THE ROLE OF RENEWABLE HYDROGEN IN ACHIEVING SUSTAINABLE URBAN TRANSPORTATION

O PAPEL DO HIDROGÊNIO RENOVÁVEL NO ALCANCE DO TRANSPORTE URBANO SUSTENTÁVEL

EL PAPEL DEL HIDRÓGENO RENOVABLE EN EL ALCANCE DEL TRANSPORTE URBANO SOSTENIBLE

VICTOR HUGO SOUZA DE ABREU, Dr. | UFRJ – Universidade Federal do Rio de Janeiro, Brasil
RAFAEL FERRAZ DOS SANTOS | UFRJ – Universidade Federal do Rio de Janeiro, Brasil
ANDREA SOUZA SANTOS, Dra.| UFRJ – Universidade Federal do Rio de Janeiro, Brasil
SANDRA ODA, Dra. | UFRJ – Universidade Federal do Rio de Janeiro, Brasil

ABSTRACT
The increasing global demand for a more sustainable economy is propelling the exploration of alternatives to conventional practices. The adoption of a hydrogen production and distribution system is gaining global consensus, driven by its lower environmental impact compared to fossil fuels. This study delves into the feasibility of renewable hydrogen, sourced from avenues like solar and wind power, particularly in the realm of sustainable urban transportation. The urgency for innovative technologies, underscored by emissions targets and sustainable development goals, positions hydrogen as a promising solution with superior calorific value and reduced emissions to mitigate the impacts of the transport sector on the environment. Nonetheless, challenges, including limited infrastructure and the requirement for substantial investment, pose significant hurdles to its widespread adoption. The pertinence of this study is further emphasized by the necessity to continually update the literature, ensuring alignment with the dynamic developments in this field.

KEYWORDS
Sustainable economy; Renewable hydrogen; Innovative technologies; Sustainable urban transportation.

RESUMO
A crescente demanda global por uma economia mais sustentável está impulsionando a exploração de alternativas às práticas convencionais. A adoção de um sistema de produção e distribuição de hidrogênio está ganhando consenso global, impulsionada por seu menor impacto ambiental em comparação com os combustíveis fósseis. Este estudo investiga a viabilidade do hidrogênio renovável, proveniente de vias como a energia solar e eólica, especialmente no âmbito do transporte urbano sustentável. A urgência de tecnologias inovadoras, ressaltada por metas de emissões e objetivos de desenvolvimento sustentável, posiciona o hidrogênio como uma solução promissora com valor calorífico superior e emissões reduzidas para mitigar os impactos do setor de transportes no meio ambiente. No entanto, desafios, incluindo infraestrutura limitada e a necessidade de investimentos substanciais, representam obstáculos significativos para sua adoção generalizada. A pertinência deste estudo é ainda mais enfatizada pela necessidade de atualizar continuamente a literatura, garantindo o alinhamento com os desenvolvimentos dinâmicos nesse campo.

PALAVRAS-CHAVE
Economia sustentável; hidrogênio renovável; tecnologias inovadoras; transporte urbano sustentável.

http://dx.doi.org/10.29183/2447-3073.MIX2024.v10.n3.163-173
ISSN: 2447-0899 (IMPRESSA) | 2447-3073 (ONLINE)

RESUMEN

La creciente demanda global de una economía más sostenible está impulsando la exploración de alternativas a las prácticas convencionales. La adopción de un sistema de producción y distribución de hidrógeno está ganando consenso a nivel mundial, impulsada por su menor impacto ambiental en comparación con los combustibles fósiles. Este estudio investiga la viabilidad del hidrógeno renovable, proveniente de fuentes como la energía solar y eólica, especialmente en el ámbito del transporte urbano sostenible. La urgencia de tecnologías innovadoras, resaltada por metas de emisiones y objetivos de desarrollo sostenible, posiciona al hidrógeno como una solución prometedora con un mayor valor calorífico y emisiones reducidas para mitigar los impactos del sector del transporte sobre el medio ambiente. Sin embargo, desafíos, como la infraestructura limitada y la necesidad de inversiones sustanciales, representan obstáculos significativos para su adopción generalizada. La relevancia de este estudio se enfatiza aún más por la necesidad de actualizar continuamente la literatura, garantizando el alineamiento con los desarrollos dinámicos en este campo.

PALABRAS CLAVE

Economía sostenible; hidrógeno renovable; tecnologías innovadoras; transporte urbano sostenible.

1. INTRODUCTION

Today, there is an increasing global demand for a more sustainable economy, driven by nations' commitment to achieving emissions targets and sustainable development (SAEEDMANESH, MAC KINNON & BROUWER, 2018). In this context, the urgency for new technologies and solutions to replace traditional practices is more evident than ever (CEVALLOS-ESCANDÓN et al., 2023). The need for change is imperative to meet the expectations of a more sustainable future (EHRENSTEIN et al., 2020; SANTOS et al., 2021; DE ASSIS et al., 2022a; 2022b).

Thus, the implementation of a hydrogen production and distribution system, which has greater calorific value and reduced carbon emissions compared to fossil fuels (WIDERA, 2020; LAL & YOU, 2023), has gradually become a global consensus (SANTOS et al., 2021; CAPURSO et al., 2022). Hydrogen can be used as a feedstock, fuel or energy carrier and store to balance electricity supply and demand (EUROPEAN COMMISSION, 2019), resulting in an estimated global demand of more than US$12 trillion - equivalent to R$62.56 trillion - by 2050 (ONI et al., 2022).

Currently, hydrogen production is predominantly divided into three main categories: (i) renewable origin; (ii) fossil-origin with carbon capture and storage (CCS) or carbon capture, utilization and storage (CCUS); and (iii) fossil origin. Presently, hydrogen production processes are predominantly driven by non-renewable sources. However, To boost the development of the clean hydrogen market, global discussions have been held on standards for renewable hydrogen (LIU et al., 2022). Renewable hydrogen is produced using renewable energies such as solar and wind power and represents a more promising long-term solution for the transition to a carbon-free economy in various sectors including transportation (GULOTTA et al., 2022).

The use of renewable hydrogen as an energy source in urban transportation offers substantial advantages for promoting environmental sustainability (ACAR & DINCER, 2020). By eliminating harmful emissions and contributing to climate change mitigation, hydrogen stands out for its versatility and storage efficiency, providing vehicles with extended autonomy (DE ASSIS et al., 2022a; 2022b). In addition to the environmental benefits, the transition to renewable hydrogen drives technological innovation, the creation of specialized jobs and promotes an improvement in air quality, positively impacting public health and solidifying the position of cities at the forefront of the energy revolution.

Despite the obvious advantages, the widespread adoption of renewable hydrogen in the urban transportation sector faces significant challenges such as limited hydrogen production, distribution and supply infrastructure, requiring substantial investments to become widely accessible, among others. Thus, this paper aims to conduct a literature review to identify the advantages of hydrogen for sustainable urban transport, as well as assess its main challenges and best practices that can be implemented to minimize them.

2. METHODOLOGY

The methodology of this study consists of the following steps:

- Formulation of the Research Question: The research is guided by the question: "What is the role of renewable hydrogen in achieving a sustainable urban transportation matrix?"

- Search strategy: To identify relevant studies, relevant keywords were selected, such as "renewable hydrogen", "green hydrogen", "fuel cells" and "sustainable urban transportation". The search was conducted in specialized databases, including Web of Science, Scopus, and others related to energy and sustainability.

- Source selection: Articles were meticulously chosen based on predetermined inclusion and exclusion criteria. Only studies directly addressing the role of hydrogen in sustainable urban transportation were deemed relevant, prioritizing methodological rigor and contemporary relevance.

- Organization of the Review: The selected studies were grouped into thematic categories, including hydrogen technologies, public policies, challenges and opportunities. This approach aims to provide a comprehensive and structured overview of the current state of research on the topic.

- Reading and Synthesis: A critical reading of the scientific papers highlighted essential information on the role of hydrogen in sustainable urban transport. Synthesis involves condensing the main conclusions, methodologies and findings, providing an in-depth understanding of the topic.

• Critical Analysis: The reviewed studies underwent rigorous scrutiny, identifying potential biases, methodological constraints, and strengths. This comprehensive approach is intended to foster a nuanced interpretation of the evidence presented in the literature, ensuring a balanced.

• Contextualization and Integration: The results were contextualized within the broader panorama of sustainable urban transport and energy policies. The integration of findings from different sources seeks to build a cohesive narrative about the role of hydrogen in this context.

• Writing and structuring the text: The literature review will be structured according to a logical organization, including an introduction that contextualizes the topic, a development that addresses the thematic categories and a conclusion that highlights the specific contributions of the studies reviewed.

• Review and Update: To uphold the relevance of the review, regular assessments of the literature will be conducted. Ongoing surveillance of emerging developments in the hydrogen and sustainable transportation sectors will guarantee the integration of the latest information.

3. MAIN ADVANTAGES OF USING RENEWABLE HYDROGEN IN THE URBAN TRANSPORTATION SECTOR

Over the years, the transportation sector has stood out as the most promising for the adoption of hydrogen as an energy source (FRANZITTA et al., 2017). It is important to note that transportation is responsible for approximately a quarter of all energy-related greenhouse gas (GHG) emissions, and of these emissions, around 72% come from road transport (IEA, 2020). These figures reinforce the urgent need to explore innovative solutions, such as the use of hydrogen, especially renewable hydrogen, to mitigate the negative environmental impacts caused by the transportation sector (MANIATOPOULOS, ANDREWS & SHABANI, 2015; SANTOS et al., 2021).

Renewable hydrogen can be used as a vehicle fuel in various ways, depending on the chemical composition of the fuel and the energy converter used to transform chemical energy into mechanical energy. In terms of fuel composition, hydrogen can be used in its pure form or as a raw material for the synthesis of more complex molecules, such as ammonia, hydrocarbons, or alcohols (PROENÇA et al., 2023). As for energy conversion equipment, the most common devices applied in vehicles are internal combustion engines and gas turbines, both conventional technologies and fuel cells, which are based on the direct electrochemical conversion of a fuel into electrical energy, which can be used in an electric powertrain (DE ABREU, PROENÇA and SANTOS, 2023).

Fuel cell systems typically have higher efficiency (around 50%), lower pollutant emissions and lower maintenance requirements than existing technologies but are still characterized by a higher cost. Typically, vehicles are powered by polymer electrolyte membrane fuel cells (PEMFCs) fed by pure hydrogen, but other solutions are being developed using other types of cells or different fuels, such as alcohols and hydrocarbons (PROENÇA et al., 2023). The use of hydrogen as an energy source in the transport sector offers several significant advantages for promoting sustainable urban transport, as shown in Table 1.

Advantage	Description
Improved energy security	In terms of energy security, renewable hydrogen offers the advantage of being able to be produced through different routes, mainly from clean and domestic sources, such as renewable energies, nuclear, biomass and biofuels (DE ABREU et al., 2023a). This diversity of production routes is extremely important for ensuring energy security in countries that have a high dependence on fossil fuel imports to supply their transportation sector (BALL & WIETSCHEL, 2009; LI & TAGHIZADEH-HESARY, 2022).
Reducing GHG emissions	Renewable hydrogen used as a fuel in vehicles produces only water as a by-product of its combustion, resulting in zero GHG emissions at the point of use (MNEIMNEH et al., 2023). This contributes to reducing the carbon footprint and mitigating the impacts of climate change (SALVI & SUBRAMANIAN, 2015; DE ABREU, PROENÇA and SANTOS, 2023).
Reducing air pollution	Hydrogen-powered vehicles do not emit harmful air pollutants such as nitrogen oxides (NOx) and fine particles, helping to improve air quality in urban areas, reducing risks to human health and reducing respiratory and cardiovascular problems (WEGER, LEITÃO & LAWRENCE, 2021).
Renewable energy source	Hydrogen can be produced from renewable energy sources such as solar, wind and hydroelectric power. By using these clean sources, hydrogen contributes to the decarbonization of the transport sector and reduces dependence on non-renewable fossil fuels (SINGH et al., 2015; DE ABREU et al., 2023a, 2023b).
Energy storage	Hydrogen is used to store intermittent renewable energy. intermittent renewable energy. Excess renewable energy can be converted into hydrogen through electrolysis. This hydrogen is stored and can later be used to generate electricity or fuel vehicles, balancing the supply and demand of renewable energy (BALL & WIETSCHEL, 2009; LI & TAGHIZADEH-HESARY, 2022; CAPURSO et al., 2022).
Longer range and faster refueling times	Hydrogen-powered vehicles offer a generally longer range compared to battery electric vehicles, for example. In addition, hydrogen refueling can be carried out in similar times to refueling conventional liquid fuels, allowing for a smoother and more convenient transition for users (WEGER, LEITÃO & LAWRENCE, 2021).
Diversifying energy options	The use of hydrogen in urban transportation helps to diversify the energy options available, reducing exclusive dependence on fossil fuels. This helps to promote energy resilience, making the transportation system less susceptible to fluctuations in oil prices and supply interruptions (BALL & WIETSCHEL, 2009; LI & TAGHIZADEH-HESARY, 2022).
Flexibility of application	Hydrogen can be used in different types of vehicles, including small, medium and large passenger and cargo vehicles. Its application covers a wide range of transportation modes, enabling the transition to a more sustainable fleet in various sectors (SINGH et al., 2015; LI & TAGHIZADEH-HESARY, 2022; PROENÇA et al., 2023).
Noise reduction	Hydrogen-powered vehicles have quieter operation compared to conventional internal combustion vehicles. This contributes to reducing noise pollution in urban areas, providing a quieter and healthier environment (BALL & WIETSCHEL, 2009).
Reuse of existing infrastructure	In many cases, existing infrastructure for the supply of liquid fuels, such as gas stations, can be adapted to supply hydrogen. This allows for an easier transition to the use of hydrogen as a fuel, using already established infrastructure and reducing implementation costs (WEGER, LEITÃO & LAWRENCE, 2021).
Potential long-term cost savings	Although hydrogen-powered infrastructure and vehicles may have higher initial costs, economic benefits can be achieved in the long term. Mass production, technological advances and reduced manufacturing costs could make hydrogen competitive with traditional fossil fuels, as well as reducing the volatility of oil prices (PROENÇA et al., 2023).
Stimulating innovation and job creation	The transition to the use of hydrogen as a fuel in urban transportation drives innovation and technological development. This transition also creates opportunities for industry, stimulating job creation in sectors related to the production, storage, distribution and maintenance of hydrogen and hydrogen-powered vehicles (PROENÇA et al., 2023; MNEIMNEH et al., 2023).

Advantage	Description
Extended autonomy in micromobility	Hydrogen-powered micromobility vehicles can offer extended autonomy compared to the conventional batteries used in these vehicles. This allows users to travel longer distances without the frequent need to recharge or change batteries, increasing convenience and accessibility.
Last Mile Operational Efficiency	The use of hydrogen in "last mile" vehicles provides efficient and reliable performance in the delivery of goods in congested urban areas. Hydrogen-powered vehicles offer extended autonomy and rapid refueling, ensuring continuous availability and reducing operational delays. This advantage is crucial for meeting the demands of e-commerce and fast delivery services, where speed and efficiency are essential.
Increased flight time and autonomy in drones	In contrast to conventional drones, hydrogen-powered drones offer a more efficient energy source, allowing for a greater amount of energy concerning their weight, resulting in a significantly extended flight time of up to several hours (RAGUPATHI, 2023).

Table 1: Advantages of using hydrogen-powered vehicles in relation to road transport.

Table 1 highlights the advantages of incorporating hydrogen, especially renewable hydrogen, into the energy matrix of the road transport sector. However, it is highly recommended to carry out a comprehensive technical and economic feasibility analysis of the hydrogen energy system, considering available resources, production technologies, storage, fuel transportation, distribution and use. In addition, special attention should be paid to the technical issues and their control strategy to address the problems of the transportation system using hydrogen (SALVI & SUBRAMANIAN, 2015; SINGH et al., 2015).

The advantages offered by using renewable hydrogen as an energy source in the transportation sector have a significant impact on decision-makers at all levels of jurisdiction. This information highlights the importance of considering hydrogen as a viable and promising alternative to boost sustainability and efficiency in transportation. For policymakers and business leaders, understanding the benefits of hydrogen can guide the implementation of strategies and incentives to promote its wide-scale adoption (KIM & MOON, 2008). In addition, this study can stimulate technological advances in Research and Development projects and investments in infrastructure for the use of hydrogen in transportation (DE ABREU, PROENÇA and SANTOS, 2023).

4. CHALLENGES OF USING RENEWABLE HYDROGEN IN THE URBAN TRANSPORT SECTOR

Although renewable hydrogen will play a crucial role in the energy transition, not only catalyzing decarbonization, but also driving a new era of sustainable economic development and global innovation, it is imperative to recognize that even the most promising solution is not without its challenges, be they technological or political.

As highlighted by the Green Hydrogen Portal, renewable hydrogen has the potential to replace non-renewable energy sources in different timeframes - short, medium, and long - but challenges remain in terms of price, transportation, distribution, and storage. These barriers still need to be overcome to effectively implement the technology on a large scale (BEZERRA, 2021), as shown in Table 2.

Hydrogen, when produced from renewable sources, becomes a conventional alternative. To ensure the success of the 'hydrogen economy' shortly, it is crucial to quickly address the technical and economic challenges associated with this substance. Although finding practical solutions to these challenges may take some time, technological progress through continuous efforts ensures that hydrogen will emerge as the ultimate solution to meet future energy demands in the transportation sector (SINGH et al., 2015).

Challenge	Description	How to minimize it?
Improving the Regulatory Framework	The existence of a well-established institutional, legal and regulatory framework is an essential condition for providing legal certainty for arge-scale investments in the hydrogen sector. In the context of the decarbonization of energy production and consumption systems, the market value of hydrogen can vary significantly based on its production origin, although this has no technical impact on its use (OLIVA JÚNIOR, 2021).	The market is expected to evolve to encourage the production of renewable hydrogen, due to its environmental attributes that contribute to achieving sustainability goals. This could result in a "premium" being paid depending on where the hydrogen is produced. Consequently, it is likely that, soon, governments will adopt public policies that offer subsidies and incentives for the production and consumption of renewable hydrogen by companies, further boosting the sustainable development of this sector (OLIVA JÚNIOR, 2021).
Supply and distribution infrastructure	The infrastructure for refueling renewable hydrogen in hydrogen-powered vehicles is currently limited compared to traditional fuel stations (SINGH et al., 2015). Establishing a widespread and accessible network would require substantial investments and a significant period for implementation (DE ABREU et al., 2023a).	There are options for the safe transportation of hydrogen that include those already used for the transportation of fossil fuels, such as in gaseous or liquid form in trucks or ships, and the pumping of gaseous hydrogen in its own pipelines or by sharing with the existing infrastructure for the transportation of natural gas (MIRANDA, 2017).
Storage problems	A major challenge to achieving a solid hydrogen economy is the maturation of storage technologies that are safe, compact and cost-effective (ABE et al., 2019).	Typically, hydrogen can be retained as a pressurized gas, cryogenic liquid or physically or chemically bound to specific solid materials. Among these options, solid-state storage systems based on metal hydrides stand out as promising due to their potential to offer a high gravimetric capacity for hydrogen storage. These systems provide a safe, efficient, compact and repeatedly reversible approach, gradually gaining prominence in hydrogen-related applications (ABE et al., 2019).
Availability of renewable sources	The production of renewable hydrogen depends on the availability of renewable energy sources, such as solar or wind power (YAKUBSON, 2022).	To promote a sustainable expansion in hydrogen production, it is essential to direct substantial investments into research aimed at making these technologies economically viable (SINGH et al., 2015). In addition, the implementation of strategic public incentive policies, aimed at both companies and consumers, is essential to make the option of hydrogen more attractive (YAKUBSON, 2022).
Market acceptance	The acceptance of hydrogen as a vehicle fuel represents a significant cultural challenge, as it involves changing established paradigms and promoting a transformation in attitudes and perceptions towards traditional means of propulsion (DE ABREU, PROENÇA e SANTOS, 2023).	Promoting the widespread adoption of hydrogen as a vehicle fuel requires a substantial effort in raising public awareness and overcoming entrenched prejudices. Making people aware of the environmental and economic benefits of hydrogen, while proactively addressing common concerns and misconceptions, is imperative to achieving wider and more effective acceptance of this innovative technology in the transportation landscape (DE ABREU, PROENÇA e SANTOS, 2023).

Table 2: Challenges for implementing renewable hydrogen as a promising form of sustainable urban transport.

5. FINAL CONSIDERATIONS

In terms of sustainability, hydrogen reduces GHG emissions and air pollutants, helping to mitigate climate change and improve air quality. In addition, its energy efficiency and storage capacity allow for longer flight times for drones, extended autonomy in "last mile" vehicles and a balance between supply and demand for renewable energy. Hydrogen also promotes the diversification of the energy matrix, reducing dependence on fossil fuels and boosting technological innovation in the transportation sector. These combined advantages make hydrogen a promising solution for tackling environmental and energy challenges, driving the transition to a more sustainable and efficient transportation system.

The importance of this study for decision-makers lies in the promising contribution that renewable hydrogen offers to environmental and energy challenges, driving the transition to a more sustainable and efficient transportation system. The identification of business opportunities, integration with renewable sources, and the positive impacts on the economy and the environment are points of equal importance in the current scenario. Specifically, the emphasis on integration with renewable energy sources and on economic benefits provides concrete pathways for future decision-making, always in line with sustainability indicators, among other socio-environmental and economic commitments.

However, the rapid transition to a global low-carbon hydrogen economy faces significant technical and economic challenges, including the escalating prices of fossil fuels such as gasoline and gas. Yet, these very price increases can accelerate the competitiveness of renewable fuels. With increased demand and ongoing technological advances, there's promising potential to reduce these costs, ultimately making renewable hydrogen fully competitive in the energy market.

The supply of hydrogen to industrial users presents a substantial business opportunity, particularly in coastal industrial hubs where there is an existing demand for pure hydrogen. Moreover, integrating industry and transportation applications with nearby offshore wind and solar photovoltaic sources in regions such as the North Sea in Europe, Southeast China, Western Australia, and Northwest India enhances the attractiveness of these locations for such endeavors.

The outcomes of this initiative might encompass the formulation of supportive policies and regulations, the forging of public-private partnerships to spur innovation, and the creation of a resilient infrastructure for hydrogen production, storage, and distribution. Such initiatives can potentially expedite the shift towards a more sustainable transportation ecosystem, thereby mitigating carbon emissions, enhancing air quality, and fortifying energy resilience.

REFERENCIAS

ABE, J. O.; POPOOLA, A. P. I.; AJENIFUJA, E.; POPOOLA, O. M. Hydrogen energy, economy and storage: Review and recommendation. **International Journal of Hydrogen Energy**, v. 44, p. 15072–15086, 2019. doi: 10.1016/j.ijhydene.2019.04.068

ACAR, Canan; DINCER, Ibrahim. The potential role of hydrogen as a sustainable transportation fuel to combat global warming. **International Journal of Hydrogen Energy**, v. 45, n. 5, p. 3396-3406, 2020. doi: 10.1016/j.ijhydene.2018.10.149

BALL, Michael; WIETSCHEL, Martin. The future of hydrogen–opportunities and challenges. **International Journal of Hydrogen Energy**, v. 34, n. 2, p. 615-627, 2009. doi: 10.1016/j.ijhydene.2008.11.014

BEZERRA, Francisco Diniz. **Hidrogênio Verde: Nasce um Gigante no Setor de Energia**. Engenheiro Civil. Doutor em Desenvolvimento e Meio Ambiente. Coordenador de Estudos e Pesquisas do BNB/ Etene. 2021. s1dspp01.dmz.bnb:8443/s482-dspace/handle/123456789/1109

CAPURSO, T. et al. Perspective of the role of hydrogen in the 21st century energy transition. **Energy Conversion and Management**, v. 251, p. 114898, 2022. doi: 10.1016/j.enconman.2021.114898

CEVALLOS-ESCANDÓN, Antonia et al. Assessing the Feasibility of Hydrogen and Electric Buses for Urban Public Transportation using Rooftop Integrated Photovoltaic Energy in Cuenca Ecuador. **Energies**, v. 16, n. 14, p. 5569, 2023. doi: /10.3390/en16145569

DE ABREU, Victor Hugo Souza et al. A Systematic Study on Techno-Economic Evaluation of Hydrogen Production. **Energies**, v. 16, n. 18, p. 6542, 2023a. doi: 10.3390/en16186542

DE ABREU, Victor Hugo Souza. et al. **Uma Visão Geral**

sobre a Avaliação do Ciclo de Vida do Hidrogênio Renovável. ENSUS 2023. 2023b.

DE ABREU, Victor Hugo Souza. PROENÇA, Lais. SANTOS, Andrea Souza. **Aplicação do Hidrogênio Renovável no Setor de Transporte Rodoviário**. 37º ANPET - Congresso de Pesquisa e Ensino em Transportes. 2023.

DE ASSIS, Tássia Faria et al. Enabling the Green Bonds Market for Sustainable Transport Projects Based on the Measure/Monitoring, Reporting and Verification Method. In: Carbon Footprints of Manufacturing and Transportation Industries. **Singapore: Springer Nature Singapore**, 2022a. p. 1-24.

DE ASSIS, Tássia Faria et al. Sustainable Transport Indicators and Mitigation Actions Applied to the Green Bond Principles. In: Carbon Footprints of Manufacturing and Transportation Industries. **Singapore: Springer Nature Singapore**, 2022b. p. 139-169.

EHRENSTEIN, Michael et al. Optimising fuel supply chains within planetary boundaries: A case study of hydrogen for road transport in the UK. **Applied Energy**, v. 276, p. 115486, 2020. doi: 10.1016/j.apenergy.2020.115486

EUROPEAN COMMISSION. **European green deal**. 2019. Disponível em: https://policycommons.net/artifacts/1337481/european-green-deal/1945374/

FRANZITTA, Vincenzo et al. Energy saving in public transport using renewable energy. **Sustainability**, v. 9, n. 1, p. 106, 2017. doi: 10.3390/su9010106

GULOTTA, Teresa Maria et al. Life Cycle Assessment and Life Cycle Costing of unitized regenerative fuel cell: A systematic review. **Environmental Impact Assessment Review**, v. 92, p. 106698, 2022. doi: 10.1016/j.eiar.2021.106698

IEA. **Energy Consumption in Road Transport in Selected IEA Countries, 2000-2018** (IEA, 7 December 2020). Disponível em: https://go.nature.com/3e9QWFl

IEA. **The Future of Hydrogen**, 2019. Disponível em: https://www.iea.org/reports/the-future-of-hydrogen

IPCC, 2022: **Climate Change 2022**: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Shukla, P.R., Skea, J., Slade, R., Al Khourdajie, A., van Diemen, R., McCollum, D., Pathak, M., Some, S., Vyas, P., Fradera, R., Belkacemi, M., Hasija, A., Lisboa, G., Luz, S., Malley, J. (eds.). Cambridge University Press, Cambridge, UK and New York, NY, USA (2022).

KIM, Jiyong; MOON, Il. The role of hydrogen in the road transportation sector for a sustainable energy system: a case study of Korea. **International Journal of Hydrogen Energy**, v. 33, n. 24, p. 7326-7337, 2008. doi: 10.1016/j.ijhydene.2008.09.050

LAL, Apoorv; YOU, Fengqi. Targeting climate-neutral hydrogen production: Integrating brown and blue pathways with green hydrogen infrastructure via a novel superstructure and simulation-based life cycle optimization. **AIChE Journal**, v. 69, n. 1, p. e17956, 2023. doi: 10.1002/aic.17956

LI, Yanfei; TAGHIZADEH-HESARY, Farhad. The economic feasibility of green hydrogen and fuel cell electric vehicles for road transport in China. **Energy Policy**, v. 160, p. 112703, 2022. doi:10.1016/j.enpol.2021.112703

LIU, Wei et al. Green hydrogen standard in China: Standard and evaluation of low-carbon hydrogen, clean hydrogen, and renewable hydrogen. **International Journal of Hydrogen Energy**, v. 47, n. 58, p. 24584-24591, 2022. doi: 10.1016/j.ijhydene.2021.10.193

MANIATOPOULOS, Paul; ANDREWS, John; SHABANI, Bahman. Towards a sustainable strategy for road transportation in Australia: The potential contribution of hydrogen. **Renewable and Sustainable Energy Reviews**, v. 52, p. 24-34, 2015. doi: 10.1016/j.rser.2015.07.088

MIRANDA, Paulo Emílio V. de. **O Alvorecer da Energia do Hidrogênio**. FGV Energia. Caderno Opinião, 2017. Disponível em: www.repositorio.fgv.br/server/api/core/bitstreams/1da76bbf-162a-4c60-b71b-38c5d1e2432d/content

MNEIMNEH, Farah et al. Roadmap to achieving sustainable development via green hydrogen. **Energies**, v. 16, n. 3, p. 1368, 2023.

OLIVA JÚNIOR, José Roberto. Hidrogênio Verde, Perspectivas e Regulamentação no Brasil. Artigo.In: **Revista BrasilAlemanha**, edição outubro de 2021. Disponível em: https://www.ahkbrasilien.com.br/publicacoes/revista-brasilalemanha.

OLIVEIRA, Rosana Cavalcante de. **Panorama do hidrogênio no Brasil**. IPEA, 2022. https://repositorio.ipea.gov.br/handle/11058/11291

ONI, A. O. et al. Comparative assessment of blue hydrogen from steam methane reforming, autothermal reforming, and natural gas decomposition technologies for natural gas-producing regions. Energy Conversion and Management, v. 254, p. 115245, 2022. doi: 10.1016/j.enconman.2022.115245

PROENÇA, Laís Ferreira Crispino et al. Opportunities and Challenges for the New Hydrogen Economy: Advances in Renewable Hydrogen. Transportation Systems Technology and Integrated Management. 2023. doi: 10.1007/978-981-99-1517-0_6

RAGUPATHI, Jayasurya. Hydrogen Fuel Cell Drones Against Battery Drones: Last Mile Delivery Perspective. 2023. Tese de Doutorado. Purdue University Graduate School.

SALVI, B. L.; SUBRAMANIAN, K. A. Sustainable development of road transportation sector using hydrogen energy system. **Renewable and Sustainable Energy Reviews**, v. 51, p. 1132-1155, 2015. doi:10.1016/j.rser.2015.07.030

SANTOS, Andrea Souza et al. **An overview on costs of shifting to sustainable road transport**: A challenge for cities worldwide. Carbon Footprint Case Studies: Municipal Solid Waste Management, Sustainable Road Transport and Carbon Sequestration, p. 93-121, 2021.

SAEEDMANESH, Alireza; MAC KINNON, Michael A.; BROUWER, Jack. Hydrogen is essential for sustainability. **Current Opinion in Electrochemistry**, v. 12, p. 166-181, 2018.

SINGH, Sonal et al. Hydrogen: A sustainable fuel for future of the transport sector. **Renewable and sustainable energy reviews**, v. 51, p. 623-633, 2015. doi: 10.1016/j.rser.2015.06.040

ZOHURI, B. **Hydrogen Energy: Challenges and Solutions for a Cleaner Future**. 1. ed. Cham, SWZ: Springer International Publishing, 2019. ISBN : 978-3-319-93460-0

WEGER, Lindsey B.; LEITAO, Joana; LAWRENCE, Mark G. Expected impacts on greenhouse gas and air pollutant emissions due to a possible transition towards a hydrogen economy in German road transport. **International Journal of Hydrogen Energy**, v. 46, n. 7, p. 5875-5890, 2021. doi: 10.1016/j.ijhydene.2020.11.014

WIDERA, Barbara. Renewable hydrogen implementations for combined energy storage, transportation and stationary applications. **Thermal Science and Engineering Progress**, v. 16, p. 100460, 2020. doi: 10.1016/j.tsep.2019.100460

AUTHORS

ORCID: 0000-0002-2557-2721
VICTOR HUGO SOUZA DE ABREU, Doutor | Pesquisador de Pós-Doutorado | Instituto Alberto Luiz Coimbra de Pós-Graduação e Pesquisa de Engenharia da Universidade Federal do Rio de Janeiro | Engenharia de Transportes | Correspondência para: Av. Horácio Macedo, 2030, 101 – Cidade Universitária – Rio de Janeiro, RJ, Brasil | E-mail: victor@pet.coppe.ufrj.br

ORCID: 0009-0003-5182-9513
RAFAEL FERRAZ DOS SANTOS | Mestrando | Instituto Alberto Luiz Coimbra de Pós-Graduação e Pesquisa de Engenharia da Universidade Federal do Rio de Janeiro | Engenharia de Transportes | Correspondência para: Av. Horácio Macedo, 2030, 101 – Cidade Universitária – Rio de Janeiro, RJ, Brasil | E-mail: rafael.ferraz@pet.coppe.ufrj.br

ORCID: 0000-0002-5984-6313
ANDREA SOUZA SANTOS, Doutora e Professora | Instituto Alberto Luiz Coimbra de Pós-Graduação e Pesquisa de Engenharia da Universidade Federal do Rio de Janeiro | Engenharia de Transportes | Correspondência para: Av. Horácio Macedo, 2030, 101 – Cidade Universitária – Rio de Janeiro, RJ, Brasil | E-maill: andrea.santos@pet.coppe.ufrj.br

ORCID: 0000-0002-1317-4232 |
SANDRA ODA, Doutora e Professora | Departamento de Engenharia de Transportes da Escola Politécnica da UFRJ | Correspondência para: Av. Athos da Silveira Ramos, 149 - Centro de Tecnologia - Bloco D, Sala 209. Cidade Universitária - Ilha do Fundão - CEP 21941-909 - Rio de Janeiro, RJ, Brasil | E-maill: sandraoda@poli.ufrj.br

HOW TO CITE THIS ARTICLE:
DE ABREU, Victor Hugo Souza; DOS SANTOS, Rafael Ferraz; SANTOS, Andrea Souza; ODA, Sandra. The role of renewable hydrogen in achieving sustainable urban transportation. **MIX Sustentável**, v. 10, n. 3, p. 163-173, 2024. ISSN 2447-3073. Disponível em: <http://www.nexos.ufsc.br/index.php/mixsustentavel>. Acesso em: _/_/_.doi: <https://doi.org/10.29183/2447-3073.MIX2024.v10.n3.163-173>.

SUBMETIDO EM: 20/01/2024
ACEITO EM: 28/06/2024
PUBLICADO EM: 12/08/2024
EDITORES RESPONSÁVEIS: Lisiane Ilha Librelotto e Paulo Cesar Machado Ferroli

Record of authorship contribution:
CRediT Taxonomy (http://credit.niso.org/)

VHSA: conceptualization, formal analysis, investigation, methodology, project administration, visualization, writing - original draft, writing - review and editing.

RFS: formal analysis, methodology, writing - original draft, writing - review and editing.

ASS: supervision, validation, visualization, writing - review and editing.

SO: supervision, validation, visualization, writing - review and editing.

Conflict declaration: nothing has been declared.