Green Hydrogen (H2V) Logistics in Brazil: Comparison of Modals and Environmental Impacts

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Cargo transport in Brazil is composed of road, rail, waterway, pipeline and air modes. The road modal stands out, representing about 64.8% of the total cargo transported in the country, according to data from the National Transport Confederation (CNT) in 2023. The rail modal configures 14.9%, while other modes, such as waterway, correspond to smaller portions, with cabotage and waterways, adding up to 12%. In the transport of dangerous products, the choice of the most appropriate modal must consider not onl y technical and safety aspects but also costs and environmental impacts. Green hydrogen (which is characterized as a dangerous product) has been consolidated as an essential element in the global energy transition. Ensuring its economic viability in Brazil requires optimization in transpor tation methods. Although the road modal is predominant in the transport chain of dangerous products, the other modes, such as rail, pipeline and waterway, can contribute significantly to the chain, reflecting even more relevance due to their greater efficiency, safety and contribution to the reduction of environmental impacts. To enable the use of the various modes available, it is essential to invest in infrastructure, such as the expansion of road and rail networks, retrofit or construction of new pipelines, as well as the modernization of ports and waterways. These investments are essential to improve efficiency, increase safety and enhance the contribution of these modes in reducing environmental impacts, offering more sustainable alternatives in a context of a low-carbon economy. This article proposes a detailed comparison of the modes for transporting green hydrogen. The advantages, limitations and environmental impact of each modal were analyzed. Qualitative research was used as a methodology, based on bibliographic research and observations. The article aims to contribute to the analysis of the most appropriate mode of transport for the transport of green hydrogen, in terms of sustainability and efficiency, comparing the operating scenarios (involving costs, infrastructure, among others), in order to identify viable solutions that meet the economic, environmental and technological demands for the global energy transition.
Keywords: Modes of Transport. Green Hydrogen. Renewable Energies. Decarbonization. Sustainability.

Brazil, one of the largest producers of renewable energy in the world, stands out on the global stage for its capacity to produce green hydrogen, a clean and sustainable alternative for the energy transition. Green hydrogen is produced from renewable sources, such as solar and wind energy, and its use is seen as a crucial solution for the decarbonization of sectors such as transportation, industry, and energy [1]. However, one of the biggest challenges that Brazil faces is the safe and efficient transportation of this product, especially due to its nature as a dangerous product [2].

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The logistics of green hydrogen depends on the choice of the most appropriate mode of transport, considering factors such as safety, cost, efficiency and, above all, environmental impacts. The efficiency of the green hydrogen logistics chain is essential not only to ensure the economic viability of the product, but also to ensure that it actually contributes to the reduction of carbon emissions in Brazil [3].

Theoretical Framework

The Overview of Transport Modes in Brazil

Logistics in Brazil is predominantly centered on the road modal. According to the National Transport Confederation [4], the road modal represents 64.8% of all cargo transported in the country. This high participation is a result of the flexibility and extensive network of highways,

which allows access to almost all Brazilian municipalities [4].

However, the road model, despite its high participation, presents challenges in terms of cost and environmental impact. Road transport is more expensive compared to other modes, such as rail and waterway, and contributes significantly to greenhouse gas emissions [5].

In addition to road, other modes also play important roles. Rail transport, for example, has proven to be efficient for high-volume cargo and long distances [6]. The waterway modal, which includes cabotage and waterways, also offers advantages in terms of cost and energy efficiency for heavy and bulky loads [7]. Pipeline transport, in turn, has proven to be safe and efficient for the transport of liquids and gases, such as hydrogen, but still faces structural challenges in Brazil [8].

The air modal is recognized for its speed and global reach, being ideal for high value-added, time-sensitive cargo or destined for remote locations. Representing 35% of the value of world trade, despite carrying less than 1% of the total cargo volume, it is essential to meet modern demands of markets that demand efficiency and safety. It is especially strategic in the transport of perishable products, preserving their quality, and dangerous products, where strict protocols are required. The air transport of dangerous products goods is strictly controlled by international bodies, such as IATA, which sets safety standards through the Dangerous Goods Regulations (DGR) [9].

Despite the high costs, it stands out as an efficient solution for specific loads.

Green Hydrogen and Logistical Challenges Green

Green hydrogen is a light and highly volatile molecule, which requires special care in its storage and transportation. As a dangerous product, its transport must comply with strict safety standards to avoid leaks or explosions. To ensure the safety and efficiency of transport, it is necessary to choose the most appropriate mode of transport [2,10].

Hydrogen storage presents several key challenges:

Energy Density: Hydrogen has a low energy density, which means it needs to be compressed or liquefied in order to be stored efficiently. This requires specialized equipment and consumes a lot of energy.

Extreme Conditions: To store liquid hydrogen, it is necessary to keep it at extremely low temperatures (about -253°C). For gaseous storage, it needs to be compressed to high pressures (usually between 350 and 700 bar). Both methods are technically complex and expensive.

Safety: Hydrogen is highly flammable and can form explosive mixtures with air, requiring stringent safety measures during storage and transportation.

Infrastructure: The current infrastructure for hydrogen storage and transportation is still limited and requires significant investments to scale, including the construction of specialized storage tanks and the adaptation of distribution networks.

These challenges need to be overcome if hydrogen is to become a viable and widely used alternative in the transition to a low-carbon economy. However, it can be transported by different modes, which will depend on the available infrastructure and logistical needs. However, each of these modes has advantages and limitations that need to be carefully analyzed.

Road

Road transport, despite being the most used in Brazil, has disadvantages in terms of CO_2 emissions and high costs. In the transport of green hydrogen, specialized tanker trucks would be needed, which further raises costs [3]. In addition, Brazilian roads are not always suitable for transporting dangerous cargo, which poses an additional risk [11].

Rail

The rail modal offers advantages in terms of cost per ton transported, especially for long distances. Rail transport is also more energy-efficient when compared to road transport, resulting in lower CO_2 emissions [6]. However, the railway infrastructure in Brazil is still insufficient, which limits the use of this modal for the transport of hydrogen on a large scale.

Waterway

Waterway transport, including cabotage and waterways, offers excellent value for money, especially for heavy and bulky loads. Brazil has an extensive network of waterways and ports that could be better used for the transport of green hydrogen, especially in the North and Southeast regions [7]. However, existing waterways need to be modernized and expanded to ensure transportation safety and efficiency.

Pipeline

The pipeline modal is particularly suitable for the transport of liquid and gaseous products, such as hydrogen. However, Brazil still lacks an efficient pipeline network for the transport of this type of cargo [8]. Construction or retrofit of existing pipelines would be necessary to enable the safe and large-scale transportation of green hydrogen.

The current infrastructure presents significant challenges to enable the safe and efficient transportation of this fuel, due to technical limitations, such as the fragility of the metallic materials of the pipelines and the high permeability of hydrogen [8,12].

One of the main issues is hydrogen embrittlement, which occurs due to hydrogen's ability to penetrate the microstructure of steel used in pipelines. This phenomenon reduces the mechanical strength and durability of the material, increasing the risk of cracks and catastrophic failures over time.

In addition, hydrogen has a higher leakage capacity due to its extremely small molecule, which can lead to significant losses and pose safety risks, such as explosions, if proper adaptations are not implemented.

Another challenge is the need to operate under higher pressures to transport hydrogen in a gaseous state, which requires structural reinforcement in the pipelines. The gaskets, valves and other components would also need to be updated to meet the technical specifications of this new use.

Aerial

Although air transport is the fastest, it is the most expensive and is usually used only for high value- added cargo. In the case of hydrogen, air transport is not a viable option due to high costs and low cargo volume [1].

In the specific case of hydrogen, air transport is not feasible due to two main factors: the high operating cost and the low volumetric density of hydrogen. Hydrogen, when transported in its liquid or compressed form, has a considerable volume in relation to its mass, which requires aircraft with a large load capacity for transport to be minimally efficient. However, due to the limitation of space and the high cost of operating aircraft, the volume of cargo transported of hydrogen would be small compared to the cost, making the operation economically unfeasible [1]. In addition, the lack of adequate infrastructure for the storage and safe handling of hydrogen at airports also contributes to the unfeasibility of this modal for this type of cargo.

The Energy Transition and Infrastructure Challenges

Brazil's energy transition requires the implementation of a modern and integrated infrastructure that supports the growth of the green hydrogen market. The expansion of road and rail networks, the construction of new pipelines, and the modernization of ports and waterways are essential to ensure logistical efficiency and minimize environmental impacts [3].

Significant investments are needed to overcome the current structural limitations and create a logistics network that meets the needs of the green hydrogen market. Modernizing ports, for example, could facilitate the export of green hydrogen to other countries, while building dedicated hydrogen pipelines would reduce costs and improve transport safety.

Materials and Methods

An exploratory study was conducted to evaluate transportation modes, adopting qualitative methods to characterize the different transportation modes and their current status regarding various factors important for H2V transportation. The study encompassed several stages developed between August 2024 and June 2025, with an exploratory–descriptive used to support the study with a review of the existing literature on the transport of green hydrogen. This involved analyzing academic articles, books, technical reports, and other relevant publications. The objective was to identify theories, models, and previously collected data on the subject, which helped to build a solid basis for understanding the subject [13]. A qualitative approach was also used, together with the bibliographic research, which guided us in the analysis of case studies and observations of global trends in hydrogen logistics [3]. The research sought to compare transport modes in terms of efficiency, safety, costs, and environmental impacts [14].

Results and Discussion

The choice of the most suitable modal for transporting green hydrogen depends on several factors, including costs, safety, available infrastructure, and environmental impacts. Table 1 summarizes the main characteristics of each modal.

Table 1. Main characteristics of each modal.

Modal	Advantages	Limitations
Road	Flexibility, capillarity (*)	High cost, high CO_2 emission
Rail	Lower cost per ton, energy efficiency	Insufficient infrastructure
Waterway	Cost-effective in large volumes, efficient for export	Insufficient infrastructure, need for modernization
Pipeline	Safety, efficiency for liquids and gases	Limited infrastructure, high upfront costs
Aerial	Speed, ideal for high-value loads	High cost, low volume, operational safety

(*) A physical phenomenon that occurs when a liquid rises or falls in a very thin tube (capillary) due to the interaction between the molecules of the liquid and the surfaces of the material that forms the tube.

Environmental Impacts and Sustainability

The transition to more sustainable modes of transport is essential for reducing greenhouse gas (GHG) emissions, one of the main causes of climate change. The adoption of clean and efficient alternatives contributes directly to the decarbonization of the planet. According to Carvalho (2020) [5], this change has a direct impact on the reduction of emissions in the transport sector, which is one of the largest global emitters.

The use of efficient and clean infrastructure helps to reduce dependence on fossil fuels and mitigate CO_2 emissions.

Modernizing the logistics infrastructure is key to promoting a more sustainable transportation system. This not only reduces GHG emissions but also facilitates the integration of cleaner technologies, such as electric vehicles and biofuels, which have a lower environmental impact compared to traditional fuels [1]. As Santos (2019) [15] emphasizes, Brazil must ensure that its logistics infrastructures evolve to meet global standards and contribute to a low-carbon economy.

Brazil, by assuming global climate commitments, has the responsibility to implement public policies that encourage the use of these modes and the modernization of logistics infrastructure. This will contribute not only to the reduction of CO_2 emissions, but also to the creation of a more resilient transport system, capable of facing the challenges of climate change and meeting the demand for sustainability in transport [5].

However, the transition faces challenges, such as the high costs of investing in modernization and the adoption of new technologies. The resistance of traditional sectors, such as road transport and the use of fossil fuels, is also an obstacle, in addition to the need for training professionals and the implementation of effective public policies to promote decarbonization [16]. Finally, rail, waterway, and pipeline modes, when compared to road, show a significant reduction in CO_2 emissions, which reinforces the importance of modernizing infrastructure to achieve Brazil's global climate commitments [5].

Conclusion

In the face of the logistical challenges involved in the transport of green hydrogen, it is evident that Brazil faces the need to adapt its infrastructure to ensure efficiency, safety, and sustainability in the transport of this essential product for the global energy transition. Although the road modal is predominant in the country, the rail, waterway and pipeline modes have significant advantages in terms of energy efficiency, cost reduction and lower environmental impact. The transition to a low-carbon economy therefore depends on substantial investments in the modernization and expansion of existing logistics infrastructure, especially in relation to road and rail networks, ports and pipelines.

Green hydrogen, due to its volatile nature and dangerous product, requires strict care in its transport, which makes the choice of the most appropriate modal a crucial factor to ensure its economic viability and safety in the process. The analysis of the different modes, considering their advantages and limitations, points to the need for integrated and strategic planning, which prioritizes sustainability and the reduction of greenhouse gas emissions.

Therefore, the study reinforces the importance of a holistic approach, which includes the modernization of logistics infrastructure and the improvement of green hydrogen transport capacity in Brazil. Such actions will not only contribute to the consolidation of the country as a leader in the production and export of clean energy but will also be fundamental for achieving global climate goals and building a more sustainable and resilient economy.

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