Use of H_2 in vehicular applications

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ABSTRACT

New energy sources for use in vehicles have emerged in recent years, such as CNG, vehicular natural gas, plug-in or hybrid electric batteries and, more recently, fuel cell vehicles using the H_2-hydrogen energy vector as a source of chemical electricity to drive the electric motor, that is, a fuel cell stack composes a cell that will supply the necessary electrical current to move the vehicle. This reaction is based on the use of hydrogen fed into the anode and oxygen supplied from the air to the cathode, which undergo the respective catalysts and have as emissions water in the form of steam and heated air. The objective of the work will be to investigate the main uses of fuel cells in vehicles, be they cars, trucks and buses, mainly. This solution for the use of fuel cells is presented as the most environmentally promising solution to avoid CO_2 - dioxide and particulate matter emissions as well.

INTRODUCTION

The automotive sector has been suffering an impact from the new energies that can be used in place of gasoline and diesel mainly. Similarly, industries are also under pressure to minimize and even achieve neutrality in environmental emissions, see Figure 1, especially for greenhouse gases (GHG).

Figure 1 - Environmental contamination – *source see ref. [1]

The Paris agreement is a global treaty aimed at reducing global warming, having been discussed between 195 countries and the international commitment was approved on 12 December 2015 and officially entered into force on 4 November 2016.

The oceans and atmosphere heat up year after year because of massive greenhouse gas emissions, with the biggest villains being the burning of fossil fuels and deforestation, which is responsible for renewing oxygen.

The Paris Agreement's main objective is to reduce greenhouse gas emissions to limit the average global temperature increase to 2 °C when compared to pre-industrial levels.

For vehicles we are probably in a situation similar to the introduction of motor vehicles to internal combustion and their proposal to be an alternative to animal traction sets, as shown in figures 2 and 3. As a way to contribute to the reduction of vehicular emissions, the alternative of fuel cell vehicles is emerging, using hydrogen as an energy vector in place of petroleum derivatives.

Figure 2 – Vehicle with animal traction * [2]

Figure 3 – Vehicle with internal combustion engine * [3]

Currently, solutions are sought with lower environmental contamination, that is, a substitute for the derivatives of coal, oil, wood, and in a correlated way one can imagine the impact of the introduction of internal combustion vehicles on the hygiene of streets, roads, and parking environments of vehicles with animal traction. Figures 4a. and 4b. summarize this search for environmentally appropriate fuels and green hydrogen seems to have this capacity, as it should be obtained from environmentally renewable energy sources, wind, solar or hydroelectric.

Figure.4a – Hydrocarbon * [4]

Figure 4b - Green Hydrogen * [5]

When proposing an energy alternative to vehicles with internal combustion engines some physical characteristics are fundamental in the proposed analytical:

- Impact on load capacity (tare)
- Impact on autonomy (km)
- Fuel filling time (min.)
- Vehicle safety/running
- Operating cost of running - TCO - ($/km)
- Cost of vehicle purchase ($)
- Cost of maintenance and repairs ($)
- Fuel distribution network

In the case of Brazil, we have a strategic advantage in the distribution of hydrogen, a legacy of the “pró-ácool” of the 1970s, achieved by the hydrated ethanol network that at the time aimed to mitigate the import of oil due to its very high value due to instabilities of the time. In the ethanol molecule we have C2H5OH, six hydrogen atoms.

This situation generates a very interesting research field for Brazil, because an impacting factor in the product cost H2 is logistics and there is a technological-economic possibility to obtain hydrogen through on-board reform or at the filling station to strengthen the position of ethanol as an environmentally favorable fuel for its neutrality in CO2 emissions, which is extracted from the environment, by photosynthesis, and there returns, as synthesized in Figure 5.

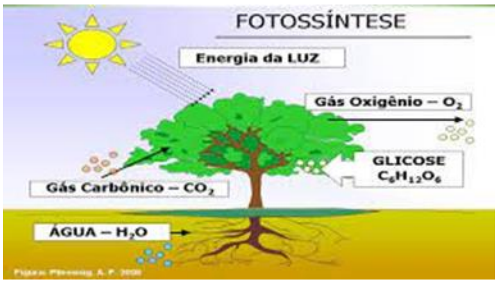

Figure 5- Summary of photosynthesis and CO2 capture *[6]

OBJECTIVES

This study aims to seek the effective actions of hydrogen use in vehicles, whether cars, trucks and buses, as an energy source in fuel cells and the results obtained. It is worth mentioning that the main sources of information are specific reports of companies that have moved in the line of research and development of the use of H2 as electrochemical energy for propulsion of their respective vehicle products.

In cars Toyota with its Mirai was the main source of shooting data, physical and dynamic characteristics of the product, other companies are more superficial, but it is to be assumed that soon they can make available data that allow to create a larger analytical spectrum.

In the case of trucks, the data for analysis are from the Hyundai company that already has commitments to supply vehicles to Switzerland. From the shared reports will be made an analysis of the advantages and benefits and the greatest benefit is the total decarbonization in the emissions of trucks operating locally, mainly in the urban environment.

For urban public transport the source of consistent information and can be considered a leading role of Brazil in this area will be used the brochure "Brazilian Hydrogen Bus", work supported by various agencies and companies, such as: Ministry of Mines and Energy, Metropolitan Transport Secretariat, EMTU, Ballard, Petrobras, Marcopolo. It is a source with practical results including the construction of a station to obtain hydrogen by electrolysis at the site in São Bernardo do Campo.

BIBLIOGRAPHIC REVIEWS

The analysis of materials, whether academic publications or articles and press-releases of companies working in the new automotive technology with the use of hydrogen will be considered in addition to the proposed context of use of this energy source in vehicles already highlighted. Other modal will also be addressed depending on their relevance or novelty.

Toyota's Mirai Model Fuel Cell Car

To report on the progress of the application of fuel cells the best reference is Toyota. The company launched the Prius hybrid in 1997 and in 2014 the MIRAI with 114 kW Fuel Cell, which brings an improvement in the power provided by Fuel Cell from 2008 that had 90 kW, see Figure 6, [7]

The reported fuel consumption records have an autonomy of up to 650 km. Recent tests released in videos by the company highlight an autonomy of 1003 km, achieved in France and with a consumption of 550 g of H2, for every 100 km. The used vehicle tank has capacity of 5.6 kg of H2. This autonomy is an outstanding achievement in the car segment.

The great advantage that one has is that with the supply at high pressures, 70 MPa (700 bar), the volume needed to supply this gas is substantially reduced, otherwise it would take 63 m3 to obtain the mass of 5.6 kg of H2 under normal pressure and temperature conditions.

But with less than 4 months of this record a new milestone was certified by the Guinness Book, with 1,360 km of autonomy with 5.65 kg of hydrogen, [8]

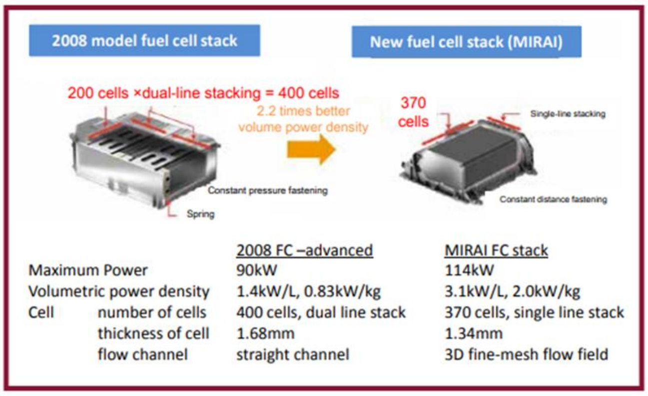

Figure 6 - 2008 fuel cell compared to the new one [7]

When using hydrogen as fuel a major challenge is presented regarding the allocation of the components of this fuel cell, and as can be seen in Figure 7 the layout of the high-pressure tanks occupies the location of the trunk, becoming a challenge in the development of the product and future vehicles.

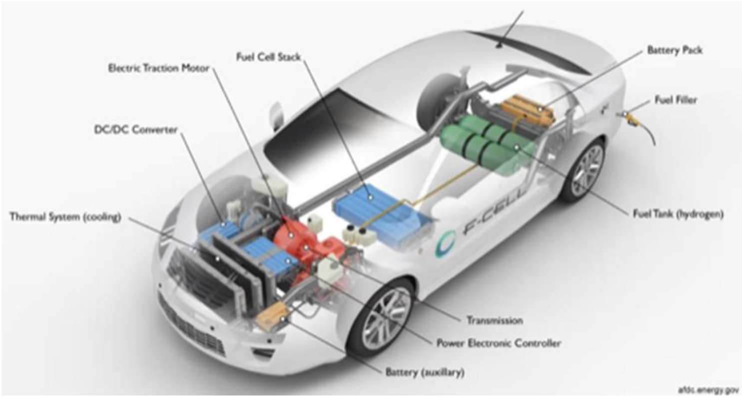

Figure 7- Layout of the components of a fuel cell car [7]

For comparative purposes, Hytron company, which produces an ethanol reformer, informs that:

- 7.6 liters of ethanol produce 1 kg of H2
- H2 stored in cars range from 5 kg to 7.5 kg
- BOSCH Fuel Cell: 1 kg H2 >>>> 150 km
- Autonomy from 750 km to 1,125 km
- Ethanol consumption 38 liters to 57 liters
- 57 liters of ethanol >>>> 1,125 km (approx. 20 km/l)
- Filling time 3 minutes

It is worth reflecting on the use of reformed ethanol in autos mainly by facilitating the layout of the components for the entire fuel cell system and not compromising the spaces of passengers and baggage handlers.

It is a fertile and promising field of research, so much so that Nissan and VW are supporting research in this direction. With the "pró-álcool" program of the 1970s, Brazil sought the use of ethanol as an alternative to mitigating the use of gasoline and oil imports. This created a network with more than 40,000 "liquid hydrogen distribution" stations contained in the ethanol molecule C2H5OH. This in itself would already be an environmental and economic contributor to the country. Much work will be needed in this direction which proves to be an excellent field for hydrogen-powered Vehicle Research & Development.

Buses with fuel cell

The public transport segment that circulates within cities is a modal that needs an urgent and priority solution in terms of more decarbonized emissions due to contamination that affects users and people who travel on the routes of these vehicles**.**

New Zealand Case

The Auckland Transport company, which is in New Zealand's largest city, has published a bid for the development of a fuel cell-powered vehicle using the hydrogen shown in Figure 8. It was an international competition. The Global Bus Ventures local bus manufacturer company was the winner. They were selected for their experience in hybrid vehicles and also by hydrogen bus design made in 2009.

Figure 8 - New Zealand's first fuel cell bus

"In terms of vehicle, Auckland Transport specified the size and seats of the bus and what type of range they wanted to go to. Ballard's fuel cell was chosen. The main reason of this choice was the negotiation, support and quality of the cell. The company needed a solid fuel cell to ensure that the Global Bus Ventures brand – GBV – was not at risk because it was associated with a low-performance fuel cell. And similarly, with all the other products used, we knew that the product of Ballard is a proven solution on roads," said Mike Parker of the company GBV.

The action in New Zealand reinforces the search for zero-emission vehicles in carbon/CO2, and public transport is highly demanding of these environmentally friendly energy solutions.

Case study for California Fuel Cell Buses

Across California, the zero-emission transition is already in progress.

Eight of the top ten public transport companies in the state are already operating zero-emission buses, including battery-powered electric vehicles and hydrogen fuel cells.

Public transport companies are looking at the best option for transitioning their zero-emission fleets without affecting service levels, are different electrical technologies to be considered. The decision central is to choose zero-emission bus propulsion:

- Electric fuel cell buses (FCEBs) - Fuel Cell Electric Bus or

- Battery electric fuel (BEBs) - Battery Electric Bus

or a combination of both.

In most cases, the decision should be based on routes served (as far as time, how flat or bumpy); service restrictions (hours per day), existing infrastructure (electrical capacity or refueling facilities and space limitations in the bus terminal).

The main difference in technologies is in how electricity is delivered to a BEB's electric motor, power train powered only by what batteries can provide in a single charge or a battery-powered FCEB power train plus a hydrogen fuel cell power generator.

Electric fuel cell buses combine the best of electric battery with bus technology with an onboard power generator.

The fuel with cell system on board of the bus generates electricity efficiently, being the fuel energy hydrogen by means of an electrochemistry reaction to leaving only water and heat as by-products, without combustion, Ballard, bus blog, 2021, [9].

Figure 9 shows the positioning of the main components of the fuel cell and functionally the positioning of hydrogen high pressure tanks on the roof of the bus without impacting on the internal layout of the seats or other vehicle system.

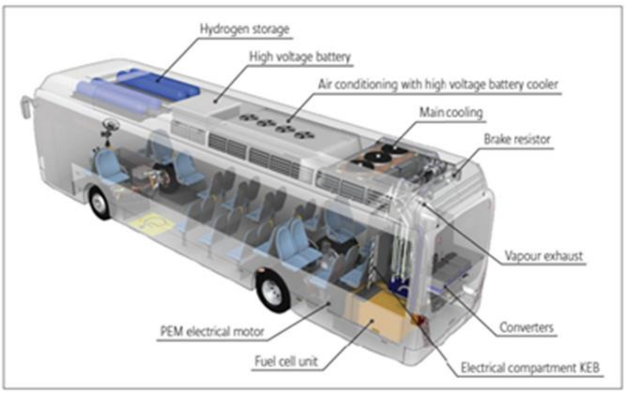

Figure 9 – Layout of bus fuel cell components [9]

The biggest impact of hydrogen production costs of an electrolysis plant is the cost of electricity. Obtaining a long-term energy purchase contract from the local electricity service for the electrolyzing plant it is the key to saving this solution.

The table 1 shows a representative calculation for an 18 MW (8,000 kg/ day H2capacity) electrolysis plant operating at a capacity factor of 40% (for a good wind resource) and amortized for 10 years at 6%.

The production cost of $0.03/kWh of power is very attractive even with the relatively low-capacity factor. The cost details are presented in tables 1 and 2.

Sensitivity to CAPEX - Capital Expenditure - becomes more pronounced as the capacity factor decreases. For example, a good solar resource can offer capacity factor of 25%, and with $ 0.03 / kWh, the cost of production jumps to $ 3.06 / kg just because the recovery costs in the CAPEX is slower. Overall, the economy of large-scale production by electrolysis is quite good considering the current and long-term prices available for solar and wind power. Information valid for the case under study.

When combined with the local "drop-and-swap" distribution, which is the "let and take" trailer with cylinders in the logistics operation (expected to add less than $2/kg in cost), the price for the end customer can be more competitive in dollar per mile compared to diesel buses and eventually even CNG buses – vehicular natural gas – $5 to $8/kg.

Capital costs on equipment in the bus company will include the Hydrogen compressor, high pressure storage and dispensers to supply fuel to the electric fuel cell bus. The cost of this equipment for our example of a fleet of 60 buses is estimated at $ 150,000 per bus or less.

HYDROGEN PRODUCTION COST CALCULATOR

Off Grid Wind 20 Year PPA	
CAPEX Electrolyzer	$12,000,000
MW Nameplate	18 MW
Electricity	$0.03 per kWh
Project Term	20 years
Purchase Amortization	10 years
Discount Rate	6%
Capacity Factor	40%
CAPEX	$0.66 per kg
OPEX	$1.63 per kg
Operation & Maintenance	$0.24 per kg
TOTAL PRODUCTION COST	$2.53 per kg

Table 1 – Hydrogen production cost calculation [9]

COST MODEL – RENEWABLE HYDROGEN DELIVERY AT SCALE

Capital Equipment Cost	
Infrastructure cost	$150,000 per bus
Operating Cost	
Hydrogen fuel (delivered price)	$8/kg
LCFS incentive (ZEV truck or pipeline delivery)	($5.40/kg)
Fuel cost	$2.60/kg
Fuel Cost per Mile	$0.31/mile

Assumptions
- Fuel economy = 8.33 mi/kg
- LCFS credit $180 per metric ton of CO_2 equivalent reduced

Rem.: consumption 8,33 mi/kg >>> 7,7 kg/100 km LCFS: credit US$ 180 per metric ton CO2 eq. reduced

Table 2 - Cost of renewable hydrogen at scale [9]

The public transport company has the option to purchase this equipment by taking advantage of the purchase incentives available.

Or, alternatively, the infrastructure provider can install, maintain and operate the equipment, maintaining ownership of storage of fuel and distribution equipment, and provide this service for a monthly fee.

This creates an operating expense for the carrier, rather than a capital expense, however incentives are not widely available for this financial model.

The other operating cost is the price of fuel. In this example, with centralized production of green hydrogen, we estimate the delivery price of hydrogen is $8/kg. Public transportation system operators can take advantage of the LCFS incentive - Low Carbon Fuel Standard - to reduce the cost to $2.60/kg, resulting in a fuel cost per mile of $0.31. Ballard, bus blog 2021. [9]

That is, there are incentives to support the decarbonization of public passenger transport in a technical and economic way by those in the sector, this in California is already a reality, and can be adopted in other countries.

Fuel cell bus - Brazilian project

Brazil has already played a leading role in fuel cell bus technology. It was a 2006 project that resulted in the construction of 1 prototype, see Figure 10 and 3 buses, see Figure 11, which ran in the ABD corridor by Metra and coordination of EMTU, Metropolitan Urban Transport Company of the State of São Paulo.[10]

Figure 10 - Ballard PEMFC bus prototype

A recent visit, June 2021, was made to Metra in São Bernardo do Campo to observe the situation of these 3 buses, which are well preserved, but in case of reactivation for shooting there was warning from Ballard that a careful process should be followed to make the vehicle operational, to reactivate the function of the fuel cell.

Figure 11 - Ballard PEMFC bus, author picture

An important data in the operational aspect was extracted from the shooting of the vehicle which was the consumption of H2 of 15 kg/100 km, and some improvements were suggested, such as improved integration of components, reduction of mass, weight balancing, which resulted in subsequent improvements.

This project had the support of several companies and agencies, namely: AES Eletropaulo, BALLARD, EPRI, HIDROG(E)NICS, Marcopolo, NUCELLSYS, PETROBRAS, tutto, FINEP, GEF, UNPD, SECRETARIA DAS TRANSPORTES METROPOLITANOS GOVERNO DE SÃO PAULO, MINISTÉRIO DAS MINAS E ENERGIA.

Hydrogen - powered aircraft

Other means of transport also aim at the use of hydrogen as clean fuel rather than petroleum derivatives.

In May 2021, Clean Sky 2 published its first Technology Evaluator.[11] One of its main conclusions is that "the main focus on aviation decarbonization should be on short-range aircraft flying at distances of less than 4,000km, but with much larger passenger capacity, well over 300, up to more than 400 passengers in the cabin. This type of aircraft doesn't exist today." This article, however, will show that the ideal type of fuel will be liquid hydrogen, see Figure 12.

Figure 12 - Hydrogen-powered airplane may be in service by 2030

The need for large aircraft optimized for flights of less than 4,000 km was identified by the DLR (German Aerospace Center) when it updated its air traffic model to include airport capacity restrictions. The study summarizes the results, with the scope of flights less than 4,000km. The result shows the percentages of CO2 produced if all flights are still using kerosene.

The end result is that almost 60% of the CO2 produced by aviation will be removed if the type of large aircraft for travel up to 4,000 km is hydrogen powered.

The current Airbus A350-900ULR provides the ideal starting point for the development of an 'A350-H' to meet the '<4,000 km' requirement. The main reason is that their fuel tanks have proven to be large enough to provide a range of more than 16,000 km when their engines run with kerosene or SAFs (sustainable aviation fuels).

The tanks are on the wings of the A350 and will be replaced by new insulated tanks designed to contain enough liquid hydrogen to fuel flights of up to 4,000 k If the new DLR forecast will lead Airbus and Boeing to develop hydrogen-powered versions of the A350 and 787, the 'emissions stigma' of flying on them will be removed and the refueling cost will be much lower than using highly taxed SAFs or kerosene. And this new form of commercial airliner will seem comfortably conventional. Therefore, passenger demand at the heart of large markets can grow even faster than the DLR is predicting.

The Clean Sky 2 report also states: "Like London's famous two-storey, high passenger capacity will be the key to responding to air traffic demand in the future, especially on short-haul routes (<4,000 km). As a result of the airport's capacity constraints, a true large-capacity ‘air bus' will be required to transport passengers from one city to another, especially on intercontinental flights."

Consequently, Airbus should now be planning to build a new version of the A350, the A350-H, powered by Rolls-Royce Ultrafans running on liquid hydrogen, producing low levels of NOx.

The A350-H will carry up to 350 passengers for up to 4,000 km and will be operated from existing airports with existing runway limitations. This promises to be the fastest way to minimize aviation CO2 production and will help accelerate progress toward global zero emissions, H2View, 09/29/2021.

Hydrogen trucks

Several companies producing cargo vehicles are strategically working on cargo transport solutions, trucks using hydrogen as an energy vector. The following are some of these actions will be addressed, but it is worth mentioning that virtually all manufacturers are operating in their respective vehicles and target markets.

Hyundai and its truck FC Xcient

According to Hyundai data see table 3, it is a rigid truck, that is, it is not one of the most trailer traction horse type, and the data stipulate a consumption of 34.51 kg of hydrogen for a range of 400 km, which seems very reasonable for a probable truck of urban distribution or even intermunicipal.[12]

This consumption calculated per 100 km wheeled results in 8.63 kg of hydrogen required and if we observe the data of the urban bus lane that was 15 kg for every 100 km, that is, each application and form of operation requires more or less energy. The storage pressure of hydrogen is 350 bar.

The vehicle is composed of two fuel cell stacks with power of 95 kW each. An important fact is the plan to supply 1600 vehicles by 2025 to Switzerland.

Manufacturer	Hyundai
Gross Vehicle Weight	36 ton (combined)
Range	400 km
Torque	3.400 Nm
Power total	350 kW
Fuel cell capacity	190 kW (2x95)
Fuel cell manifacturer	Hyundai
H2 Storage	34,51 kg @ 350 bar
Status	Planned 1.600 by 2025
Battery	73,2 kwh

Table 3 - Technical data of the Hyundai Xcient rigid truck

Figure 13 this is a rigid type truck expected to run in Switzerland in 2025, in addition to two other European countries, outside Austria, Germany, the Netherlands and Norway.

Figure 13 - Hyundai Xcient rigid truck

PEMFC – Fuel Cell

The most common type of Fuel Cell PEM (Proton Exchange Membrane), Figure14, operates with pure hydrogen gas, usually generated from the reform of steam methane or water electrolysis.

In addition to hydrogen, they only need oxygen (from the air) and water to work. The energy conversion of a PEM fuel cell is performed by two chemical reactions separated by an electrolyte membrane. Each chemical reaction occurs in a specific electrode, one electrode is called anode (with positive charge), and the other is the delight (negatively charged). Hydrogen gas enters the anode, and oxygen enters the demi through the airflow. With the help of a platinum catalyst, hydrogen is divided into protons and electrons in the anode. Electrons travel through an external circuit providing usable electricity, while protons travel through the PEM. [13]

Protons and electrons recombine with oxygen in a platinum catalyst in to make water, with water and heat being the only waste emitted, (Nafion Chemours, 2020).

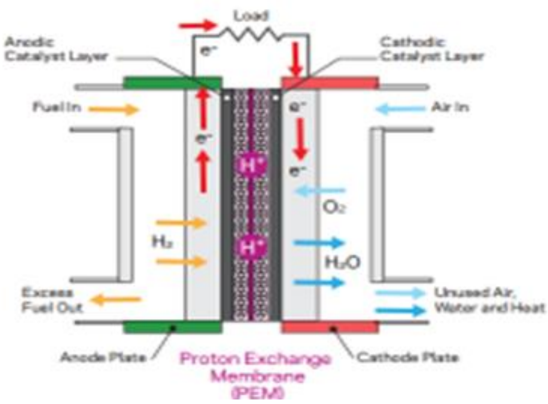

Figure 14 - PEMFC operating principle

RESULTS AND DISCUSSION

What is extracted and from this context of H2 and Fuel Cell equipment is that fortunately a technical solution is fully mature and available to start a process of decarbonization of the various transport modals that use ICE -Internal Combustion Engine - as a propellant of current cars, buses, trucks, trains, forklifts and even aircrafts.

One point that can and certainly is a strategic advantage for Brazil would be to have **ethanol** as a source of hydrogen generation with reformer or other technology that arises, with this would avoid a high cost of logistics structuring to make it available in all places where today we already have gas stations, diesel, gas and ethanol.

Several research and papers to have **ethanol or water** as a source of green hydrogen are underway at IPEN/USP, Federal University of Minas Gerais, Federal University of ABC, UNICAMP, FEI and São Carlos among others.

We are just beginning to explore more intensely the new technology and the evolutions already achieved can be expected a lot of novelty and creative economic solutions both to obtain green hydrogen, and in Pécem/ Ceará, Suape/Pernambuco and Açu/Rio de Janeiro ports there are already actions to create this hub and several researches have been done to improve the efficiency, durability, quality of catalysts and electrolytes to meet the demand that is pronounced.

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