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Hydrogen Vehicles and Sustainable Mobility: Integration of Technological Innovation, Trade, and Environmental, Social, and Governance Principles

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ABSTRACT
The growing demand for cleaner and more efficient transport solutions has placed hydrogen-powered vehicles at the center of discussions on sustainable mobility. This study adopted a qualitative approach based on two complementary procedures: a literature review, which compiled and compared scientific studies on the subject, and documentary research, grounded in technical reports, regulatory documents, and sectoral data. The main objective was to analyze how hydrogen-powered vehicles contribute to sustainable mobility by integrating technological innovation, commercial efficiency, and environmental, social, and governance principles across land, water, and air transport. The findings revealed that hydrogen vehicles are not merely an energy solution but a driving force for change that connects innovation, markets, and sustainability. When examined across different modes of transport, the research highlights the need to integrate science, public policy, and markets in the development of solutions capable of addressing the current challenges of mobility.

***Keywords**: hydrogen; sustainable mobility; technological innovation; environmental and social governance.*

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I. INTRODUCTION

With the growing pressure to reduce emissions and the need to rethink transport models and the economy in light of environmental and social commitments, the debate on new ways of mobility has been intensifying. Among the available options, hydrogen vehicles stand out as a technology with the potential to revolutionize the transport of people and goods in diverse contexts. This is not merely a matter of replacing one type of fuel with another; it involves reconfiguring transport chains, commercial flows, and sustainability criteria, while aligning technological innovation, operational efficiency, and Environmental, Social, and Governance (ESG) principles within a single agenda.

To investigate this context, a qualitative approach was employed in this study. Two research procedures were applied: a literature review, which enabled the collection and comparison of scientific contributions on the subject, and documentary research, which focused on technical reports, regulations, and sectoral data. This combination sought to provide a critical and well-founded analysis of the potential applications of hydrogen vehicles across multiple modes of transport.

The central objective of the study is to analyze how hydrogen-powered vehicles contribute to sustainable mobility by integrating technological innovation, commercial efficiency, and ESG principles in land, water, and air transport. To achieve this purpose, the following specific objectives were defined:

- To examine the concepts of sustainable mobility and the contribution of hydrogen vehicles in articulating innovation, logistical efficiency, and practices aligned with ESG principles.
- To assess how land-based hydrogen vehicles can promote sustainable urban and road transport by combining technological solutions, logistical performance, and ESG guidelines.
- To investigate how hydrogen-powered waterborne vehicles reduce environmental impacts and restructure cargo transport based on ESG criteria within port logistics.
- To analyze the contribution of hydrogen-powered aircraft to sustainable air mobility, considering technological innovation, emission reduction, and new perspectives for air commerce.
- To verify how the integration of land, water, and air vehicles can improve logistics, stimulate trade, and consolidate transport practices in line with ESG principles.

The article is organized into four main sections. The introduction contextualizes the subject, outlining the objectives and methods employed. The following section, materials and methods, presents the adopted methodology. The theoretical framework addresses the concepts and research underpinning the discussion. Finally, the concluding remarks reflect on the outcomes of the analysis and outline future directions for the implementation of hydrogen transport within a sustainable mobility agenda.

II. MATERIAL AND METHODS

The investigation followed a qualitative approach, recognized for its ability to capture the nuances, interpretations, and meanings attributed by social actors. As Silverman (2017) points out, the qualitative approach goes beyond the mere measurement of data; it seeks to understand processes and practices within their contexts. Internationally, this perspective has been crucial for studies examining technological and cultural changes, as it allows sustainable mobility to be understood not only as the outcome of technical innovations but also as a social practice under continuous construction. Thus, this methodological choice was not made at random: it is directly related to the object of investigation itself, which is shaped by multiple perspectives and layers of analysis.

The study adopted a qualitative methodology, structured around two distinct procedures. The first was a literature review, conducted through the reading and analysis of scientific articles, monographs, and recent news reports. Among the works referenced are Erthal, Vieira, and Buttenbender (2025), Figueiredo and Giocondo Cesar (2021), and Gomes et al. (2025), in addition to journalistic articles such as those by Alves (2023), FIEC Online (2023), and Xavier (2025). As emphasized by Rodrigues and Neubert (2023), literature reviews enrich the conceptual repertoire and situate the investigation within the established academic debate, offering a solid basis for integrating the reflections of this work into various lines of thought.

The second procedure was documentary research, focused on works that provide direct reference to the topic. Studies by Romaro and Serralvo (2022), Barcik (2021), and Ett et al. (2023) were reviewed, as they provide data and analyses that can guide practices and decisions related to hydrogen-powered transport. Gerhardt and Silveira (2009) note that documentary research allows the researcher not only to compile published information but also to interpret it critically, revealing connections and contradictions that are not always immediately evident. This phase enriched the literature review by incorporating more direct engagement with practical materials.

In total, more than twenty-five sources, including articles, documents, and news reports, were analyzed, providing a robust foundation for the analysis and enabling the authors to substantiate their arguments in a well-grounded manner. This methodological trajectory enhanced the consistency of the interpretations and allowed the text to integrate different registers: academic rigor, journalistic contemporaneity, and documentary consistency. By bringing these elements together, the materials and methods section reinforces the credibility of the study and, in its very process of elaboration, seeks coherence between method, object, and analysis.

III. THEORETICAL FRAMEWORK

3.1 Hydrogen Vehicles and Sustainable Mobility

The issue of hydrogen vehicles has been at the center of discussions on the energy transition, particularly in efforts to align technological innovation, commerce, and environmental preservation. Lunardi (2024) argues that the application of hydrogen across multiple modes of transport, from road to rail, creates new opportunities to reduce emissions and diversify the energy matrix. In this context, sustainable mobility is no longer merely a normative concept but becomes a concrete practice, emerging from the pursuit of integration among energy efficiency, public policy, and new fueling models.

Nevertheless, several authors remain critical of hydrogen vehicles, citing factors such as refueling, energy efficiency, and final cost. Dhakar et al. (2025) and Jiang et al. (2025) analyze the challenges of refueling these vehicles, particularly the difficulties of constructing hydrogen refueling stations and ensuring operational safety. Comparisons such as those presented by Ajanovic (2023) highlight obstacles in the hydrogen versus electric vehicle debate, explaining the current greater popularity of the latter.

Recent literature emphasizes that the issue is not simply a matter of replacing fossil fuels with hydrogen but of restructuring entire production chains, taking into account each stage and its particularities, as analyzed by Chakraborty et al. (2022). According to Barcik (2021), logistical efficiency is interwoven with innovation in vehicle electrification, creating a space where hydrogen- and electricity-powered technologies can coexist harmoniously within the same ecosystem. Gomes et al. (2025) further argue that nanotechnological solutions for hydrogen storage and utilization are already aligning with global climate mitigation strategies, demonstrating that clean mobility is simultaneously a field of scientific research and industrial development.

Table 1: Contributions of Hydrogen to Sustainable Mobility

Aspects analyzed	Contributions according to the literature
Emissions reduction	Hydrogen applied to transportation significantly decreases greenhouse gas emissions, enabling cleaner mobility (Ett, 2023).
Modal diversification	The technology can be used in land, water, and air vehicles, offering flexibility for different mobility sectors (Lunardi, 2024).
Technological innovation	Advances in fuel cells provide greater autonomy and faster refueling compared to conventional electric vehicles (Ett, 2023).
ESG integration	The use of hydrogen in transportation strengthens environmental and social commitments and encourages governance models aligned with sustainability (Lunardi, 2024).

Source: Adapted from Ett (2023) and Lunardi (2024).

Studies by Ett et al. (2023) on fuel cells indicate that hydrogen mobility is not merely a technical matter. It also supports the reduction of dependence on fossil fuels within logistics chains, thereby increasing the energy autonomy of countries and cities. This development requires collaboration among universities, the private sector, and governmental institutions, and a global movement in this direction is already underway. The logic is straightforward: more technology and infrastructure translate into a greater presence of hydrogen in passenger and freight transport.

3.1.1 ESG Aspects, Life Cycle, and Environmental Impacts in Hydrogen Vehicle Production

ESG principles are fundamental to assessing the sustainability of this technology. From an environmental perspective, hydrogen vehicles stand out for their potential to reduce greenhouse gas (GHG) emissions during use, contributing to targets such as those of the Paris Agreement. However, it is crucial to consider the waste generation impacts across the entire life cycle. In the production phase, the manufacturing of fuel cells involves

precious metals such as platinum and rare earth elements, whose mining produces toxic residues, including tailings that contaminate soil and water. Life Cycle Assessment (LCA) studies indicate that, without efficient recycling practices, this waste may account for up to 20–30% of the total environmental impact, including soil acidification and the eutrophication of water bodies. Moreover, the production of green hydrogen depends on solar panels or wind turbines, whose components—such as batteries and photovoltaic modules—generate hazardous waste at the end of their life cycle, including heavy metals and non-biodegradable plastics, requiring proper management to prevent pollution.

Figure 1. Challenges for the use of hydrogen as an energy source

Source: Anekwe et al. (2025)

Kurc et al. (2024) argue that the high cost of materials involved in the production of fuel cells, particularly platinum, remains a major obstacle to the widespread adoption of hydrogen fuel cell vehicles.

In this context, ESG principles become fundamental. Hydrogen mobility extends beyond environmental indicators and begins to spark discussions on social inclusion, equal access, and responsible governance in transport. Gomes et al. (2025) affirm that energy technologies, when made accessible, promote environmental sustainability, social justice, and economic competitiveness. Hydrogen thus emerges as an integrative element linking science, business, and social values, contributing to a more just and balanced energy transition.

During the usage phase, waste impacts are minimal, since hydrogen vehicles emit only water. However, fuel cell maintenance can generate secondary waste, such as degraded catalysts containing toxic substances like cadmium or mercury. At the end of life, the inadequate disposal of hydrogen vehicles may release these materials, contributing to indirect GHG emissions and environmental contamination. To mitigate these risks, ESG principles emphasize governance through mandatory recycling policies and material traceability, as adopted by the European Union (Wong et al., 2021).

From a social standpoint, the adoption of hydrogen vehicles promotes inclusion by providing clean mobility in polluted urban areas, improving public health and reducing inequalities in access to sustainable transport. Companies that integrate ESG principles into their operations, such as those reporting through Nikola Corporation's sustainability disclosures, demonstrate how innovation can align profit with responsibility, thereby fostering ethical investment (Anekwe et al., 2025).

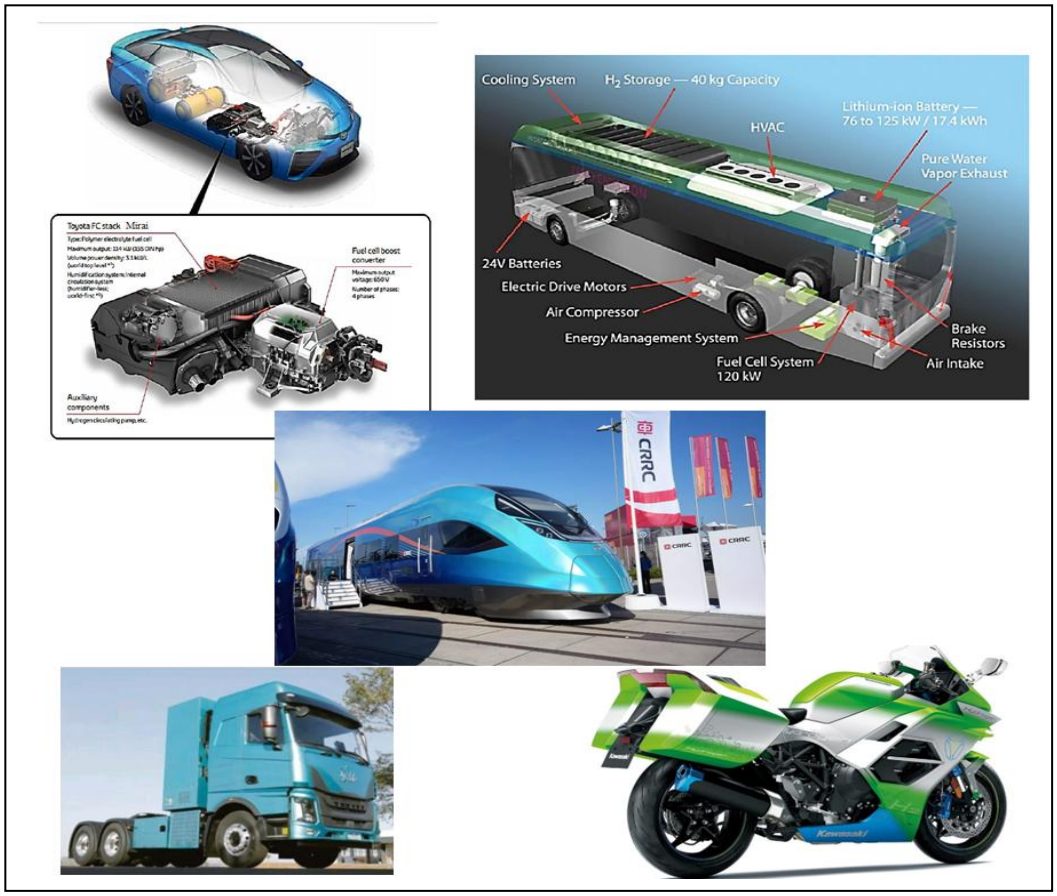
In sum, hydrogen vehicles represent a bridge to sustainable mobility, integrating technological innovation with business opportunities and ESG principles. Nevertheless, the environmental impacts of waste generation—from mining to disposal—demand proactive measures, such as the development of advanced recycling technologies and circular production chains. By prioritizing green hydrogen and robust governance, the transport sector can be transformed into a vector of sustainable development, reducing not only emissions but also the waste footprint, thus contributing to a more resilient and equitable future (Anekwe et al., 2025; Wong et al., 2021).

3.2 Hydrogen-Powered Land Vehicles: Technological Innovation and Trade

Hydrogen-powered land vehicles are no longer merely a promise; over the past decade, they have become a central topic in discussions of technological innovation and trade within the transportation sector. Cars, trains, buses, trucks, and even motorcycles are being adapted to align with this emerging energy source, demonstrating that sustainable mobility represents an interconnected set of innovations rather than isolated solutions. The concept of Power-to-X, in conjunction with mobility, is examined in the work of Ett et al. (2023), particularly regarding

cars (such as the Toyota Mirai) and buses, with a focus on the integration of fuel cells across various transport modes. This process not only produces clean energy but also establishes efficient logistical routes, thereby minimizing environmental impact. Figure 1 below illustrates examples of hydrogen-powered land vehicles, highlighting the coordinated and progressive efforts of multiple manufacturers in this technological domain.

Figure 2 – Hydrogen-Powered Land Vehicles



Souce: Vinholes (2025); Xavier (2025); Alves (2023); Ett et al. (2023).

When it comes to trucks, this issue becomes even more critical, given that long-distance road freight transport accounts for a significant portion of greenhouse gas emissions. In Brazil, according to Vinholes (2025), the first hydrogen-powered truck was introduced to assess the feasibility of this type of transport on highways. The pursuit of such solutions by companies and regulatory bodies is not limited to energy efficiency but also encompasses the ESG agenda, as it translates socio-environmental responsibility into concrete actions. In this context, commerce plays an active role, since the adoption of these vehicles can reduce operational costs associated with diesel while enabling the development of more competitive and less fossil fuel-dependent supply chains.

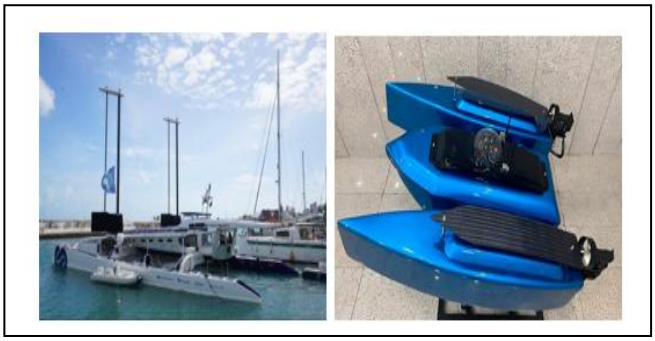
Hydrogen-powered motorcycles also represent a promising area. Alves (2023) notes that Kawasaki, together with Toyota, is designing vehicles that balance performance with environmental responsibility. This collaboration between manufacturers demonstrates that innovation does not occur in isolation but through strategic partnerships that accelerate results and render market implementation more viable. Observing these initiatives, it is evident that two-wheeled transport not only enriches the portfolio of sustainable mobility options but also strengthens the reputation of brands investing in socio-environmental responsibility, appealing to a public increasingly attentive to corporate practices aligned with ESG criteria.

In summary, passenger vehicles, public transport, freight trucks, and motorcycles powered by hydrogen are not merely advanced technological innovations. They also pave the way for a transformation in commerce, making logistics more efficient and less polluting, while aligning industrial operations with environmental and social commitments. This ongoing movement demonstrates that sustainable mobility is the result of concrete decisions integrating science, market dynamics, and social values.

3.3 Hydrogen-Powered Watercraft: Sustainability and Efficiency in Trade

The maritime sector has increasingly shown openness to the use of hydrogen, particularly in response to growing international demands for a low-carbon economy and the need to reduce emissions along major trade routes. The green hydrogen-powered ship showcased in Fortaleza in 2023, according to FIEC On Line (2023), represents a technological shift and a new operational logic within ports and the connected logistics chains. This transformation is part of a global trend in which innovation and commerce converge to address increasingly stringent environmental and social demands. By introducing hydrogen as an energy source, a robust foundation is established for re-evaluating sustainability in maritime transport. As illustrated in Figure 3, there are various types of hydrogen-powered watercraft, ranging from large ships to experimental prototypes.

Figure 3 – Hydrogen-Powered Watercraft



Source: Mattana (2025); FIEC On Line (2023)

In addition to large-scale projects, the advancement of smaller boats illustrates how the technology can be adapted for diverse purposes. According to Mattana (2025), an experimental boat was able to navigate for one hour using only 500 ml of water, indicating that it is feasible to develop reduced-scale models for recreational activities, short-distance passenger transport, and specialized logistical services. This flexibility maximizes the innovation's potential, allowing the same technology to serve both major commercial routes and the local needs of marinas and smaller ports. The introduction of these vessels opens new market opportunities while contributing to global emission reduction targets.

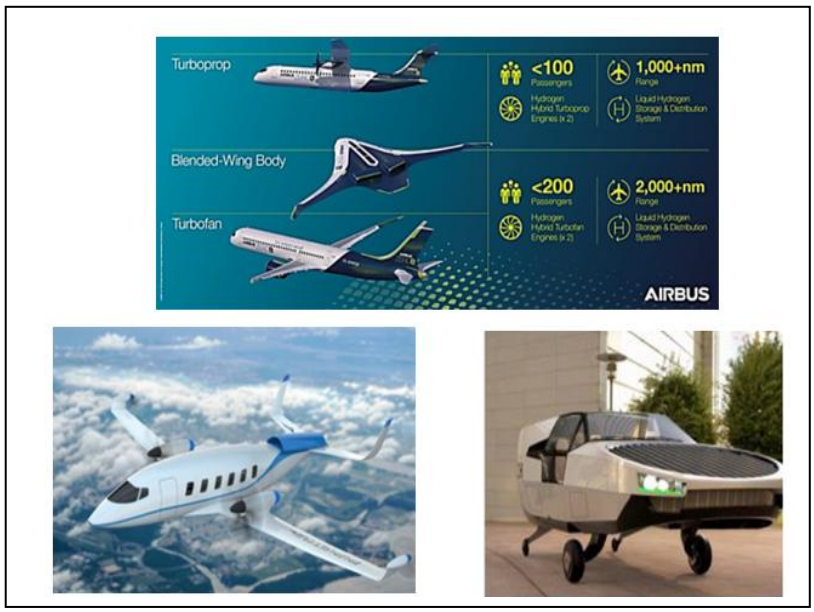
In terms of energy efficiency, Barcik (2021) emphasizes the relevance of electrification technologies that combine performance with low emissions. This issue becomes even more significant when considering hydrogen-powered boats, given that the maritime industry has historically relied heavily on fuels with substantial environmental impact. Furthermore, Ett et al. (2023) argue that the Power-to-X concept can be applied to the naval sector, enabling the conversion of renewable energy into forms that can be stored and used in fuel cells. This perspective not only makes the environmental agenda more tangible but also aligns with ESG criteria increasingly demanded by investors and international trade.

Thus, hydrogen-powered watercraft represent a viable alternative for making maritime transport more sustainable, efficient, and compliant with global environmental preservation commitments. Although many of these projects are still in the testing phase, we can already envision a future in which ships and vessels have a reduced environmental impact, fostering a stronger connection between technological innovation, commerce, and socio-environmental responsibility.

3.4 Hydrogen-Powered Aircraft: Innovation and Sustainable Mobility

Aerial mobility is exploring ways to reduce emissions, and hydrogen has emerged as one of the most promising options to achieve this goal. Airbus, for instance, has already unveiled fuel cell-powered aircraft concepts testing various configurations, including turboprops, blended fuselages, and turbofans, each designed to carry different passenger capacities and operate on medium-range flights. This initiative by the industry indicates that the energy transition is being integrated into the strategic planning of leading manufacturers, not merely in response to environmental pressures but also as an opportunity to develop new markets. Sürer and Arat (2018) highlight that the introduction of hydrogen in aviation can not only enhance energy efficiency but also transform airport infrastructure and related air commerce. The illustrations depict several interpretations of hydrogen-powered aircraft and prototypes, emphasizing the application of innovation at different levels.

Figure 4 – Hydrogen-Powered Aircraft



Source: Ett et al (2023)

In applied research, for instance, Ribeiro et al. (2022) explore the use of fuel cells in hybrid propulsion systems for aircraft and argue that hydrogen should not be considered in isolation but rather as part of broader energy configurations that ensure safety, performance, and reduced environmental impact. This approach enables the development of new aircraft models capable of balancing flight range with lower maintenance costs, making aviation more competitive in regional and short-haul flights. International trade is also attentive to this transformation, as reducing fossil fuel consumption can lower operational costs and decrease reliance on global oil supply chains.

When considering urban aerial mobility and commercial operations, it is important to include drones and personal aerial vehicles as part of the innovations. According to Vieira (2025), hydrogen-powered drones can enable commercial delivery operations and extended flights, as they do not face the same limitations as conventional batteries, according to the business plan developed by the author. This perspective enriches the discussion on sustainable mobility, as urban aerial logistics becomes a key element for companies seeking agility without compromising their environmental commitments. Ett et al. (2023) also explore the Power-to-X concept, which allows hydrogen to be integrated into various applications, such as aviation or airport energy distribution systems.

Figure 5 – Hydrogen-Powered Drone

Source: Vieria (2025)

Hydrogen-powered aircraft, therefore, not only contribute to reducing emissions in the sector but also signal a fundamental reorganization of aerial mobility and its relationship with commerce. Although many projects are still in the testing phase, it is already possible to envision a future in which aircraft, drones, and hybrid aerial vehicles are part of a more sustainable, efficient transport network that aligns with ESG guidelines.

3.5 Integration Across Transport Modes and ESG Perspectives

The connection of hydrogen-powered transport modes—land, water, and air—creates a new framework for rethinking logistics and commerce in a sustainable manner. This concept goes beyond the mere substitution of fossil fuels, reshaping the structure of transport chains worldwide. According to Erthal, Vieira, and Buttenbender (2025), sustainable mobility aligned with ESG principles extends beyond environmental metrics, also strengthening social and governance practices, thereby enhancing the credibility of companies and governments among investors and local communities. Therefore, the energy transition in transportation is not merely a technical issue but also a matter of culture and values.

In practice, Barcik (2021) highlights the relevance of low-emission technologies that can improve energy efficiency in integrated systems. When hydrogen-powered trucks are connected to ships utilizing the same energy vector, which in turn communicate with fuel cell-powered aircraft, a more integrated and less fragmented logistics network emerges. This integration can minimize bottlenecks at ports, airports, and distribution centers while ensuring greater cost predictability within international supply chains. In this context, hydrogen serves as the unifying element across multiple transport modes, enabling continuous operations with reduced environmental impact.

Simultaneously, simulations of decarbonization strategies for freight transport, as presented by Ghisolfi, Chaves, and Ribeiro (2025), demonstrate that combining different transport modes can be organized to enhance commercial flows without compromising emission reduction targets. Such planning encompasses not only vehicle routes but also the modernization of supporting infrastructure, including hydrogen-fueled logistic corridors and intermodal terminals prepared for new energy requirements. These perspectives align with the analyses of Ett et al. (2023), who discuss Power-to-X as an integrative solution for hydrogen production, storage, and application across various mobility contexts.

Finally, it is important to emphasize that the integration of transport modes does not occur without a regulatory and corporate framework. Romaro and Serralvo (2022) argue that ESG should be understood in a pluralistic sense, meaning that companies and managers must recognize the interdependence between technology, market dynamics, and socio-environmental responsibility as crucial. Policies should be implemented to promote cross-sector collaboration, encourage investment in infrastructure, and strengthen transparent governance practices. According to Figueiredo and Cesar (2021), research on hydrogen as an alternative energy source provides the scientific foundation for these decisions, bridging theory and practice in a rapidly evolving sector. It is at this intersection of technological innovation, logistics efficiency, and ESG principles that a horizon emerges in which mobility becomes not only more sustainable but also more integrated, equitable, and strategically aligned with global commerce.

IV. DISCUSSION AND CONCLUSION

This article aimed to explore the role of hydrogen-powered vehicles within the current context of sustainable mobility, which is driven by environmental, economic, and social pressures in the search for cleaner and more integrated alternatives. The investigation encompassed not only technical and logistical aspects but also perspectives on technological innovation, commerce, and ESG principles, providing a comprehensive overview of feasible changes in the transport sector.

A qualitative approach was chosen, which enabled the development of this study. The literature review allowed for the identification and comparison of available academic production, revealing diverse interpretations and perspectives on the subject. Documentary research was essential for providing robustness to the work, relying on technical reports, legislation, and sector data, which helped form a practical and concrete understanding. This combination of methodologies offered a complementary perspective and added rigor to the discussion.

All objectives proposed in this research were achieved. The study fully met its goal of analyzing the contribution of hydrogen-powered vehicles to sustainable mobility, in the context of technological innovation, commercial efficiency, and ESG principles across land, water, and air transport modes. Similarly, each specific objective was addressed: the relationship between sustainable mobility and hydrogen vehicles was examined; the role of urban and road transport in promoting ESG-aligned solutions was assessed; the relevance of waterborne transport in logistical reorganization and emission reduction was investigated; aerial mobility was analyzed with a focus on innovation and emission reduction; and, finally, the integration of different transport modes was evaluated as a means of enhancing trade efficiency and sustainability.

Key findings were also reflected in the theoretical framework. As discussed in Section 3.1, hydrogen vehicles can be integrated into a global sustainable mobility agenda, reconciling environmental and social promises. Section 3.2 demonstrated that land transport already features prototypes and commercial models that combine logistical efficiency with technological innovation. As shown in Section 3.3, the use of hydrogen as a fuel for vessels is increasingly viable, enabling significant emission reductions in port areas and along commercial shipping routes. In Section 3.4, the analysis highlighted how the aviation industry is striving to develop technologies that reduce reliance on fossil fuels, benefiting international air commerce. Section 3.5 presented the

unification of transport modes as a strategic solution to balance efficiency, commerce, and ESG principles on a global scale.

In sum, the study demonstrated that hydrogen-powered vehicles are not merely an energy solution but a driver of change that connects innovation, market dynamics, and sustainability. By examining the subject across multiple transport modes, the research underscores the need to integrate science, public policy, and market strategies in developing solutions to current mobility challenges.

Although this study achieved its objectives, further research remains necessary. Future investigations could examine the economic feasibility of large-scale initiatives, study the social effects of the energy transition, and monitor progress in international hydrogen policies. It would also be valuable to analyze cases of intermodal integration in other regions, which could provide practical examples to strengthen sustainable mobility in diverse contexts.

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