find their niche in this country when battery-only vehicles come short in terms of zero emissions, range, duty cycle, or payload requirements.

Only one article represents South Africa in this category. Gajjar and Mondol [28] pose three scenarios with different electric, hybrid, and FCEVs adoption levels by the year 2030. The authors explore that if the trend in diesel vehicles continues and no alternative vehicle is introduced, the increase in GHG emissions could not be compensated with fuel efficiency because of the estimated vehicle increase. On the other hand, they state that hybrid vehicles would be necessary to help transition towards full electric drivetrains after renewable energies become a significant portion of the country's energy matrix.

Finally, the only South American article based on a case study is published by Machado et al. [27]. The authors focus on a state of Brazil and the reduction of GHG emissions and other pollutants within the road freight transport sector. Electric options including hybrid, battery, and FCEVs would have the best results for reducing emissions, but they still have barriers to overcome, e.g., the financial support needed to pursue these projects.

4.4. Drivetrain technology

From the retrieved papers from the database research, two fundamental premises arise. While some of the articles center their discussion around HFCTs and their components, others focus on comparing mainly diesel engines to HFCTs, as this is the baseline for explaining the main contributions of hydrogen technology.

Within the first category, several articles about FCEVs' drivetrain stand out. They focus predominately on the vehicle itself, and three perform a general analysis and review of HFCTs. Bethoux [4] and Hong et al. [89] describe the vehicles' main components, future uses, and the prospects of the technology. Staffell et al. [90] introduce a comprehensive review of the role of hydrogen in different energy sectors, and focus on depicting several hydrogen fuel cell drivetrains, from passenger cars to airplanes. These research papers present an opportunity to get a profound understanding of hydrogen technology, its state of knowledge, and the vehicles' contribution to reducing CO_2 emissions.

Other authors examine the differences between a specific drivetrain and FCEVs. This is the case of Marcinkoski et al. [91], who investigate the suitability of converting medium and heavy-duty diesel trucks into hydrogen trucks, while ensuring the same performance in terms of weight, speed, and acceleration time. Other research is performed by Burke and Zhao [92] and Smallbone et al. [93], who study medium and heavy-duty diesel vehicles and compare them to electric and hydrogen technologies from fuel consumption and GHG emissions viewpoints. In the first case, the authors calculate that, for a 105 km/h driving speed, energy use per km for heavy-duty trucks decreases 21% when using HFCTs instead of diesel engines. Likewise, Cunanan et al. [94] compare diesel, battery, and HFCTs in the heavy-duty sector, in terms of mechanics, performance, and recent developments. For HFCTs, the authors present an average autonomy of 800 to 1,600 km depending on the cargo, with a single refueling and two hydrogen tanks with 40 to 60 kg of hydrogen each at 350 bars. Additionally, hydrogen consumption for a class 8 truck would be between 8.9 to 14.8 km/kg. Moreover, they pose that, even though battery and HFCTs would slowly eliminate barriers from the costs, infrastructure, and performance limitations points of view, diesel drivetrains for heavy-duty transportation would remain the leading technology used in the short-term due to existing infrastructure and lower costs. In addition to these comparative studies, the article written by Pagliaro and Meneguzzo [7] compares BEVs and FCEVs from materials' production and consumer demands' viewpoints.

As with the other aforementioned research topics, some articles are based on countries' case studies. Forrest et al. [95] center their investigation on a medium and heavy-duty vehicle dataset from California and evaluate how FCEVs and BEVS can meet the travel demand. BEVs could replace between 62 and 76% of light-duty commercial trucks, however, for replacing heavy-duty trucks, FCEVs would be a better alternative due to weight, long distances, and fast refueling time, and could replace up to 27% of the travel demand. Another case study is presented by Mojtaba Lajevardi et al. [6], which shows how, by using real driving cycles from 1,600 trucks in Canada, different technologies and drivetrains can be chosen according to costs and GHG emissions. A similar Canadian case study is pursued by Ribberink et al. [96], in which the authors conduct feasibility studies to discern between BEVs and FCEVs for replacing medium and heavy-duty buses and trucks based on parameters like practicality, economics, and emissions reductions. For the trucks segment, they propose that battery trucks would not be able to complete a full driving day without a stop at a fast-charging station because of their limited range, and that HFCTs have higher operational costs due to hydrogen price. However, lower hydrogen costs could imply operational costs savings in the long-term. Romejko and Nakano [97] center their research in Poland, where they apply a model for predicting a portfolio of renewable energy fuel vehicles, including improvements in technology, energy security requirements, petroleum prices, and subsidies. Finally, a German case study is developed by Gnann et al. [98] in which the authors compare different types of electric and FCEVs in terms of technological readiness, investments, infrastructure costs, and GHG reductions for users' demand data projected for 2030. Catenary trucks seem to imply less installation of additional renewable power than HFCTs due to their high efficiency, and from a cost perspective, HFCTs could be a promising alternative in the long-term, although they require high initial infrastructure investments.

Using theoretical processes, vehicle technology alternatives can be evaluated for freight transportation according to different approaches, like business and market-related, environmental and legal, maintenance and repair availability, safety, and vehicle performance. This is investigated in depth by Jaller and Otay [99]. Two other similar studies are conducted by Guerrero de la Peña et al. [100] and Lombardi et al. [101]. In the first article, a decision-making process is developed for fleets that allocate different drivetrain vehicles on freight delivery routes considering future policies, economic factors, and the availability of charging infrastructure. The second article evaluates energy performance and environmental impacts for different drivetrains.

Four papers within this research topic have a practical implementation worth mentioning. In 2013, hydrogen use in heavy-duty trucks was in its early stages and started to be studied in the laboratory. To justify if hydrogen fuel cells could replace batteries in freight transportation, a pilot study was conducted by Shabani et al. [102] using a small-scale replica of a heavy-duty truck with hydrogen fuel cells. Three years later, BMW tried a hydrogen fuel cell drive system for industrial trucks in Germany, which proved the technology was ready to market [103]. Another three years later, after having some heavy-duty hydrogen trucks in operation worldwide, studies started to become more specific. Some of them focused on range prediction with a single filling of hydrogen to ensure continuous operation of the vehicle and avoid excessive energy consumption. Chandrasekar and Amruth Kumar [104] studied and tested a prediction model that assists the driver in implementing a driving strategy to optimize vehicle range. Lastly, Sun et al. [105] tested an HFCT in China with different driving cycles to evaluate energy consumption and driving range.

4.5. Fuel cell applications

When considering the vehicle itself, the heart of a hydrogen system is the fuel cell because it powers the vehicle and is one of the most expensive and critical components. Here, hydrogen from the storage tanks and oxygen from the outside air react in a cell with an anode, a cathode, and an electrolyte, producing electricity and water. Most commercial HFCTs use Proton-Exchange Membrane (PEM) fuel cells because of their high efficiency, fast start-up time, low operating temperatures, high power density, and small size [106,107]. No carbon dioxide emissions or particulate matter are obtained with this reaction, and only water is expelled through the tail pipe.

All the articles in this category apply specifically to HFCTs and were recently published between 2019 and 2021, although research on light-duty and bus applications has been studied before and is worth mentioning authors like Lototskyy et al. [108], Liu et al. [109], Liu et al. [110], and Usman et al. [106]. In the case of heavy-duty trucks, studies about the necessary hydrogen environment or the vehicles' environmental impact have been proposed earlier. Hence, from 2019 onwards, new advances in vehicle technology have been promoted concomitantly to these general matters. Another peculiarity of these studies is that most of them focus their investigation on materials or components of the fuel cell, with only two studies focusing on hydrogen or oxygen inputs [111,112], and only one study focusing on a different type of fuel cell which is not commonly used in vehicles [113].

From a general point of view, Cullen et al. [114] pose that the PEM fuel cell application focus is shifting from light-duty to heavy-duty vehicles, therefore, cost-effective and durable materials need to leverage to meet the increased efficiency and durability heavy-duty trucks need. The authors also summarize market trends and outlooks for different PEM fuel cell applications. Simons and Azimov [115] raise the impact fuel cells have on the environment during their manufacturing process. Using an LCA, the authors state that even though the construction of fuel cells is energy-intensive in terms of material extraction, it is possible to reduce GHG emissions by 34 to 87% compared to internal combustion engines, depending on the source of hydrogen used. Additionally, FCEVs would be a viable option for heavy-duty transport because it helps reach the target emissions reduction levels by the year 2050. Reverdiau et al. [116] additionally, bring to the scene an analysis of platinum, the main component of the fuel cell, that serves as a catalyst for the electricity production reaction. It seems essential to improve the platinum load per unit of power to ensure platinum reserves. The authors also propose that if platinum-catalyzed fuel cells are used in buses and trucks, the penetration rates of FCEVs would be much higher than with standard fuel cells.

Conversely, some studies focus solely on improving elements of the fuel cells from the materials' design point of view. A theoretical approach is explored by Saadat et al. [117], who study carbon materials that enhance the performance of the fuel cell bipolar plates. They also make recommendations on costs and performance for future developments. Furthermore, the same authors perform a practical lab experiment by modifying the graphitic structure of the carbon nanomaterials, obtaining a lightweight bipolar composites plate with high performance, which they recommend using in medium and heavy-duty HFCTs applications [118]. Also, Gittleman et al. [119] investigate proton conductors' performance under high temperatures and dynamic operating conditions. In the long-term, the target would be to achieve thermal stability and tolerance to high energy density liquid fuels for heavy-duty fuel cells.

Bhaskar et al. [120] study a key element within the fuel cell: the DC-DC multi-stage power converter. This element (which presents different topologies and challenges) is in charge of regulating the output voltage of the fuel cell, therefore, more efficiency and lower costs could be achieved depending on the power converter selected.

Based on a theoretical analysis, another alternative to improve the fuel cell performance according to Wiebe et al. [111], is by supplying more hydrogen than needed and sending back to the anode the unused hydrogen with the help of a hydrogen pump. The efficiency of the fuel cell system using this strategy would improve by 2.8%, and reduce hydrogen consumption, achieving a revolution in FCEVs.

Furthermore, when analyzing the fuel cell as a whole, another subsystem studied to improve efficiency is the air supply subsystem. There could be problems between the airflow and the pressure, so Sun et al. [112] approached a theoretical control strategy for the air supply in HFCTs. With this study, they assert that not only the centrifugal air compressor could significantly increase its working efficiency, but also the output current of the fuel cell could meet the load requirement in a shorter time.

However, not all studies concern PEM fuel cells. Other investigations are conducted by lab experimentation with different types of fuel cells, e.g., the Solid Oxide Fuel Cell (SOFC). This fuel cell can operate at higher temperatures and is more efficient than the PEM fuel cell [107]. A practical implementation is performed by Al-Masri et al. [113], who investigate a new design of SOFC stack for the vehicle's auxiliary power unit that uses the fuel cell electrical energy as a source for air conditioning, while eliminating engine idling and reducing fuel consumption. A ferritic stainless-steel alloy composition would give the cell mechanical strength, stiffness, and robustness, therefore, SOFCs could have potential use as auxiliary power units, according to the authors. The new design was manufactured and tested in the laboratory.

4.6. Storage tank applications

Another essential component of a FCEV is the storage tank system. Pressured vessels are filled with hydrogen gas at 350 or 700 bar pressure, and their physical location depends on the type of vehicle. Once again, this is not the most popular topic in scientific research about HFCTs, and the articles in this category focus their studies on tanks' materials and their dimensions. However, it is worth mentioning that other authors who have studied storage tanks for light-duty applications, like Lototskyy et al. [121] or Yamaguchi et al. [122] might complement the articles presented next.

The design of the tanks and location within a HFCT is thoroughly studied by a group of researchers in three different articles by Gangloff et al. [123], Kast et al. [124], and Kast et al.

[125]. The authors initially state that it seems technically possible to use hydrogen storage in medium and heavy-duty trucks. Furthermore, they go beyond this statement by suggesting where to install the tanks and finding that the best configuration would be under the side rails, behind the cab, and/or under the chassis.

These vessels must be thoughtfully designed and tested rigorously. For steel pressure vessels, tests are performed in the lab to obtain estimates of the crack initiation phase, and probabilistic models are used to determine the vessel's safety [126].

Besides compressed hydrogen gas, the application of liquid hydrogen is studied to prove if it is a viable option for heavy-duty applications. Some advantages of using liquid hydrogen are demonstrated by Wang et al. [127]. The tests show that the gas supply pressure of the liquid hydrogen would remain stable during operating conditions, so liquid hydrogen would be an interesting option to use with fuel cells in heavy-duty applications.

5. Discussion and conclusions

After scanning 369 documents retrieved from high-quality databases, 95 relevant papers that have studied HFCTs in the last ten years are selected and analyzed in-depth in terms of bibliometrics and content. It is worth mentioning that technical reports, other documents regarding this topic, and information published outside the considered time frame, are out of the scope and, therefore, a limitation of this review.

In the past two years there has been a significant increase in published papers, especially between articles, with clear leadership from the United States (28%), Germany (18%), and the United Kingdom (15%). The least represented continents are South America and Africa. The documents have been published in high-ranking journals, and the most popular is the “International Journal of Hydrogen Energy”, with 15% of the published articles.

Governments should adopt recommendations and strategies from academic institutions to build a more sustainable future by considering the deployment of HFCTs. Since academia produces more than 70% of the papers published about HFCTs but has only two collaborations with governments, it is important to ponder how scientific cooperation between these institutions could be increased. Concomitantly, since HFCTs have few commercial vehicle types available, it would be beneficial if academia could test companies' solutions for spreading objective results and educate society on this technology so that information barriers could be reduced.

Six research areas emerge from the publications about HFCTs. Each paper on public policies, hydrogen supply chain, environmental impact, drivetrain technology, fuel cell application, and storage tank system application was reviewed and evaluated to unveil research gaps, which are presented below. It is important to highlight that practical applications in the laboratory or evaluation results from theoretical applications were scarce (only 12%). Most of the published papers about HFCTs include topics such as hydrogen supply chain, environmental impact, and drivetrain technology (74%), focusing the discussion on transport alternatives to decrease diesel consumption and GHG emissions, hydrogen production, and refueling networks for the vehicle’s daily operations.

The public policy topic is vast in terms of discussion, and almost all the documents are based on case studies, ranging from specific projects to countries' associations. Several strategies are presented for implementing HFCTs in the future, and their findings relate to the impact of introducing or reinforcing policies that promote alternatives to decrease GHG emissions and contribute to the transition to a hydrogen economy. The articles on this topic focus on developed countries in Europe or Asia. Particularly, the United States is not represented in this investigation, which is a paradox because it is one of the countries that contributes the most to research in HFCTs topics, has developed several hydrogen projects for mobility, and has deployed more than 11 thousand passengers and commercial FCEVs [128]. Another research gap in this category is the lack of joint studies between political or economic organizations regarding HFCTs, even though there are previous joint efforts in passenger and light-duty hydrogen mobility sub-sectors. These policies could be scaled up and adapted to the specific application in the heavy-duty sector. Efforts that countries can make towards reducing transport's GHG emissions should be framed in a series of measures and commitments on a global, or at least a regional level, e.g., the pledge for addressing worldwide challenges and needs taken within the COP. For instance, the International Renewable Energy Agency (IRENA) summarizes public policies needed to accelerate the global energy transition in the medium and long-term to achieve COP's 2050 goals, and emphasizes that public funding would facilitate this and that it also needs to work alongside the private sector [129]. Even more, the impact of these emissions restrictions also affects the automotive sector, which needs to carefully plan its vehicle portfolio to comply with the restrictions [130].

Some of the authors researching about hydrogen supply chain agree that introducing HFCTs implies that the first diesel engine vehicles to be converted to fuel cells should be heavy-duty, especially freights or public transportation [45,51,64]. This is due to the expectation that the levelized cost of hydrogen would become more competitive in the future, mainly if green hydrogen can be produced with renewable resources [45,46,53,55,57,58,63]. Consequently, scholars suggest the need to promote tax laws and incentives to produce and use hydrogen for transportation [35,40,41,51,65]. However, green hydrogen production may not be a realistic objective to pursue in every country, and different hydrogen production sources must be investigated according to their primary energy matrix. In addition, a strong refueling station network is part of the backbone of the hydrogen ecosystem, which encourages hydrogen consumption and HFCTs adoption. Authors suggest using stations at their maximum capacity taking location into account, connecting them with pipelines or trailers for hydrogen distribution, and using mathematical models to predict the optimal number of stations needed. Since developing a hydrogen supply chain system is expensive [44,64,67], the International Energy Agency (IEA) suggests cost savings through the use of existing retail infrastructure for conventional fuels and captive fleets to guarantee high utilization rates [131]. Additionally, IRENA suggests that more pilot projects need to be encouraged by governments and international banks to create commercial-scale solutions and tailored financing instruments to meet end-users and companies' needs. International cooperation has an essential role in sustainable development and shared prosperity, and therefore, foreign aid could be critical for the development of low-income countries [129]. Taking this into consideration, pilot projects could be encouraged in countries that have the conditions to produce green hydrogen but cannot afford it. These projects could promote building a starting point for experiences in the heavy-duty sector and a hydrogen economy that could increase future HFCTs' deployment and cost savings. Other research gaps in this area include scarce research on hydrogen production from different energy sources, hydrogen distribution from production sites to retail distribution points, and lack of commercialization and business models that could be reproduced to expand hydrogen consumption and vehicle adoption. An additional key finding is that documents related to hydrogen storage (chemical, physical or underground) and its direct application to HFCTs were not found in this research. If scholars need to deepen on this topic because of its importance as one of the most expensive components of the supply chain, these applications should be further investigated, or at least conclusions should be extrapolated from related articles such as Oldenbroek et al. [60], Eberle et al. [132], Helmolt and Eberle [133], and Li et al. [134], that study this application for other types of hydrogen vehicles.

Most of the studies related to the environmental impact of HFCTs are based in Europe, North America, and Asia, clearly showing that these countries are concerned about adopting CO_2 mitigation strategies in the transport sector and can also support scientific research on the topic. Authors have compared different drivetrains using a WtW analysis, and FCEVs seem to have less GHG emissions than their diesel counterparts [68,70,83]. However, with the LCA analysis performed, it seems necessary to consider the impact of hydrogen production, which depends on its energy source. Renewable energy sources are necessary to continue with a GHG emission mitigation policy in the transport sector. IEA states that it is necessary to supply hydrogen from clean electricity and capture CO_2 emissions from hydrogen production from fossil fuels [135]. Additionally, IRENA poses that green hydrogen is expected to grow rapidly in the coming years and will approach economic competitiveness soon due to decreasing costs in renewable power and systems integration with increasing this variable renewable power supply [136]. Still, there is no consensus on whether FCEVs would be an appropriate alternative to replace light, medium, or heavy-duty vehicles because it depends on each country's political economy regarding CO_2 emissions reductions and their primary energy matrix composition [3,73,74,78]. This complements the recommendation aforementioned about supporting beneficial tax policies and pilot projects to encourage renewable energy production sources. A research gap in this area is the lack of studies about the green hydrogen potential of countries with high renewable energy electricity production, e.g., Costa Rica, Uruguay, or Angola, that could decrease GHG emissions in the transport sector. Some of these countries are implementing hydrogen projects for transportation [137], and it would be interesting to disclose their economic feasibility and prospects. A future research approach related to this topic would be studying hydrogen’s water footprint, BEVs’ batteries recovery and reuse, and battery aging for BEVs and hybrid FCEVs [138].

Since 2013, practical research has been carried out regarding HFCTs’ drivetrain technology to determine if fuel cells could replace diesel engine vehicles and if hydrogen technology was ready to market in the transport sector. This has set up the baseline for more complex studies which analyze different approaches to the technology of HFCTs. On the one hand, some authors have performed in-depth studies about HFCTs’ components, while others have generally reviewed the differences between drivetrains to determine the best solution for each country’s needs. Analysis for freight transportation has also been made, which has helped deploy and allocate different types of trucks in several operational routes [96,98–100]. This topic could be considered sufficiently covered by the number of publications found. Nonetheless, research about optimizing the truck’s general performance or improving individual components should be encouraged to produce a technology leap and help transition from a niche application to a broader one.

Even though there is a general interest in the way fuel cells work and impact the environment, most studies about this topic in the HFCTs sector concern performance improvements from different perspectives, from supplying hydrogen in excess to the fuel cell, to modifying materials’ composition or choosing the best components according to specific needs. Almost all papers are based on PEM fuel cells, and as this topic allows hands-on laboratory experimentation [113,118], there is enough room to continue researching this subject with other technologies, e.g., SOFCs are a relatively new technology with more benefits that can be further explored. Moreover, there are several studies about fuel cells in passengers and light-duty applications, hence, these results could be extrapolated or adapted to the specific application in the heavy-duty sector.

Finally, hydrogen storage tanks in heavy-duty trucks are not the broadest research topic, but since they are an essential and expensive vehicle component as they work under pressure, they must meet several requirements and norms for safety reasons [125,126]. The documents analyzed show detailed information about this component, from the location within the truck to laboratory testing. However, more materials should be researched regarding new compositions, quality, and tests, to improve safety, resistance, pressure, volume, space, and weight. This research topic could be considered the weakest in terms of publishing about HFCTs, and as the previous topic, studies about light-duty applications should be extrapolated to the heavy-duty sector to deepen the analysis.

To significantly decarbonize the global road transport sector, countries should continue to coordinate efforts in the heavy-duty sub-sector, which is the most pollutant. Nevertheless, the determination and investment to achieve zero-net mobility heavy-duty alternatives depend, not only on governments or multilateral banks, but also on companies themselves, mainly from the logistics sector. They also have environmental accountability for their CO_2 emissions and need to contribute with positive actions. Few papers about companies implementing HFCTs strategies are found, and businesses should start planning their vehicle conversion before more rigid policies for decreasing emissions come into effect.

As seen, HFCTs are still in an early development stage with some current pilot projects being carried out. Therefore, since many initiatives are in progress and several countries have introduced hydrogen roadmaps in the past two years [128], more research articles and scientific experiences will thrive in the near future. Hopefully, the research gaps identified in this article can help researchers and governments to fill in the gaps and continue decreasing global transport emissions.

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Abbreviations

ASAN: Association of Southeast Asian Nations.
BEVs: battery electric vehicles.
FCEVs: fuel cell electric vehicles.
GHG emissions: greenhouse gas emissions.
HFCTs: hydrogen fuel cell trucks.
LCA: life cycle assessment.
PEM: proton-exchange membrane fuel cell.
SOFC: solid oxide fuel cell.
WtW: well-to-wheel.

Appendix A

#	Research area	Type	Application	Title	Authors	Year	Country	Journal/Event	Affiliation
1	Public policies	Article	Theoretical analysis	The economics of electric roads	Börjesson, M.; Johansson, M.; Kågeson, P.	2021	Sweden	Transportation Research Part C: Emerging Technologies	Research institute,University
2	Public policies	Article	Theoretical analysis	Economic competitiveness and environmental implications of hydrogen energy and fuel cell electric vehicles in ASEAN countries: The current and future scenarios	Li, Y.; Kimura, S.	2021	China,Indonesia	Energy Policy	Research institute,University
3	Public policies	Conference paper	Practical implementation	Creating the European vision for hydrogen transportation	Ruf L.; Stewart A.; Ojakovoh M.; Oladini D.; Chatterji P.	2017	United Kingdom	Event: International Electric Vehicle Symposium and Exhibition	Company
4	Public policies	Conference paper	Theoretical analysis	Hydrogen Mobility France -De-risking the rollout of hydrogen vehicles and infrastructure in France	Stewart, A.; Ferrari, F.; Bouillon-Delporte, V.;	2017	Germany,United Kingdom	Event: International Electric Vehicle Symposium and Exhibition	Company,Hydrogen Association
5	Public policies	Article	Theoretical analysis	Potential impact of transition to a low-carbon transport system in Iceland	Shafiei, E; Davidsdottir, B; Leaver, J; Stefansson, H; Asgeirsson, EI	2014	Iceland,New Zealand	Energy Policy	University
6	Public policies	Article	Theoretical analysis	Global Scenarios of Air Pollutant Emissions from Road Transport through to 2050	Takeshita, T.	2011	Japan	International Journal of Environmental Research and Public Health	University
7	Public policies	Article	Theoretical analysis	Analyzing the competitiveness of low-carbon drive-technologies in road-freight: A total cost of ownership analysis in Europe	Noll, B.; del Val, S.; Schmidt, T.S.; Steffen, B.	2022	Switzerland	Applied Energy	Government,Research institute
8	Public policies	Article	Theoretical analysis	Prospects and impediments for hydrogen and fuel cell vehicles in the transport sector	Ajanovic, A.; Haas, R.	2021	Austria	International Journal of Hydrogen Energy	University
9	Public policies	Conference paper	Theoretical analysis	Heavy duty transport descarbonization: Legislation and Standards for Hydrogen and Battery Electric Buses and Heavy-Duty Trucks	Borbujo, I.C.;Pereirinha, P.G.;Vega, M.G.;Del Valle, J.A.;Anton, J.C.A.	2021	Portugal,Spain	Event: IEEE Vehicle Power and Propulsion Conference	University
10	Public policies	Article	Theoretical analysis	How to decarbonize the transport sector?	Van der Zwaan, B.;Keppo, I.;Johnsson, F.	2013	Italy,Netherlands,Sweden ,United Kingdom,United States	Energy Policy	Research institute,University
11	Public policies	Article	Theoretical analysis	South Korea’s hydrogen economy program as a case of weak ecological modernization	Havertz, R.	2021	South Korea	Asia Europe Journal	University
12	Hydrogen supply chain	Conference paper	Theoretical analysis	Pathway to Sustainable Carbon Free Energy and Transportation: Part 2	Jamerson, F.	2021	United States	Event: SAE WCX Digital Summit	Company
13	Hydrogen supply chain	Article	Theoretical analysis	Macro-Level optimization of hydrogen infrastructure and supply chain for zero-emission vehicles on a canadian corridor	Shamsi H.; Tran M.-K.; Akbarpour S.; Maroufmashat A.; Fowler M.	2021	Canada	Journal of Cleaner Production	University
14	Hydrogen supply chain	Article	Theoretical analysis	Investigating the investments required to transition new zealand’s heavy-duty vehicles to hydrogen	Kotze, R.; Brent, A.C.; Musango, J.; de Kock, I.; Malczynski, L.A.	2021	New Zealand,South Africa,United States	Energies	University
15	Hydrogen supply chain	Article	Practical implementation	Nikola Motors: a case study in bundling as a market entry strategy	Woo H.; Grandy J.	2021	United States	Journal of Business Strategy	University
16	Hydrogen supply chain	Article	Theoretical analysis	Flexible grid-based electrolysis hydrogen production for fuel cell vehicles reduces costs and greenhouse gas emissions	Zhang C.; Greenblatt J.B.; Wei M.; Eichman J.; Saxena S.; Muratori M.; Guerra O.J.	2020	United States	Applied Energy	Company,Government,Research institute
17	Hydrogen supply chain	Article	Theoretical analysis	Hydrogen fuel cell road vehicles and their infrastructure: An option towards an environmentally friendly energy transition	Bethoux, O.	2020	France	Energies	University
18	Hydrogen supply chain	Article	Theoretical analysis	Hydrogen refueling station networks for heavy-duty vehicles in future power systems	Rose, P.K.; Neumann, F.	2020	Germany	Transportation Research Part D: Transport and Environment	Research institute
19	Hydrogen supply chain	Article	Theoretical analysis	Technical and economic analysis of one-stop charging stations for battery and fuel cell EV with renewable energy sources	Bansal, S.; Zong, Y.; You, S.; Mihet-Popa, L.; Xiao, J.	2020	China,Denmark,Netherlands,Norway	Energies	University
20	Hydrogen supply chain	Article	Practical implementation	Supply system of cryo-compressed hydrogen for fuel cell stacks on heavy duty trucks	Xu, Z.; Yan, Y.; Wei, W.; Sun, D.; Ni, Z.	2020	China	International Journal of Hydrogen Energy	Research institute,University
21	Hydrogen supply chain	Article	Theoretical analysis	Techno-economic calculations of small-scale hydrogen supply systems for zero emission transport in Norway	Ulleberg, Ø.; Hancke, R.	2020	Norway	International Journal of Hydrogen Energy	Government
22	Hydrogen supply chain	Article	Theoretical analysis	Optimal development of alternative fuel station networks considering node capacity restrictions	Nugroho, R.; Gnann, T.; Plötz, P.; Wietschel, M.; Reuter-Oppermann, M.	2020	Germany	Transportation Research Part D: Transport and Environment	Research institute,University

#	Research area	Type	Application	Title	Authors	Year	Country	Journal/Event	Affiliation
23	Hydrogen supply chain	Article	Theoretical analysis	Future hydrogen markets for transportation and industry: The impact of CO2 taxes	Cerniauskas S.; Grube T.; Praktiknjo A.; Stolten D.; Robinius M.	2019	Germany	Energies	Research institute,University
24	Hydrogen supply chain	Article	Theoretical analysis	Fuel cell electric vehicles: An option to decarbonize heavy-duty transport? Results from a Swiss case-study	Çabukoglu, E.; Georges, G.; Küng, L.; Pareschi, G.; Boulouchos, K.	2019	Switzerland	Transportation Research Part D: Transport and Environment	Research institute
25	Hydrogen supply chain	Conference paper	Theoretical analysis	The regional impact of heavy-duty fuel cell trucks on electricity demand - A case study for Germany	Kluschke P.; Manz P.; Gnann T.; Plötz P.	2019	Germany	Event: ECEEE Summer Study on Energy Efficiency: Is Efficient Sufficient?	Research institute
26	Hydrogen supply chain	Article	Theoretical analysis	Evaluating national hydrogen refueling infrastructure requirement and economic competitiveness of fuel cell electric long-haul trucks	Liu, NW; Xie, F; Lin, ZH; Jin, MZ	2020	United States	Mitigation and Adaptation Strategies for Global Change	Research institute,University
27	Hydrogen supply chain	Article	Theoretical analysis	Dutch hydrogen economy: evolution of optimal supply infrastructure and evaluation of key influencing elements	Konda, N.V.S.N.M.; Shah, N; Brandon, NP	2012	United Kingdom	Asia-Pacific Journal of Chemical Engineering	University
28	Hydrogen supply chain	Article	Theoretical analysis	Synergies between renewable energy and flexibility investments: A case of a medium-sized industry	Wanapinit, N.; Thomsen, J.	2021	Germany	Energies	Research institute
29	Hydrogen supply chain	Article	Theoretical analysis	Low carbon scenario analysis of a hydrogen-based energy transition for on-road transportation in california	Vijayakumar, V.; Jenn, A.; Fulton, L.	2021	United States	Energies	University
30	Hydrogen supply chain	Article	Theoretical analysis	Cost of a potential hydrogen-refueling network for heavy-duty vehicles with long-haul application in Germany 2050	Nugroho, R.; Rose, P.K.; Gnann, T.; Wei, M.	2021	Germany,Indonesia,United States	International Journal of Hydrogen Energy	Company,Research institute,University
31	Hydrogen supply chain	Article	Theoretical analysis	Hydrogen road transport analysis in the energy system: A case study for germany through 2050	Reuß, M.; Dimos, P.; Léon, A.; Grube, T.; Robinius, M.; Stolten, D.	2021	Germany	Energies	Research institute,University
32	Hydrogen supply chain	Article	Theoretical analysis	Mathematical model for the placement of hydrogen refueling stations to support future fuel cell trucks	Hernández, B.; Alkayas, A.; Azar, E.; Mayyas, A.T.	2021	United Arab Emirates	IEEE Access	University
33	Hydrogen supply chain	Article	Theoretical analysis	Fuel cell electric vehicles and hydrogen balancing 100 percent renewable and integrated national transportation and energy systems	Oldenbroek, V.; Wijtzes, S.; Blok, K.; van Wijk, A.J.M.	2021	Netherlands	Energy Conversion and Management	University
34	Hydrogen supply chain	Review	Theoretical analysis	Future power train solutions for long-haul trucks	Peters, R.; Breuer, J.L.; Decker, M.; Grube, T.; Robinius, M.; Samsun, R.C.; Stolten, D.	2021	Germany	Sustainability (Switzerland)	Research institute,University
35	Hydrogen supply chain	Conference paper	Theoretical analysis	Techno-economic evaluation of hydrogen refueling stations with trucked-in gaseous or liquid hydrogen	Mayer, T.;Semmel, M.;Bauer, A.;Guerrero-Morales, M.;Schmidt, K.M.;Wind, J.	2017	Germany	Event: International Electric Vehicle Symposium and Exhibition	Company
36	Hydrogen supply chain	Article	Theoretical analysis	Analytical Size Estimation Methodologies for Electrified Transportation Fueling Infrastructures Using Public-Domain Market Data	El-Taweel, N.A.; Khani, H.;Farag, H.E.Z.	2019	Canada	IEEE Transactions on Transportation Electrification	University
37	Environmental impact	Article	Theoretical analysis	How to reduce the greenhouse gas emissions and air pollution caused by light and heavy duty vehicles with battery-electric, fuel cell-electric and catenary trucks	Breuer, J.L.; Samsun, R.C.; Stolten, D.; Peters, R.	2021	Germany	Environment International	Research institute,University
38	Environmental impact	Article	Theoretical analysis	Comparative life cycle assessment of heavy-duty drivetrains: A Norwegian study case	Booto, G.K.; Aamodt, Espegren, K.; Hancke, R.	2021	Norway	Transportation Research Part D: Transport and Environment	Research institute
39	Environmental impact	Article	Theoretical analysis	Hydrogen from wood gasification with CCS-a techno-environmental analysis of production and use as transport fuel	Antonini, C.; Treyer, K.; Moioli, E.; Bauer, C.; Schildhauer, T.J.; Mazzotti, M.	2021	Switzerland	Sustainable Energy and Fuels	Research institute
40	Environmental impact	Article	Theoretical analysis	Deployment of fuel cell vehicles in China: Greenhouse gas emission reductions from converting the heavy-duty truck fleet from diesel and natural gas to hydrogen	Liu, F.; Mauzerall, D.L.; Zhao, F.; Hao, H.	2021	China,United States	International Journal of Hydrogen Energy	University
41	Environmental impact	Article	Theoretical analysis	Reducing atmospheric pollutant and greenhouse gas emissions of heavy duty trucks by substituting diesel with hydrogen in Beijing-Tianjin-Hebei-Shandong region, China	Lao, J.; Song, H.; Wang, C.; Zhou, Y.; Wang, J.	2021	China	International Journal of Hydrogen Energy	Company,University
42	Environmental impact	Article	Theoretical analysis	Does Size Matter? The Influence of Size, Load Factor, Range Autonomy, and Application Type on the Life Cycle Assessment of Current and Future Medium- and Heavy-Duty Vehicles	Sacchi, R.; Bauer, C.; Cox, B.L.	2021	Switzerland	Environmental Science and Technology	Research institute
43	Environmental impact	Article	Theoretical analysis	A fork in the road: Which energy pathway offers the greatest energy efficiency and CO2 reduction potential for low-carbon vehicles?	Haugen, M.J.; Paoli, L.; Cullen, J.; Cebon, D.; Boies, A.M.	2021	United Kingdom	Applied Energy	University
44	Environmental impact	Article	Theoretical analysis	Life cycle emissions assessment of transition to low-carbon vehicles in Japan: combined effects of banning fossil-fueled vehicles and enhancing green hydrogen and electricity	Watabe, A.; Leaver, J.; Shafiei, E.; Ishida, H.	2020	Japan,New Zealand,Norway	Clean Technologies and Environmental Policy	Company,Research institute,University
45	Environmental impact	Conference paper	Theoretical analysis	Life cycle assessment of hydrogen fuelcell-based commercial & heavy-duty vehicles	Tahir, S.; Hussain, M.	2020	Germany,Saudi Arabia	Event: Canadian Society for Civil Engineering Annual Conference	University
46	Environmental impact	Article	Theoretical analysis	Electricity system and emission impact of direct and indirect electrification of heavy-duty transportation	Keller, V.; Lyseng, B.; Wade, C.; Scholtysik, S.; Fowler, Mc.; Donald, J.; Palmer-Wilson, K.; Robertson, B.; Wild, P.; Rowe, A.	2019	Canada,United States	Energy	University

#	Research area	Type	Application	Title	Authors	Year	Country	Journal/Event	Affiliation
47	Environmental impact	Article	Theoretical analysis	The impact of fuel cell vehicle deployment on road transport greenhouse gas emissions: The China case	Liu, F.; Zhao, F.; Liu, Z.; Hao, H.	2018	China	International Journal of Hydrogen Energy	University
48	Environmental impact	Conference paper	Theoretical analysis	Well-to-wheel driving cycle simulations for freight transportation: Battery and hydrogen fuel cell electric vehicles	Guandalini, G.; Campanari, S.	2018	Italy	Event: International Conference of Electrical and Electronic Technologies for Automotive	University
49	Environmental impact	Article	Theoretical analysis	Life-cycle implications of hydrogen fuel cell electric vehicle technology for medium- and heavy-duty trucks	Lee, D.-Y.; Elgowainy, A.; Kotz, A.; Vijayagopal, R.; Marcinkoski, J.	2018	United States	Journal of Power Sources	Government
50	Environmental impact	Article	Theoretical analysis	Air quality impacts of fuel cell electric hydrogen vehicles with high levels of renewable power generation	Mac Kinnon, M.; Shaffer, B.; Carreras-Sospedra, M.; Dabdub, D.; Samuelsen, S.; Brouwer, J.	2016	United States	International Journal of Hydrogen Energy	University
51	Environmental impact	Article	Theoretical analysis	The role of hydrogen in Australia's transport energy mix	Ally, J.; Pryor, T.; Pigneri, A.	2015	Austria	International Journal of Hydrogen Energy	Government,University
52	Environmental impact	Article	Theoretical analysis	Hydrogen giving reduced carbon emissions from vehicles	Perham, S.	2012	United Kingdom	International Journal of Low-Carbon Technologies	Company
53	Environmental impact	Article	Theoretical analysis	Assessment of Greenhouse Gases and Pollutant Emissions in the Road Freight Transport Sector: A Case Study for Sao Paulo State, Brazil	Machado, PG; Teixeira, ACR; Collaco, FMD; Hawkes, A; Mouette, D.	2020	Brazil,United Kingdom	Energies	University
54	Environmental impact	Article	Theoretical analysis	Electrification of road freight transport: Policy implications in British Columbia	Talebian, H; Herrera, OE; Tran, M; Merida, W.	2018	Canada	Energy Policy	University
55	Environmental impact	Article	Theoretical analysis	Multi-disciplinary design optimization of life cycle eco-efficiency for heavy-duty vehicles using a genetic algorithm	Wolff, S.; Seidenfus, M.; Brönner, M.; Lienkamp, M.	2021	Germany	Journal of Cleaner Production	University
56	Environmental impact	Review	Theoretical analysis	Review of life cycle greenhouse gases, air pollutant emissions and costs of road medium and heavy-duty trucks	Machado, P.G.;Teixeira, A.C.R.;Collaço, F.M.A.;Mouette, D.	2021	Brazil,United Kingdom	Wiley Interdisciplinary Reviews: Energy and Environment	University
57	Environmental impact	Article	Theoretical analysis	Prospective techno-economic and environmental assessment of a national hydrogen production mix for road transport	Navas-Anguita, Z.;García-Gusano, D.;Dufour, J.;Iribarren, D.	2020	Spain	Applied Energy	Research institute,University
58	Environmental impact	Article	Theoretical analysis	Long-term production technology mix of alternative fuels for road transport: A focus on Spain	Navas-Anguita, Z.;García-Gusano, D.;Iribarren, D.	2020	Spain	Energy Conversion and Management	Research institute,University
59	Environmental impact	Article	Theoretical analysis	Technoeconomic comparison of alternative vehicle technologies for South Africa's road transport system	Gajjar, H.;Mondol, J.D.	2016	South Africa,United Kingdom	International Journal of Sustainable Transportation	Research institute,University
60	Environmental impact	Article	Theoretical analysis	Health Cost Estimation of Traffic-Related Air Pollution and Assessing the Pollution Reduction Potential of Zero-Emission Vehicles in Toronto, Canada	Shamsi, H.;Munshed, M.;Tran, M.-K.;Lee, Y.;Walker, S.; The, J.;Raahemifar, K.;Fowler, M.	2021	Canada,United States	Energies	University
61	Drivetrain technology	Conference paper	theoretical analysis	Evaluating Sustainable Vehicle Technologies for Freight Transportation Using Spherical Fuzzy AHP and TOPSIS	Jaller, M.; Otay, I.	2021	Turkey,United States	Event: Advances in Intelligent Systems and Computing	University
62	Drivetrain technology	Article	Theoretical analysis	Hydrogen fuel cell road vehicles: State of the art and perspectives	Bethoux, O.	2020	France	Energies	University
63	Drivetrain technology	Article	Theoretical analysis	Estimating the technical feasibility of fuel cell and battery electric vehicles for the medium and heavy duty sectors in California	Forrest, K.; Mac Kinnon, M.; Tarroja, B.; Samuelsen, S.	2020	United States	Applied Energy	University
64	Drivetrain technology	Article	Theoretical analysis	Powering the future through hydrogen and polymer electrolyte membrane fuel cells current commercialisation and key challenges with focus on work at Hyundai	Hong, B.K.; Kim, S.H.; Kim, C.M.	2020	South Korea	Johnson Matthey Technology Review	Company
65	Drivetrain technology	Article	Theoretical analysis	Projecting adoption of truck powertrain technologies and CO2 emissions in line-haul networks	Guerrero de la Peña A.; Davendralingam N.; Raz A.K.; DeLaurentis D.; Shaver G.; Sujan V.; Jain N.	2020	United States	Transportation Research Part D: Transport and Environment	Company,University
66	Drivetrain technology	Article	Theoretical analysis	Energy performance and well-to-wheel analysis of different powertrain solutions for freight transportation	Lombardi, S.; Tribioli, L.; Guandalini, G.; Iora, P.	2020	Italy	International Journal of Hydrogen Energy	University
67	Drivetrain technology	Article	Theoretical analysis	The impact of disruptive powertrain technologies on energy consumption and carbon dioxide emissions from heavy-duty vehicles	Smallbone, A.; Jia, B.; Atkins, P.; Roskilly, A.P.	2020	China,United Kingdom	Energy Conversion and Management	University
68	Drivetrain technology	Conference paper	Practical implementation	A Novel Approach on Range Prediction of a Hydrogen Fuel Cell Electric Truck	Chandrasekar, C.V.; Amruth Kumar, L.R.	2019	India	Event: SAE NuGen Summit	Company
69	Drivetrain technology	Article	Theoretical analysis	Comparing alternative heavy-duty drivetrains based on GHG emissions, ownership and abatement costs: Simulations of freight routes in British Columbia	Mojtaba Lajevardi, S.; Axsen, J.; Crawford, C.	2019	Canada	Transportation Research Part D: Transport and Environment	University
70	Drivetrain technology	Conference paper	Theoretical analysis	Fuel economy analysis of medium/heavy-duty trucks -2015-2050	Burke, A.; Zhao, H.	2017	United States	Event: International Electric Vehicle Symposium and Exhibition	University
71	Drivetrain technology	Conference paper	Theoretical analysis	What is the best alternative drive train for heavy road transport?	Gnann, T.; Plötz, P.; Wietschel, M.; Kühn, A.	2017	Germany	Event: International Electric Vehicle Symposium and Exhibition	Research institute
72	Drivetrain technology	Article	Theoretical analysis	Driving an industry: Medium and heavy duty fuel cell electric truck component sizing	Marcinkoski, J.; Vijayagopal, R.; Kast, J.; Duran, A.	2016	United States	World Electric Vehicle Journal	Government

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73	Drivetrain technology	Article	Practical implementation	H2IntraDrive proves hydrogen fuel cell drive at BMW facility	Ströbel M.; Schöbel H.; Micheli R.	2016	Germany	Fuel Cells Bulletin	Company,University
74	Drivetrain technology	Conference paper	Practical implementation	Novel concept of long-haul trucks powered by hydrogen fuel cells	Shabani B.; Andrews J.; Subic A.; Paul B.	2013	Australia	Event: Lecture Notes in Electrical Engineering	University
75	Drivetrain technology	Article	Theoretical analysis	The driving power of the electron	Pagliaro, M.; Meneguzzo, F.	2019	Italy	Journal of Physics: Energy	University
76	Drivetrain technology	Article	Theoretical analysis	Portfolio analysis of alternative fuel vehicles considering technological advancement, energy security and policy	Romejko, K; Nakano, M.	2017	Japan	Journal of Cleaner Production	University
77	Drivetrain technology	Conference paper	Practical implementation	Experimental Study on Fuel Economy of Fuel Cell Truck under Different Driving Cycle	Sun, T.; Chen, G.; Lan, H.; Guo, J.; Wang, X.; Hao, D.	2021	China	Event: Asia Conference on Energy and Electrical Engineering	Research institute
78	Drivetrain technology	Article	Theoretical analysis	Electrification opportunities in the medium- and heavy-duty vehicle segment in Canada	Ribberink, H.; Wu, Y.; Lombardi, K.; Yang, L.	2021	Canada	World Electric Vehicle Journal	Research institute
79	Drivetrain technology	Review	Theoretical analysis	The role of hydrogen and fuel cells in the global energy system	Staffell, I.;Scamman, D.;Velazquez Abad, A;Balcombe, P;Dodds, P.E.;Ekins, P;Shah, N;Ward, K.R.	2019	United Kingdom	Energy and Environmental Science	University
80	Drivetrain technology	Review	Theoretical analysis	A Review of Heavy-Duty Vehicle Powertrain Technologies: Diesel Engine Vehicles, Battery Electric Vehicles, and Hydrogen Fuel Cell Electric Vehicles	Cunanan, C.;Tran, M.-K.;Lee, Y.;Kwok, S.;Leung, V.;Fowler, M.	2021	Canada	Clean Technologies	University
81	Fuel cell application	Article	Practical implementation	Expanded and nano-structured carbonaceous graphite for high performance anisotropic fuel cell polymer composites	Saadat, N.; Dhakal, H.N.; Jaffer, S.; Tjong, J.; Yang, W.; Tan, J.; Sain, M.	2021	Canada,China,United Kingdom,United States	Composites Science and Technology	Company,University
82	Fuel cell application	Conference paper	Theoretical analysis	Hydrogen pump for hydrogen recirculation in fuel cell vehicles	Wiebe, W.; Unwerth, T.V.; Schmitz, S.	2020	Germany	Event: International Symposium on Hydrogen Energy and Energy Technologies	University
83	Fuel cell application	Article	Theoretical analysis	Survey of DC-DC non-isolated topologies for unidirectional power flow in fuel cell vehicles	Bhaskar, M.S.; Ramachandaramurthy, V.K.; Padmanaban, S.; Blaabjerg, F.; Ionel, D.M.; Mitolo, M.; Almakhles, D.	2020	Denmark,Malaysia,Saudi Arabia,United States	IEEE Access	University
84	Fuel cell application	Article	Theoretical analysis	Recent advances and future perspectives of carbon materials for fuel cell	Saadat, N; Dhakal, HN; Tjong, J; Jaffer, S; Yang, WM; Sain, M.	2021	Canada,China,United Kingdom,United States	Renewable and Sustainable Energy Reviews	Company,University
85	Fuel cell application	Article	Theoretical analysis	Coordination control strategy for the air management of heavy vehicle fuel cell engine	Sun, T; Zhang, X; Chen, B; Liu, X.H.	2020	China	International Journal of Hydrogen Energy	Research institute,University
86	Fuel cell application	Article	Practical implementation	3D multiphysics modeling aided APU development for vehicle applications: A thermo-structural investigation	Al-Masri, A; Peksen, M; Khanafer, K.	2019	Canada,China,Germany,Kuwait	International Journal of Hydrogen Energy	Research institute,University
87	Fuel cell application	Article	Theoretical analysis	Will there be enough platinum for a large deployment of fuel cell electric vehicles?	Reverdiau, G.; Le Duigou, A.; Alleau, T.; Aribart, T.; Dugast, C.; Priem, T.	2021	France	International Journal of Hydrogen Energy	Government,Hydrogen Association,Research institute,University
88	Fuel cell application	Article	Theoretical analysis	Comparative life cycle assessment of propulsion systems for heavy-duty transport applications	Simons, S.; Azimov, U.	2021	United Kingdom	Energies	University
89	Fuel cell application	Review	Theoretical analysis	New roads and challenges for fuel cells in heavy-duty transportation	Cullen, D.A.; Neyerlin, K.C.; Ahluwalia, R.K.; Mukundan, R; More, K.L.; Borup, R.L.; Weber, A.Z.; Myers, D.J.; Kusoglu, A.	2021	United States	Nature Energy	Research institute
90	Fuel cell application	Review	Theoretical analysis	Proton conductors for heavy-duty vehicle fuel cells	Gittleman, C.S.;Jia, H.;De Castro, E.S;Chisholm, C.R.I.;Kim, Y.S.	2021	United States	Joule	Company,Research institute
91	Storage system application	Conference paper	Practical implementation	Technical assessment and feasibility validation of liquid hydrogen storage and supply system for heavy-duty fuel cell truck	Wang, Q.; Li, J.; Bu, Y.; Xu, L.; Ding, Y.; Hu, Z.; Liu, R.; Xu, Y.; Qin, Z.	2020	China	Event: CAA International Conference on Vehicular Control and Intelligence	Research institute,University
92	Storage system application	Article	Theoretical analysis	Designing hydrogen fuel cell electric trucks in a diverse medium and heavy duty market	Kast, J.; Morrison, G.; Gangloff, J.J.Jr.; Vijayagopal, R.; Marcinkoski, J.	2018	United States	Research in Transportation Economics	Government
93	Storage system application	Article	Theoretical analysis	Design Space Assessment of Hydrogen Storage Onboard Medium and Heavy Duty Fuel Cell Electric Trucks	Gangloff, J.J.; Kast, J.; Morrison, G.; Marcinkoski, J.	2017	United States	Journal of Electrochemical Energy Conversion and Storage	Government
94	Storage system application	Article	Theoretical analysis	Clean commercial transportation: Medium and heavy duty fuel cell electric trucks	Kast, J.; Vijayagopal, R.; Gangloff, J.J.Jr.; Marcinkoski, J.	2017	United States	International Journal of Hydrogen Energy	Government
95	Storage system application	Conference paper	Practical implementation	Probabilistic life prediction of hydrogen steel pressure vessels in industrial electric trucks	Minas C.; Patel S.	2014	United States	Event: ASME International Mechanical Engineering Congress and Exposition	Company