AN ECONOMY BASED ON HYDROGEN AND ITS UTILIZATION IN RENEWABLE ENERGIES

Kauana Alessandra dos Santos[a*], Beatriz Jacob-Furlan[b], Paulo Alexandre Silveira da Silva[b], Lauber de Souza Martins[b], Matheus Ben-Hur Ramirez Sapucaia[c], Rafael Silva Ribeiro Gonçalves[c], Dhyogo Miléo Taher[c], Wellington Balmant[c] and José Viriato Coelho Vargas[a,b,c]

[a]Federal University of Paraná, Sustainable Energy Research and Development Center – (NPDEAS), Department of Mechanical Engineering at UFPR – (DEMEC), Curitiba, Brazil kauanasantos@ufpr.br
[b]Federal University of Paraná, Sustainable Energy Research and Development Center – (NPDEAS), Graduate Program in Materials Science and Engineering at UFPR – (PIPE), Curitiba, Brazil beatrizfurlan@ufpr.br; paulo.alexandre@ufpr.br; lauber@ufpr.br
[c]Federal University of Paraná, Sustainable Energy Research and Development Center – (NPDEAS), Graduate Program in Mechanical Engineering at UFPR – (PGMEC), Curitiba, Brazil, ben-hur@ufpr.br; rafael.silva@ufpr.br; dhyogo@ufpr.br; wbalmant@gmail.com; viriato@ufpr.br

ARTICLE INFO

***Keywords**:*
green hydrogen,
hydrogen,
power generation,
sustainable chain,
renewable fuel.

Received: Feb 12, 2024
Reviewed: Feb 20, 2024
Accepted: Mar 03, 2024

ABSTRACT

A great technological advent is the use of renewable energies with the objective of promoting the migration of the world energy matrix. For this, alternatives to generate and store energy are sought. Among them, the use of hydrogen stands out - the most abundant chemical element in our universe - produced from various sources, such as natural gas, biomass and water electrolysis, making it a viable option as a renewable fuel, in addition to being considered a source of clean energy, as its burning does not emit gases such as carbon dioxide (CO2), one of the main responsible for global warming. In addition, hydrogen can be used in a range of applications, including transportation, power generation, heating and industry, making it versatile with fossil fuels. Its intrinsic properties such as its high energy density become advantageous from the perspective of the economy based on hydrogen. When used in fuel cells, it can generate electricity efficiently and without pollutants, after all, the only emission from the fuel cell system is water. The most common way to produce hydrogen is from natural gas, through a process called steam reforming, where methane from natural gas is combined with water vapor to produce hydrogen and carbon dioxide as a by-product. However, this approach still emits CO_2, in a smaller amount, when compared to the direct burning of fossil fuels. Another option is the production of hydrogen from biomass, such as agricultural and forestry waste, through gasification processes or anaerobic fermentation, which can be neutral in terms of CO_2 emissions, as the carbon released during production is offset by the carbon absorbed. by plants during their growth. In addition, water electrolysis, which uses electricity to split water into hydrogen and oxygen, is another option for producing hydrogen without CO_2 emissions when the electricity used comes from renewable sources. With its vast production, hydrogen can be used as a form of renewable energy storage, after all, one of the main limitations of renewable energies, such as solar and wind, is their intermittency, that is, energy generation depends on climatic conditions. Hydrogen can be produced when there is a surplus of renewable energy available, being stored in liquid or gaseous form, in large spoons, facilitating its transport for later use, and also, meeting the growing world energy demand.

* Corresponding author: Kauana Alessandra dos Santos. [a]Federal University of Paraná, Sustainable Energy Research and Development Center – (NPDEAS), Department of Mechanical Engineering at UFPR – (DEMEC), Curitiba, Brazil. kauanasantos@ufpr.br

1. INTRODUCTION

Renewable energy refers to energy sources that are naturally replenished or are virtually inexhaustible. They are environmentally friendly energies because, even with their continuous use, they do not contribute to the emission of carbon dioxide (CO_2) in the atmosphere that causes global warming (Solarim et al, 2022). Some examples of renewable energies are: hydro, solar, wind, biomass and geothermal. On the other hand, non-renewable energies have fossil energy as their main polluting contributor (Feng, Zheng, 2022), derived from the use of fossil fuels (mineral coal, natural gas, oil) that use resources that are depleted in nature and are the origin of the emission of polluting gases into the atmosphere (Araújo R. S et al, 2022).

In this way, with all its negative effects on the climate, it attracts widespread attention in decarbonizing the global energy sector, because even though renewable energies have resources that may present contingencies, that is, variability in the availability of wind and sun (Chattopadhyay, 2020), they are energies that serve as a pillar for the sustainable growth model of clean energy (Feng, Zheng, 2022).

Environmental pollution problems originating from carbon dioxide emissions make many governments implement renewable energy regulatory policies, including feed tariffs and tradable emissions permits (Feng, Zheng, 2022). These policies exert significant influence on the behavior and initiatives of industry and private companies, intensifying efforts for zero carbon emissions in the global energy network. This has been aided by the new wave of Industrial Revolution 4.0, as investors and manufacturers have joined this trend by directing attention to technological innovations that design clean and smart energy grids for current and future needs (Solarim et al, 2022). This development has resulted in the implementation of improvements in renewable energy resources, such as robots that are powered by artificial intelligence to monitor the efficiency of hydroelectric power plants and reduce the cost of maintenance and hydroelectric power battery hybrids to improve services on the grid (Solarim et al. al, 2022).

Renewable energy is also present in the mitigation of other problems, such as the water crisis, which has been considered the fourth global risk in terms of impact on society (He et al, 2022). Desalination is a promising technology to solve the water resources crisis and that is why institutions and programs are investing in order to obtain fresh water for agricultural irrigation, domestic supply, among other uses, which comes from sea water. However, traditional desalination technologies consume a lot of fossil energy, causing environmental pollution and limiting their use. Thus, ways to boost this process using solar energy and wind energy are being developed and applied, for seawater desalination based on renewable sources in search of a solution to the problem of freshwater availability (He et al, 2022).

2. HYDROGEN

Hydrogen is an important element for the global energy sector. Although it is not widely used because it is an energy vector, i.e. produced from other naturally occurring species having a significant energy cost, it is an element that provides considerable storage capacity and amount of energy (Lutz et al, 2003). The applications of hydrogen in addition to energy, currently, are concentrated in the production of ammonia, methanol and use in refineries, steel mills, food industry and semiconductors (Oliveira, 2022).

Global conventional hydrogen production is dominated by the use of fossil fuels. According to the United States Department of Energy, commonly used methods are steam reforming and gasification. The first consists of reacting gas or other sources of hydrocarbons with water vapor at high temperatures (700-1000°C) and moderate pressures, in the presence of a catalyst. The process produces hydrogen, carbon monoxide (CO) and carbon dioxide (CO_2). The hydrogen is then separated from the other gases through purification processes, such as CO removal. The second, the production takes place from coal where the material is heated to high temperatures (800-1500ºC) in an environment with little or no oxygen, resulting in the breakdown of molecules and in the production of a synthesis gas containing hydrogen, carbon monoxide, carbon dioxide and other gases.

Thus, because conventional hydrogen is produced from resources that emit carbon dioxide into the atmosphere, contributing negatively to the environment, it is characterized as gray hydrogen (Oliveira, 2022). Therefore, from this scenario arises the need to develop the production of hydrogen from renewable sources, due to the importance of the characteristics and properties that this element has and collaborates to solve the problem of global scarcity of energy sources (Capitanescu, 2021) together with the mitigation of the emission of polluting gases that strengthen global warming.

2.1 Green hydrogen

For the purpose of the requirements of sustainable production, many advances have been achieved in the last 20 years (Burgos-Martinez et al, 2021), because while the pressure for new energy alternatives to replace fossil fuels is increasing, the urgency of an economy for the low-carbon hydrogen (Oliveira, 2022). According to the report presented by the International Energy Agency, hydrogen was identified as a promising source for the

decarbonization of the energy sector due to the development of production processes for this element without generating carbon dioxide emissions during combustion.

Hydrogen generation is distinguished by various forms of primary energy sources, which can be distinguished by different colors. Depending on the hydrogen production technology, they are classified in green, gray, blue, brown, yellow, purple and turquoise, as follows: green hydrogen - obtained through the electrolysis of water using renewable sources; gray hydrogen - obtained from fossil fuels without capturing CO_2; blue hydrogen - obtained from fossil fuels but captures and stores CO_2 from a process called Steam Methane Reforming (SMR); brown hydrogen - produced from coal gasification; yellow hydrogen - obtained by electrolysis of water using electricity generated from different energy sources; purple hydrogen - obtained by nuclear energy, and turquoise hydrogen - obtained by methane pyrolysis (Figueiredo et al, 2023).

Green hydrogen, since it is obtained from renewable sources, is considered a clean energy source without CO_2 emissions, known as “renewable hydrogen”, “clean hydrogen” or “clean carbon hydrogen” (Figueiredo et al, 2023). Voltaic electrolysis is the most common technique used to obtain green hydrogen, which uses solar panels to generate electricity and feed an electrolysis system that separates water into hydrogen and oxygen. Another method is to use concentrated solar energy, which is characterized by the use of mirrors or lenses in order to concentrate sunlight in a small area, generating heat and feeding the electrolysis system (Figueiredo et al, 2023).

The International Renewable Energy Agency (IRENA) and the World Economic Forum have launched a Green Hydrogen Action Roadmap. Thus, the aim is to replace the definitions of hydrogen by color with low-carbon hydrogen production certifications, aiming to encourage the creation of greater market opportunities, encouraging future innovations and being compatible with import markets. With decreasing costs for renewable energy, interest is growing in the electrolysis of water to produce hydrogen and its conversion to hydrogen-based fuels. In addition, the production and increasing use of green hydrogen may have geopolitical implications worldwide, with the potential to redraw the maps of energy, economic, social and security relations (Oliveira, 2022). Thus, the global demand for green hydrogen and its applications is expected to increase exponentially in the next decade (Kumar et al, 2022).

2.2 Hydrogen as a fuel

The quest to find a sustainable and clean alternative fuel is ongoing, as the worldwide demand for internal combustion engines, especially diesel engines, continues to increase even in this era of emerging technologies such as electric, hybrid and fuel cell vehicles, due to their superior energy efficiency and significant durability. Vehicles powered by internal combustion engines are very polluting and responsible for 60% of carbon dioxide emissions in the world, harming both the environment and human health (Nag et al, 2019).

Hydrogen's clean-burning characteristics and ease of renewability add to its numerous advantages (Nag et al, 2019). When hydrogen is burned or combined with oxygen in a fuel cell, for example, it produces energy and only emits water vapour, making it a clean, renewable source of energy. However, the use of hydrogen as a fuel still presents challenges due to production, storage, transportation and supply difficulties (Figueiredo, 2023), even though it has several applications as a fuel, including transportation, power generation and industrial processes. In transportation, hydrogen can be used in fuel cells to power vehicles, in power generation hydrogen can be used in stationary fuel cells to generate electricity and heat, in industrial processes, hydrogen can be used in oil refineries, production of ammonia and methanol (Figueiredo, 2023).

Studies point out that a practical alternative to the use of hydrogen as a fuel is to use it as an additive in fossil fuels, because in controlled amounts hydrogen can be a secondary fuel with diesel aiding in combustion, ambiguously affecting engine performance (Nag et al, 2019). Research indicates that adding small amounts of hydrogen to a diesel engine reduces the heterogeneity of fuel spraying inside the combustion chamber due to high diffusivity allowing the mixture to become homogeneous, i.e. pre-mixed with air more uniformly, thus providing improved performance, reduced consumption and greenhouse gas emission rates (Figueiredo, 2023).

The use of hydrogen as fuel has been allied in island economies that depend on tourism. Islands that depend on mass tourism have significant emissions generated by car rentals especially in places where public transport is poor (Rensburg, 2023). In this context, islands with large renewable resources, not connected to mainland energy networks and vulnerable to the effects of climate change are well suited to sustainable transport that continues to boost tourism and the local economy.

3. FUEL CELLS

The fuel cell is an electrochemical device that directly converts the chemical energy of a fuel and an oxidant (such as hydrogen and oxygen) into electrical energy, heat, and by-products (such as water) - see Eq. 3 below - without the need for combustion. In essence, it produces electricity through a controlled chemical reaction.

Anode reaction: $H_{2(g)} + 2OH^-_{(aq)} \rightarrow 2H_2O_{(l)} + 2e^-$ (1)

Cathode reaction: $\frac{1}{2} O_{2(g)} + 2 H_2O_{(l)} + 2e^- \rightarrow 2OH^-_{(aq)} + H_2O_{(l)}$ (2)

Overall Cell reaction: $H_{2(g)} + \frac{1}{2} O_{2(g)} \rightarrow H_2O_{(l)}$ + electrical energy + heat (3)

A fuel cell is composed of a set of essential components, namely: bipolar plates, electrodes and electrolyte, as shown in Fig. 1 reveals. The crucial role of bipolar plates is to ensure the perfect mechanical integration of these components. They play a crucial role in achieving an even distribution of fuel and oxidant gases over the electrode, while also facilitating electron communication (Vargas et. al., 2004). On the other hand, the electrode takes on the responsibility of facilitating the dissociation reactions, while the electrolyte performs the vital function of conducting ions and, in some cases, molecules (Breeze, 2017; Godula-Jopek et. al., 2023).

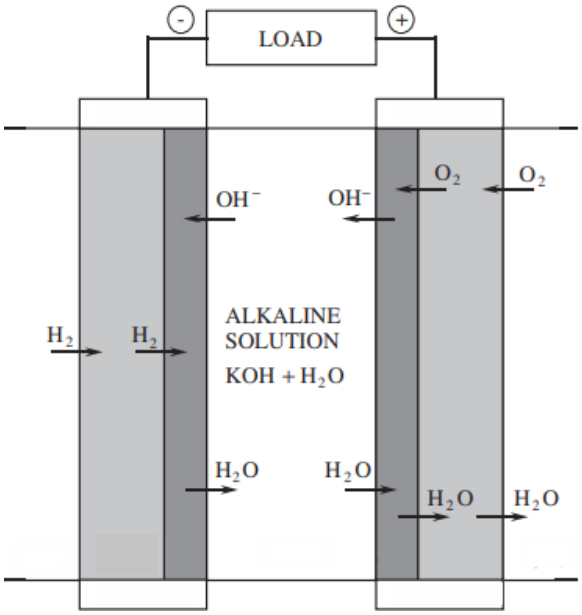

Figure 1. The Fuel Cell System.
Source: Adapted from Vargas and Bejan, 2004

The main advantage of fuel cells is that they are more efficient in terms of converting energy into electricity compared to conventional internal combustion engines, as they have no moving parts and therefore reduce mechanical losses. Additionally, fuel cells generally have low pollutant emissions and do not directly release carbon dioxide, making them a more environmentally friendly option compared to traditional combustion engines.

There are several types of fuel cells, such as hydrogen oxygen fuel cell (proton exchange membrane fuel cell, PEMFC), hydrogen air fuel cell (solid oxide fuel cell, SOFC), direct methanol fuel cell (DMFC) and others, each with its specific characteristics and applications. Fuel cells have been extensively researched for use in zero-emission vehicles, stationary power generation, portable applications, and even as power sources for spacecraft and submarines (Godula-Jopek et. al., 2023).

Fuel cells have significant potential to transform the automotive industry, especially with regard to electric vehicles, presenting themselves as a promising alternative to conventional batteries. They function as electrochemical devices that directly convert the chemical energy of a fuel into energy readily usable by the vehicle. Hydrogen is the most commonly used fuel in these cells, but other options, such as methanol and ethanol, are also viable (FRAGIACOMO et al., 2022).

The 5 main advantages of fuel cells in electric vehicles are shown in Table 1 below:

Table 1. Top 5 Advantages of Fuel Cells in Electric Vehicles

Advantage	Description	References
Greater autonomy	Fuel cells provide significantly longer range compared to conventional batteries.	AMINUDIN et al., 2022
Faster recharge times	Refueling with hydrogen in fuel cells is carried out in a few minutes, making recharging faster.	SHAH et al., 2022
Low environmental impact	Fuel cells generate electricity without emitting greenhouse gases or air pollutants, reducing environmental impact.	YU; GUO; MA, 2023
Constant performance	Fuel cells maintain constant performance throughout their lifetime, unlike batteries which can deteriorate.	YANG et al., 2023
Application versatility	Fuel cells can be used in many types of vehicles, from passenger cars to buses and marine vessels.	JENG et al., 2007

However, despite its advantages, the widespread adoption of fuel cells in electric vehicles still faces some challenges. One of the main obstacles is the hydrogen fueling infrastructure, which is still limited in many regions of the world. Furthermore, the cost of producing and storing hydrogen is still relatively high compared to fossil fuels and electric batteries (ASSADI et al., 2023).

Despite this, several automakers and technology companies have invested in research and

development of fuel cells for electric vehicles, seeking to make this technology more accessible and commercially viable. With the continued advancement of technology and increased awareness of the importance of environmental sustainability, it is possible that fuel cells will play a significant role in future electric mobility (MEDA; RAJYAGURU; PANDEY, 2023).

4. ELECTRIC CARS AND FUTURE PERSPECTIVES AROUND THE WORLD

The growth in demand for electric vehicles has been increasingly expressive around the world, driven by factors such as the search for greater sustainability, concern about global climate change and technological advances in the field of electric mobility. According to the Global Transport Report of the International Energy Agency (IEA), sales of electric vehicles in the world, in the base year of 2021, surpassed the mark of 5 million units, representing an increase of more than 40% compared to the year previous.

Also, according to the IEA, the number of electric vehicles in circulation in the world reached the 10 million mark in the base year of 2020, a significant increase of 43% compared to 2019. This growth has stood out even more in countries like China, where the sale of electric vehicles increased by more than 200% in 2020, justified by the impulses of government policies to encourage electric mobility.

In Brazil, although there is still a small share of electric vehicles in the market, the growth trend has been observed in recent years. Data from the Brazilian Electric Vehicle Association (ABVE) show that, in 2020, 9012 electric vehicles were sold in the country, an increase of 66.4% compared to 2019. The Brazilian automotive sector has been following this trend and more and more automakers are betting on electric models for the national market. This growing demand for electric vehicles on Brazilian soil can be explained by several factors, such as the fact that the country has a predominantly clean electrical matrix, with more than 80% of its electricity generation coming from renewable sources, that is, the hydroelectric. In addition, government policies, such as tax exemption for electric vehicles and the installation of charging points on highways and urban areas, have encouraged the adoption of electric vehicles in the country (ABVE, 2020).

However, there are still challenges to be overcome so that the demand for electric vehicles in Brazil reaches a higher level. The main one that stands out is the lack of charging infrastructure across the country, which may limit the expansion of the electric vehicle market. In addition, the high cost of electric vehicles compared to conventional models can be a barrier to the mass adoption of these vehicles. For the demand for electric vehicles in Brazil to grow more significantly, it is necessary to implement public policies to encourage the production and sale of electric vehicles, in addition to investments in charging infrastructure in urban areas and on highways. The adoption of electric vehicles in Brazil can contribute significantly to the reduction of greenhouse gas emissions in the transport sector and to the promotion of a more sustainable mobility (FRAGIACOMO et al., 2022; MEDA et. al, 2023).

3.1 Worldwide vehicular supply for electric vehicles

The global supply for electric vehicles has been an area of growing interest and investment in recent years. According to the IEA report (2022), called “Global EV Outlook 2022”, the charging infrastructure for electric vehicles has been growing dramatically around the world, with a significant increase of 60% in the number of charging stations through the base year of 2021, when compared to the previous year. While leading electric vehicle countries such as China, the United States and Europe have invested heavily in charging infrastructure, there are still significant challenges to implementing a comprehensive network of charging stations worldwide. The lack of standardization of connectors, the costly installation of fast charging stations and uncertainty about the profitability of these stations are some of the main obstacles that countries face in terms of engineering.

In order to overcome these challenges, governments and companies are working together to develop effective charging station deployment strategies, increasing standardization and providing incentives for the installation of charging stations in strategic locations, such as urban areas and highways. In short, the world's supply for electric vehicles is a complex challenge, yet there is vital investment in such a transition to a sustainable transport future.

Under the overview of the top 10 countries that have a supply network for electric vehicles worldwide, Brazil is in 39th place, as shown in Table 2 below:

Table 2. Supply Network for Electric Vehicles: Top 10 Countries Worldwide and Brazil's Ranking.
Source: Adapted from Global EV Outlook 2022, IEA.

Position	Country	Number of public electric vehicle filling stations
1	China	1,641,216
2	United States (US)	114,831
3	Japan	50,381
4	Germany	45,400
5	France	43,853
6	United Kingdom (UK)	35,017
7	Canada	24,084
8	Norway	11,800

9	Netherlands	10,491
10	Switzerland	6,474
	...	
39	Brazil	584

From Table 2, it can be seen that Brazil does not appear among the top 10 countries with the highest number of electrical service stations. However, it is important to emphasize that Brazil has been advancing in the expansion of its electric supply network for vehicles, and that there are already several charging points for electric vehicles in the country, including public and private stations. Data from the Brazilian Electric Vehicle Association (ABVE) indicate that there are around 700 charging points in Brazil – when private and public points are added – however, most are located in the Southeast region, with the state of São Paulo leading in number of charging stations.

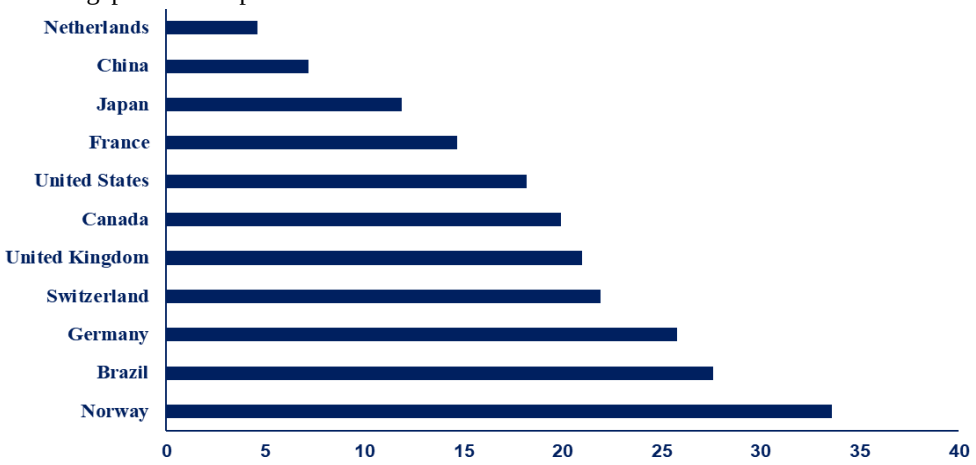

Figure 2. Number of cars per unit of electric charging point.
Source: Adapted from IEA, 2022

According to the Global EV Outlook 2022 report by the International Energy Agency (IEA), Brazil had 584 public charging points for electric vehicles in 2021, a number that is expected to grow in the coming years. In addition, the country has seen an increase in sales of electric vehicles in recent years, which indicates a growing demand for a broader and more accessible electricity supply infrastructure. Another very interesting analysis to be highlighted is the number of cars competing per public unit of available electric charging points, which the IEA carried out in 2022, as Figure 2 demonstrates this relationship between the countries cited in the ranking in Table 2.

What can be seen in Fig. 2 above is that, the lower the demand ratio, the better the quality of service to be provided to the customer as a whole, since the high adhesion of the electrical network, linked to the high adhesion of the charging stations in the region, conveys superior quality of service provided. And again, when Brazil's position in this ranking is observed, it is in penultimate place, losing to Norway, however, its low ranking still prevails when taking into account the territorial size of Brazil and Norway, and public policies adopted, also emphasizing the precariousness of the technology.

5. ENVIRONMENTAL IMPACTS: EMISSIONS, ECONOMY AND SUSTAINABILITY

The Earth's temperature has been steadily rising and it is a problem that should not be taken for granted. In 1988, scientist James Hansen presented evidence that ongoing global warming is largely caused by human emissions of greenhouse gases and warned of irreversible impacts if immediate and serious action is not taken. Thus, the issue of global warming and its causes has been the agenda of congresses and development research for decades and since then numerous scientific studies have been conducted and the Intergovernmental Panel on Climate Change (IPCC) was established (Wang, 2023).

The increase in global energy demand resulting from population growth and developing economies has led to a steady and rapid increase in CO2 emissions. Intercurrences such as the COVID-19 pandemic, caused a decrease in emissions in 2020, due to the need for social isolation of the world's population, adhering to the home office model in work activities and studies in order not to transmit or run health risks until vaccines are available. developed, however, in the following year there was a rapid increase to previous levels from the moment that activities were normalized, albeit with restrictions, as the global demand for energy increased even more due to the delays that occurred in several processes that were consequence of the pandemic period (Hjeij et al, 2023).

In this context of the COVID-19 pandemic, together with the various consequences that were present in families, in the health and political system, the negative economic impact was very significant, affecting the global economy and reducing the

availability and economic viability of sources of income. traditional energy around the world. The Russia-Ukraine conflict brought concerns about energy security as well, as searches for new energy sources generally intensify when geopolitical risk increases (He et al, 2022).

This interdependence between economy, energy availability and emissions that mainly affect sustainability is structured every time globalization advances. This is because, although there are renewable sources for energy generation that are found in nature, they are not present everywhere in the world according to the demand of each region. There are countries with less water resources, with less exposure to sunlight due to the type of climate or that are located in reliefs that are not favorable for the winds to move the wind turbines. Unplanned events such as the worldwide spread of a new disease and geopolitical conflicts between countries balance the economy with new needs, demanding that energy matrices are favorable to the context (He et al, 2022). It is worth mentioning that even in small territories, there are regions that depend primarily on tourism and receive a large volume of conventional cars from tourists that emit high levels of carbon in the atmosphere, but that do not have easy access to renewable energy due to the lack of available natural resources. in their localities (Rensburg, 2022). Consequently, the importance of developing and studying alternative renewable energy sources with great storage potential, such as green hydrogen, for example, is fundamental, as well as investment in this sector, even if it is a high cost, to balance the economy together with environmental preservation.

Costs associated with the adoption of renewable energy sources affect international trade in terms of its exports and imports (Ilechukwu, Lahiri, 2022). In countries where the demand for energy is high, such as China, roadmaps for the large-scale commercialization of hydrogen have been developed through a very detailed methodology that includes SWOT and Delphi techniques. Extensive research on the economics of renewable hydrogen has also been carried out assessing the economic viability under Pakistani conditions, where researchers have estimated the commercially beneficial price of hydrogen at USD 3.92. Some perspectives suggest that hydrogen production costs can be reduced to less than two euros per kilogram by 2050 (Uchman et al, 2022).

6. CONCLUSION

The use of renewable energy and the hydrogen economy is fundamental to face the global challenges related to climate change and sustainability. The importance of developing energy generation alternatives to meet global demand is increasingly evident, since statistics show the significant amount of CO2 emissions into the atmosphere, including in geopolitical contexts where demand increases even more and consequently emissions as well. Governments are implementing regulatory policies which are directly impacting the activities of industries that, as a result, are undergoing internal changes and formulating new manufacturing and production strategies for products that have the lowest possible environmental impact. Today, investing in environment-friendly policies is getting more financial support, stimulus and growth prospects.

Hydrogen, in turn, plays a key role in the transition to a more sustainable energy system. The hydrogen economy involves the production, storage, distribution and use of this gas as a clean and versatile energy source, presenting itself as a promising technology, and in this article, it is demonstrated the advantages of its use and the advances that are still needed, mainly in cost reduction, as it is still a very expensive technology.

Evidence of the potential of green hydrogen produced from water and its applications are highlighted. There is a relevant difference compared to Brazil in the use of hydrogen in fuel cells and electric cars, which makes it possible to make a political and economic analysis of each country and identify the reasons why in some countries there is not so much growth in the use of these technologies.

It is assumed that hydrogen plays a key role in the global decarbonization process, mainly in the transport, industry and electricity generation sectors, and that green hydrogen has been disseminated as a reality to achieve zero carbon dioxide emissions. In addition, the use of hydrogen presents an opportunity for economic development by boosting innovative and sustainable sectors, stimulating investments in research, development and infrastructure.

7. ACKNOWLEDGMENTS

To the Brazilian National Council of Scientific and Technological Development - (CNPq) - [projects 407198/2013-0, 403560/2013-6, 407204/2013-0, 430986/2016-5, 443823/2018-9, 313646/2020-1, 310708/2017-6, 308460/2020-0, 446787/2020-5, no. 25/2021, 405864/2022-1, 408073/2021-7, 408080/2022-1, and to project 300093/2022]; CAPES; Ministry of Education (MEC), Brazil - (projects 062/14 and CAPES-PRINT-UFPR-88881.311981/2018-01); Araucaria Foundation of Parana, Brazil (project 115/2018, no. 50.579 – PRONEX), to FUNDEP, Renault and UFPR for the funding and the development of the project called “ROTA 2030”.

8. REFERENCES

ASSOCIAÇÃO BRASILEIRA DE VEÍCULOS ELÉTRICOS - ABVE. Veículos elétricos no Brasil: uma visão de futuro. São Paulo:

ABVE, 2021. Disponível em: https://abve.org.br/wp-content/uploads/2021/07/ABVE_Livro_VEs_Brasil_2021_final.pdf.

AMINUDIN, M. A. et al. An overview: Current progress on hydrogen fuel cell vehicles. International Journal of Hydrogen Energy, nov. 2022.

Araújo, R. S. de.; Sousa, F. L. N de.; Vanderley, P. S.; Bentes, S. O. da S.; Gomes, L. M.; Ferreira, F. C. L., 2022. Fontes de energias renováveis: pesquisas, tendências e perspectivas sobre as práticas sustentáveis. Publisher Research, Society and Development.

ASSADI, A. A. et al. Challenges and Prospects of automated Disassembly of Fuel Cells for a Circular Economy.

Resources, Conservation & Recycling Advances, p. 200172, 17 jul. 2023.

Breeze, Paul. (2017). The Fundamentals of Fuel Cell Operation. In: BREEZE, Paul. Fuel Cells. London: Academic Press, Cap. 2, p. 11-21

Capitanescu, F., 2021. Evaluating reactive power reserves scarcity during the energy transition toward 100% renewable supply. Publisher Electric Power Systems Research.

Chattopadhyay, M. and Chattopadhyay, D., 2020. Renewable energy contingencies in power systems: Concept and case study. Publisher Energy for Sustainable Development.

Departamento de Energia dos Estados Unidos. Hydrogen Production: Natural Gas Reforming. Disponível em: https://www.energy.gov/eere/fuelcells/hydrogen-production-natural-gas-reforming. Acesso em: 17 jul. 2023.

Feng, G. and Zheng, M., 2022. Economic policy uncertainty and renewable energy innovation: International evidence.

Published Innovation and Green Development.

Figueiredo, R. L.; Silva, J. M. and Ortiz, C. E. A., 2023. Green hydrogen: Decarbonization in mining - Review.

Publisher Cleaner Energy Systems.

FRAGIACOMO, P. et al. Strategic Overview on Fuel Cell-Based Systems for Mobility and Electrolytic Cells for Hydrogen Production. Procedia Computer Science, v. 200, p. 1254–1263, 2022.

Godula-Jopek, Dr.-Ing. Agata and Andreas Westenberger. "FC Types: PEMFC/DMFC/AFC/PAFC//MCFC/SOFC/." (2021).

Hassan, Q.; Al-Hitmi, M.; Sohrabi Tabar, V.; Zuhair Sameen, A.; Salman, H. M. and Jaszczurf, M., 2023. Middle East energy consumption and potential renewable sources: An overview. Publisher Cleaner Engineering and Technology.

He, Q.; Zheng, H.; Ma, X.; Wang, L.; Kong, H. and Zhu, Z., 2022. Artificial intelligence application in a renewable energy-driven desalination system: A critical review. Publisher Energy and AI.

Hydrogen Newsletter. Hydrogen Production from Coal Gasification. Disponível em: https://www.hydrogennewsletter.com/hydrogen-production-from-coal-gasification/. Acesso em: 09 de julho 2023.

INTERNATIONAL ENERGY AGENCY. Global EV Outlook 2021. Paris: IEA, 2021. Disponível em: https://www.iea.org/reports/global-ev-outlook-2021.

International Energy Agency (IEA). "Matriz energética mundial 2020". Available on: June 2th, 2022. In: https://www.iea.org/data-and-statistics?country=WORLD&fuel=Energy%20supply&indicator=TPESbySource.

Ilechukwu, N. and Lahiri, S., 2022. Renewable-energy consumption and international trade. Publisher Energy Reports. Instituto de Pesquisa Econômica Aplicada. Disponível em:

https://repositorio.ipea.gov.br/bitstream/11058/11291/1/td_2787_web.pdf4. Acesso em: 09 de julho 2023.

JENG, K.-T. et al. A versatile electrochemical fuel sensor for direct membrane fuel cell applications. Sensors and Actuators B: Chemical, v. 125, n. 1, p. 278–283, 16 jul. 2007.

Kumar, S. S. and Lim, H., 2022. An overview of water electrolysis technologies for green hydrogen production.

Publisher Energy Reports.

Lutz, A. E.; Bradshaw, R. W.; Keller, J. O.; Witmer, D. E., 2003. Thermodynamic analysis of hydrogen production by steam reforming. Publisher International Journal of Hydrogen Energy.

MEDA, U. S.; RAJYAGURU, Y. V.; PANDEY, A. Generation of green hydrogen using self-sustained regenerative fuel cells: Opportunities and challenges. International Journal of Hydrogen Energy, 22 abr. 2023.

Nag, S.; Sharma, Priybat, Gupta, A.; Dhar, A., 2019. Experimental study of engine performance and emissions for hydrogen diesel dual fuel engine with exhaust gas recirculation. Publisher International Journal of Hydrogen Energy.

Oliveira, R. C. DE. TD 2787 - Panorama do hidrogênio no Brasil. Texto para Discussão, p. 1–59, 4 ago. 2022. Organização das Nações Unidas. Disponível em: https://news.un.org/pt/story/2021/08/1759272. Acesso em: 09 de julho 2023.

Shah, A. et al. Single-atom catalysts for next-generation rechargeable batteries and fuel cells. v. 45, p. 301–322, 1 mar.

2022.

Solarin, S. A.; Bello, M. O. and Tiwari, A. K., 2022. The impact of technological innovation on renewable energy production: accounting for the

roles of economic and environmental factors using a method of moments quantile regression. Publisher Heliyon.

THOMAS; BRENNAN, N.; HOWARD, A. Tourist preferences for fuel cell vehicle rental: going green with hydrogen on the island of Tenerife. 1 abr. 2023.

Uchman, W.; Kotowicz, J. and Sekret, R., 2022. Investigation on green hydrogen generation devices dedicated for integrated renewable energy farm: Solar and wind. Publisher Applied Energy.

VARGAS, J. V. C., ORDONEZ, J. C., BEJAN, A. Constructal flow structure for a PEM fuel cell. 2004. International Journal of Heat and Mass Transfer. Elsevier, v.47, Ed. 19-20, p. 4177-4193.

VARGAS, J.; BEJAN, A. Thermodynamic optimization of internal structure in a fuel cell. v. 28, n. 4, p. 319–339, 23 fev. 2004.

Wang, L.; Wang, L.; Li, Y. and Wang, J., 2023. A century-long analysis of global warming and earth temperature using a random walk with drift approach. Publisher Decision Analytics Journal.

Woods, P.; Bustamante, H. and Aguey-Zinsou, K.-F., 2022. The hydrogen economy - Where is the water?. Publisher Energy Nexus.

YANG, Y. HONG et al. Study of the influence under different operating conditions on the performance of hydrogen fuel cell system for a bus. Process Safety and Environmental Protection, 19 jul. 2023.

YU, Y.; GUO, Y.; MA, T. Prioritizing the hydrogen pathways for fuel cell vehicles: Analysis of the life-cycle environmental impact, economic cost, and environmental efficiency. Energy, v. 281, p. 128322, 15 out. 2023.

9. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.