THE UNFOLDING POTENTIAL OF GREEN HYDROGEN IN BRAZIL

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INTRODUCTION

Hydrogen (H2) is increasingly gaining global recognition as decisive in the quest for environmentally sustainable energy, particularly within the renewable energy sector. Its role in electricity generation through fuel cell conversion not only produces energy that is free from carbon dioxide but also yields pure water as the only byproduct, framing it as a true zero-emission solution.

In accordance with the Paris Agreement, there is an urgent need to scale up hydrogen production from renewable sources to combat the climate crisis, which poses a significant threat due to the catastrophic impacts of environmental pollution from human activities. CO2 emissions from fossil fuels have surged, contributing to global warming, rising sea levels and extreme weather events. Addressing this problem, including the significant methane emissions from human activities, is crucial, as transitioning to hydrogen as a clean fuel can play a vital role in mitigating CO2 emissions and fostering global sustainability.

This article explores the potential of green hydrogen as a clean fuel that produces no CO2 emissions. It details the production methods for green hydrogen and discusses the practical challenges involved, particularly in the context of Brazil.

Brazil is strategically positioning itself to lead the charge in green hydrogen production, harnessing its vast renewable energy resources, including hydropower, solar energy and wind potential. The green hydrogen sector in Brazil is actively developing through several operational and planned projects, such as the Federal University of Rio de Janeiro's pilot initiative and the Itumbiara facility, which utilizes solar and hydropower for hydrogen production, with notable upcoming projects including Fortescue Future Industries' facility in Ceará and Qair Brasil's investments in offshore wind and electrolysis plants. However, significant challenges remain, including high production costs, technological needs and infrastructure development, as shall be discussed in detail below.

Federal Law No. 14.948, enacted in August 2024, establishes a legal framework for hydrogen activities, designating the National Agency of Petroleum, Natural Gas and Biofuels (ANP) as the regulatory body and introducing incentives for low-carbon hydrogen production. As such, it marks a significant regulatory step forward in creating the favorable environment for investment and growth in Brazil's green hydrogen industry essential for realizing its potential.

THE EVOLUTION OF HYDROGEN REGULATION AND POLICY IN BRAZIL

Brazil has instituted a range of programmatic policy measures aimed at promoting the development and integration of renewable energy sources and has increasingly focused on the advancement of hydrogen technology as an element of this energy strategy. This interest is rooted in initiatives and legislation that have evolved significantly over the years.

By way of overview, the genesis of this energy strategy implementation in Brazil was in the early 2000s, complementing the increasing global shift towards considering alternative energy sources to reduce dependency in fossil fuels and mitigate climate change[1] and the developing interest in Europe, Japan and the United States to integrate hydrogen into the energy mix.[2]

In 2002, Federal Law No. 10.438 established the Alternative Electricity Sources Incentives Program (PROINFA), which aimed to add 3,300 MW of renewable energy – primarily from wind potential, biomass and small hydroelectric sources – by the end of 2007 through subsidies funded by an increase in energy bills, exempting low-

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[1] From the 1970s to the early 2000s, the global energy landscape transformed significantly due to rising oil prices and increased environmental awareness. The 1973 Arab oil embargo and the Iranian Revolution-caused 1979 oil crisis spurred countries to explore alternative energy sources and conservation measures, leading to advances in renewable energy such as solar energy and wind potential, exemplified by the establishment of the U.S. Solar Energy Research Institute (now The National Renewable Energy Laboratory (NREL)) in 1977 and Denmark's pioneer investment and leadership in wind potential at the time.

Energy efficiency improved through regulations such as the U.S. Energy Policy and Conservation Act of 1975 and nuclear power continued to expand. In 1987 the Montreal Protocol (a landmark international treaty aimed at phasing out substances that deplete the ozone layer, including chlorofluorocarbons (CFCs) and other ozone-depleting chemicals) was signed and in 1992 the United Nations Conference on Environment and Development (UNCED) was hosted in Rio de Janeiro, Brazil. This Earth Summit produced several key outcomes, including the Agenda 21 Rio Declaration on Environment and Development, which provided a comprehensive plan for achieving sustainable development across various sectors, including energy, and also led to the establishment of the United Nations Framework Convention on Climate Change (UNFCCC), adopted in 1992, and the United Nations Convention on Biological Diversity (CBD), enacted in 1993.

The Kyoto Protocol, adopted in 1997 at the Third Conference of the Parties (COP3) to the UNFCCC in Kyoto, Japan, established binding emission reduction targets for developed countries by introducing carbon trading and creating market-based mechanisms to help countries achieve their emissions reduction goals. In 2002, U.S. President Bush revealed the U.S. alternative to the Kyoto Protocol, proposing a plan to cut the intensity of greenhouse gases by 18 percent over a 10-year period.

[2] In the 1990s, Germany began funding the development of stationary hydrogen fuel cells for building energy supply. By way of other example, in 2002, Japan´s Toyota company introduced the Toyota FCHV, the world´s first government certified commercially available hydrogen fuel cell vehicle. Also in 2002, and significantly, the U.S. Department of Energy (DOE) Hydrogen Program was officially established, focusing on hydrogen production, storage and fuel cell technologies research and development.

income consumers. In its second phase, PROINFA aimed to increase renewable energy's share to 10% of total consumption within 20 years, requiring renewable generators to issue certificates based on their annual clean energy output.[3]

Also in 2002, Brazil launched the "Brazilian Hydrogen and Fuel Cell Systems Program - PROCAC" (subsequently renamed in 2005 as the "Science, Technology and Innovation Program for the Hydrogen Economy - PROH2") and in 2003 joined the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE), established by the U.S. Department of Energy aiming to advance the development and adoption of hydrogen and fuel cell technologies.

The creation of the Brazilian Energy Planning Agency (EPE) in 2004 under Federal Law No. 10.847 denoted an important step for advancing energy research and strategic initiatives in Brazil, including those related to hydrogen. The EPE was tasked with formulating and coordinating the Country's long-term energy strategies, integrating various aspects of energy policy, including supply, demand and infrastructure planning.

In 2005, the Brazilian Ministry of Mines and Energy (MME) published the "Roadmap for the Structuring of the Hydrogen Economy in Brazil," which laid the foundational principles for national hydrogen development.[4] This was followed by Brazil's National

[3] International Energy Agency (IEA), IEA/IRENA Policy and Measures Database, *Programme of Incentives for Alternative Electricity Sources - PROINFA*, (Apr. 29, 2024), available at https://www.iea.org/policies/4019-programme-of-incentives-for-alternative-electricity-sources-programa-de-incentivo-a-fontes-alternativas-de-energia-eletrica-proinfa.

[4] The roadmap outlined a vision for developing a hydrogen economy, with specific intermediate goals. Initially, by 2015, the focus was to be on producing hydrogen from natural gas reforming, leveraging existing infrastructure and technology. By 2020, the aim was to shift to hydrogen production via water electrolysis, with the goal of integrating renewable energy sources. The 2025 target involves producing hydrogen from ethanol reforming and biomass, utilizing Brazil's renewable resources. By 2030, the roadmap envisioned exploring alternative hydrogen production processes. It emphasized the strategic importance of these technological routes for Brazil's competitive advantage, the transitional role of natural gas in developing hydrogen infrastructure and the application of hydrogen in distributed generation, remote regions and urban buses to enhance energy security and reduce emissions. Energy Assets do Brasil, *National Experience*, Caroline Chantre et. al., The Hydrogen Economy: Transition, Decarbonization and Opportunities for Brazil, Nivalde de Castro et. al. (eds.), (2023), available at https://gesel.ie.ufrj.br/wp-content/uploads/2023/04/livro_economia_do_h2.pdf; Ministry of Mines and Energy (MME), Guidelines for the National Hydrogen Program (PNH2), (Jul. 2021), available at https://www.gov.br/mme/pt-br/assuntos/noticias/mme-apresenta-ao-cnpe-proposta-de-diretrizes-para-o-programa-nacional-do-hidrogenio-pnh2/HidrognioRelatriodiretrizes.pdf.

This roadmap harmonizes with the broader global trend, particularly in Europe, where the European Union is committed to accelerating decarbonization and expanding renewable energy use to achieve climate neutrality – defined as "net-zero emissions" or "emissions balanced by removals" – by 2050. This goal is central to the European Green Deal, which affirms the Union's commitment to global climate initiatives under the Paris Agreement (see infra note 8 and accompanying text). To meet its climate neutrality target, EU Regulation 2021/1119 establishes a binding objective to reduce net greenhouse gas emissions by at

Plan on Climate Change in 2008, which formally introduced Brazil´s “Green Growth” strategy emphasizing the need to reduce greenhouse gas emissions and support clean energy technologies,[5] which was further detailed in the MME’s 2020 Decennial Plan for Energy Expansion - DPEE 2020, presented in 2011.[6]

The 2007-adopted Brazilian National Energy Plan 2030 (PNE 2030) demonstrated a continuing commitment by Brazil to diversifying its energy matrix by prioritizing renewable sources such as wind potential, solar energy and biomass[7] and on September 12, 2016, Brazil, one of the 194 signatory states and the EU of the 1992-established United Nations Framework Convention on Climate Change (UNFCCC), ratified its adoption of the Paris Agreement,[8] committing to reduce economy-wide greenhouse gas emissions by 37% below 2005 levels by 2025, increase renewable

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least 55% by 2030 compared to 1990 levels. Regulation (EU) 2024/1735 of the European Parliament and of the Council of June 13, 2024, available at https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=OJ:L_202401735.

[5] Amazon Environmental Research Institute - IPAM, Website, *What is the objective of the National Plan and Policy on Climate Change created in Brazil?*, available at https://ipam.org.br/entenda/qual-e-o-objetivo-do-plano-e-da-politica-nacional-sobre-mudanca-do-clima-criados-no-brasil/.

[6] Ministry of Mines and Energy (MME), 2020 Decennial Plan for Energy Expansion - DPEE 2020, Final Report, (Nov. 2011), available at https://www.epe.gov.br/sites-pt/publicacoes-dados-abertos/publicacoes/PublicacoesArquivos/publicacao-51/topico-88/Relat%C3%B3rio%20Final%20do%20PDE%202020.pdf.

[7] Ministry of Mines and Energy (MME), Brazilian National Energy Plan 2030, (Nov. 2007), available at https://www.gov.br/mme/pt-br/assuntos/secretarias/sntep/publicacoes/plano-nacional-de-energia/plano-nacional-de-energia-2030/relatorio-final/plano-nacional-de-energia-2030-pdf.pdf/@@download/file. The PNE 2030 was a long-term strategy for ensuring a sustainable, affordable and secure electricity supply nationally. It projected electricity demand and supply over the next 10 to 20 years, identifying needs for expanding generation, transmission and distribution, promoting a diversified, cleaner energy matrix by prioritizing renewable sources such as wind potential, solar energy and biomass, while also focusing on energy efficiency, technological innovation and job creation. Energia que Inova, Website, Publications, Kleyson Carvalho, *Trends and Perspectives of the National Electric Energy Plan (PNE)*, (Jul. 18, 2023), available at https://energiaqueinova.com/en/publicacoes/tendencias-e-perspectivas-do-plano-nacional-de-energia-eletrica-pne/.

[8] The Paris Agreement, a legally binding international treaty addressing climate change, was adopted during the UN Climate Change Conference (COP21) held in Paris, France, on December 12, 2015, and became effective on November 4, 2016. The overarching objective of the Paris Agreement is to restrict global warming to "well below" 2°C above pre-industrial levels, and ideally limit the temperature increase to 1.5°C. To achieve this 1.5°C target, global greenhouse gas emissions must peak by 2025 at the latest and then be reduced by 43% by 2030. United Nations Framework Convention on Climate Change (UNFCCC), The Paris Agreement, available at https://unfccc.int/process-and-meetings/the-paris-agreement.

resources to 45% of the energy mix by 2030 and increase the share of non-hydropower renewables in the electricity mix to 23% by 2030.[9]

The 2017-enacted Federal Law No. 13.576 established the RENOVABIO policy whereby distributors of fossil fuels are required to purchase decarbonization credits (CBIOs) issued by producers and importers of biofuels,[10] a commitment to renewable fuels paving the way for the inclusion of other technologies.

In 2018, supported by Brazil's Ministry of Science, Technology, Innovation and Communication, as well as the International Association for Hydrogen Energy (IAHE) and other partners, the 22nd World Hydrogen Energy Conference (WHEC), was held in Rio de Janeiro. The issues the conference – themed "Power and Biomass to Hydrogen" – addressed included hydrogen in internal combustion engines, hydrogen storage alloys, applications of hydrogen and fuel cells and the use of hydrogen as a vector for developing renewable fuels for aviation. Additionally, discussions covered the use of natural resources and biomass for hydrogen production,[11] setting the stage for the 2020 Brazilian National Energy Plan 2050 (PNE 2050) initiative aimed at integrating hydrogen into Brazil's energy strategy.

As defined under PNE 2050, hydrogen – a "disruptive technology" with significant potential but with uncertainty about how and when it will be incorporated into the existing energy system as well as what specific developments will follow[12] – is a versatile energy carrier that can be used in various industrial processes. With

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[9] In their Nationally Determined Contributions (NDCs), signatory countries delineate the measures they intend to implement to reduce greenhouse gas emissions in accordance with the objectives of the Paris Agreement. Brazil's current NDC targets a reduction of greenhouse gas emissions by 53% (equivalent to 1.2 gigatons of CO2) by 2030, with a goal of achieving net-zero emissions by 2050 via balancing emissions with the removal of greenhouse gases from the atmosphere, particularly through the carbon sequestration capacity of forests. Federative Republic of Brazil Nationally Determined Contribution (NDC) to the Paris Agreement Under the UNFCCC, (Oct. 27, 2023), available at https://unfccc.int/sites/default/files/NDC/2023-11/Brazil%20First%20NDC%202023%20adjustment.pdf; Ministry of the Environment and Climate Change (MMA), *NDC: Brazil's Climate Ambition*, available at https://www.gov.br/mma/pt-br/composicao/smc/plano-clima/ndc-ambicao-climatica-do-brasil.

[10] Federal Law No. 13.576 of December 26, 2017, available at https://www.planalto.gov.br/ccivil_03/_ato2015-2018/2017/lei/l13576.htm.

[11] The International Institute for Sustainable Development - IISD, SDG Knowledge Hub, *22nd World Hydrogen Energy Conference*, available at https://sdg.iisd.org/events/22nd-world-hydrogen-energy-conference/.

[12] "Disruptive technologies" are defined by the Plan as "those capable of significantly altering the energy market" but for which there are "few elements to anticipate their integration into the energy matrix and the resulting developments." Ministry of Mines and Energy (MME), Brazilian National Energy Plan 2050 (PNE 2050), Final Report, (Dec. 16, 2020), available at https://www.gov.br/mme/pt-br/assuntos/secretarias/sntep/publicacoes/plano-nacional-de-energia/plano-nacional-de-energia-2050/relatorio-final/relatorio-final/relatorio-final-do-pne-2050.pdf/@@download/file.

production methods including steam reforming, gasification and water electrolysis it can aid in decarbonizing hard-to-reduce-emission sectors, store renewable energy and enhance energy security due to its versatile production sources and wide range of applications. Technologically, hydrogen production includes gray (with greenhouse gas emissions), blue (with carbon capture and storage) and green (from renewable energy) variants. As noted by the plan, Brazil is advancing hydrogen technology through projects on hydrogen buses, vessels and water electrolysis. As identified under the plan, key issues include developing regulations, ensuring safety and building infrastructure and establishing robust regulatory frameworks and fostering international collaboration to support hydrogen's integration into the global energy landscape.[13]

In August 2022, Brazil's National Council for Energy Policy (CNPE) introduced CNPE Resolution 6, establishing the National Hydrogen Program (PNH2), aiming to advance Brazil's hydrogen sector through a comprehensive strategy of promoting research and development in hydrogen technologies, including production, storage and fuel cells and on building essential infrastructure such as production facilities and refueling stations, targeting greenhouse gas reductions, enhancing energy security and diversifying the energy mix.[14] It also emphasized international collaboration to leverage global expertise and investment and included financial provisions and incentives to attract private sector investment.[15]

In August 2023, Brazil´s MME launched the PNH2´s three-year action plan, targeting establishing pilot hydrogen plants nationwide by 2025, becoming a top global hydrogen producer by 2030 and creating hydrogen hubs by 2035.[16] Key priorities include developing a legal framework for the sector, increasing research and development investments sevenfold by 2025 and securing significant financing.[17]

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[13] Id.

[14] National Council for Energy Policy (CNPE) Resolution No. 6 of June 23, 2022, available at https://www.gov.br/mme/pt-br/assuntos/conselhos-e-comites/cnpe/resolucoes-do-cnpe/2022/Res62022.pdf.

[15] Id.

[16] Ministry of Mines and Energy (MME), National Hydrogen Program Triennial Action Plan 2023-2025, available at https://www.gov.br/mme/pt-br/assuntos/noticias/PlanodeTrabalhoTrienalPNH2.pdf.

[17] Id.

On August 2, 2024, Federal Law No. 14.948[18] was enacted, establishing, significantly, a comprehensive framework for low-carbon hydrogen[19] within Brazil's National Energy Policy. This landmark legislation creates the National Low-Carbon Hydrogen Policy and designates the National Agency for Oil, Natural Gas and Biofuels (ANP) as the regulatory authority for the low-carbon hydrogen value chain. The law introduces the Brazilian Hydrogen Certification System (SBCH), which certifies the emissions intensity of hydrogen, critical particularly for meeting export requirements and supplying clean hydrogen to European markets, which are anticipated to be significant players in Brazil's hydrogen industry. And it establishes the Special Incentive Regime for Low-Carbon Hydrogen Production (REHIDRO), which provides a five-year suspension of PIS/PASEP and COFINS taxes[20] for qualifying entities. The ANP shall oversee hydrogen activities, with support from the National Electric Energy Agency (ANEEL) in regulatory and infrastructure matters, to foster technological and industrial development in the low-carbon hydrogen sector.[21]

THE ECONOMIC POTENTIAL OF GREEN HYDROGEN IN BRAZIL

According to the McKinsey & Company November 4, 2022-dated article "The Green Hidden Gem – Brazil's Opportunity to Become a Sustainability Powerhouse,"[22] Brazil is endowed with a diverse array of renewable energy resources, including hydropower, biomass, wind potential and solar energy and, citing projections from the 2021 The United Nations Statistics Division Electric Energy Statistical Yearbook,[23] suggests that by 2040 wind potential and solar energy could represent

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[18] Federal Law No. 14.948 of August 2, 2024, available at https://www.in.gov.br/en/web/dou/-/lei-n-14.948-de-2-de-agosto-de-2024-576003914. As formally summarized in its heading the law "[e]stablishes the legal framework for low-carbon hydrogen; provides for the National Low-Carbon Hydrogen Policy; establishes incentives for the low-carbon hydrogen industry; institutes the Special Incentive Regime for Low-Carbon Hydrogen Production (REHIDRO); creates the Low-Carbon Hydrogen Development Program (PHBC); and amends Federal Laws No. 9.427 of December 26, 1996 and No. 9.478 of August 6, 1997."

[19] The law defines "low-carbon hydrogen" as hydrogen fuel or industrial input derived from various sources, which, based on life cycle analysis, has greenhouse gas (GHG) emissions that initially amount to 7 kgCO2eq or less per kilogram of hydrogen. Id.

[20] PIS/PASEP and COFINS are federal Brazilian taxes levied on a company's gross revenue, with PIS/PASEP funding employment-related benefits and COFINS supporting social security and welfare programs.

[21] Id. supra note 18.

[22] McKinsey & Company, Website, Article, *The Green Hidden Gem – Brazil's Opportunity to Become a Sustainability Powerhouse*, (Nov. 4, 2022), available at https://www.mckinsey.com/br/en/our-insights/all-insights/the-green-hidden-gem-brazils-opportunity-to-become-a-sustainability-powerhouse#/.

[23] The 2021 United Nations Statistics Division Electric Energy Statistical Yearbook includes data from 2018 to 2021 for over 200 countries and regions, detailing the production, trade

approximately 47% of the Country's total installed electricity generation capacity. This transition presents significant market opportunities, estimated at USD 5 billion in 2030 and USD 11 billion in 2040, enhancing the competitive potential of green hydrogen production.[24]

As noted in the 2021 McKinsey & Company report "Green Hydrogen: An Opportunity to Create Sustainable Wealth in Brazil and the World," Brazil ranks seventh globally in energy generation and sources 85% of its energy from renewables, positioning the country competitively in green hydrogen production.[25] Projected levelized costs for green hydrogen could fall below USD 1.50 per kilogram by 2030 and approximately USD 1.25 per kilogram by 2040.[26]

As highlighted in the McKinsey report, the focus on green hydrogen in Brazil is bolstered by both hydrogen production national advantages and international economic opportunities. Domestically, eleven major applications for hydrogen are identified for Brazil, including its use in steel production and fertilizers, decarbonizing passenger vehicles, long-distance rail freight, road freight (including mining trucks), as well as heating for industrial processes, combined cycle turbines for electricity and blending with natural gas for residential and commercial use.[27]

Domestic hydrogen demand could reach approximately 9 million tons by 2040, accounting for 5-10% of the country's energy matrix, if carbon pricing financial cost on carbon emissions is implemented, or approximately 7 million tons without carbon pricing.[28] Additionally, hydrogen fuel cells are projected to achieve cost parity with diesel engines in the trucking sector before 2030, which would accelerate their adoption in the industry.[29]

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and consumption of various energy source – solid, liquid and gaseous fuels, electricity and heat – along with per capita consumption statistics.

[24] Id. supra note 22.

[25] McKinsey & Company, Website, Report, *Green Hydrogen: An Opportunity to Create Sustainable Wealth in Brazil and the World*, (Nov. 25, 2021), available at https://www.mckinsey.com/br/en/our-insights/hidrogenio-verde-uma-oportunidade-de-geracao-de-riqueza-com-sustentabilidade-para-o-brasil-e-o-mundo.

[26] Id. According to The World Bank, presently, the cost of green hydrogen is approximately USD 4 to 5 per kilogram at optimal locations, which is two to three times higher than the production costs of gray hydrogen, derived from fossil fuels, or blue hydrogen, which is produced from natural gas with carbon capture and storage support. The World Bank Group, Website, Blog, *Unleashing the Power of Hydrogen for the Clean Energy Transition*, (Apr. 21, 2023), available at https://blogs.worldbank.org/en/energy/unleashing-power-hydrogen-clean-energy-transition.

[27] Id. supra note 25.

[28] Id.

[29] Id.

On the international front, Brazil has the potential to secure USD 1-2 billion from hydrogen exports to the U.S. and EU markets by 2030, with projections for exports expanding to USD 4-6 billion or 2-4 million tons of green hydrogen by 2040.[30] These exports would benefit from competitive landed costs in these regions, further solidifying Brazil's position in the global hydrogen market.[31]

BRAZIL'S GREEN HYDROGEN PROJECTS: CURRENT STATUS AND FUTURE PROSPECTS

Operational Projects

Brazil's green hydrogen sector is presently evolving with a diverse portfolio of projects at various stages of development. Operational projects include The Federal University of Rio de Janeiro (UFRJ)'s green hydrogen pilot project in Rio de Janeiro and PTI/Furnas' certified green hydrogen production using hydropower in Itumbiara, Goiás, both set to advance through 2025.

Launched in 2022, in collaboration with the German Agency for International Cooperation, the UFRJ Solar Energy and Green Hydrogen Laboratory uses nine AEM (Anion Exchange Membrane) electrolysers to produce high-purity (99.999%) green hydrogen, stored at 400 bar pressure.[32] This project is intended to demonstrate hydrogen production from photovoltaic (solar) energy and its use in fuel cells, and explores applications in urban mobility with hydrogen bicycles and as a substitute for natural gas, aiming to establish "a scalable model for clean energy solutions."[33]

The Itumbiara renewable hydrogen plant, operated by the Eletrobras Furnas hydroelectric facility in the state of Minas Gerais (bordering the state of Goias), Brazil's first operational renewable hydrogen facility,[34] has its energy sourced from

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[30] Id.

[31] Id.

[32] One bar is approximately equal to atmospheric pressure at sea level. Four hundred bar stands for approximately 5,800 psi. Such high pressure is essential for efficiently storing (and transporting) hydrogen. Hydrogen can be stored in two primary forms: as a gas or a liquid. Gas storage necessitates high-pressure tanks, typically operating at 350 to 700 bar (approximately 5,000 to 10,000 psi). In contrast, liquid hydrogen storage requires cryogenic temperatures, as hydrogen's boiling point at one atmosphere pressure is -252.8 °C (-423.04 °F). Additionally, hydrogen can be stored through adsorption on solid surfaces or absorption within solid materials. U.S. Department of Energy, Website, Office of Energy Efficiency & Renewable Energy, Hydrogen and Fuel Cell Technologies Office, *Hydrogen Storage*, available at https://www.energy.gov/eere/fuelcells/hydrogen-storage.

[33] H2 Core Systems GmbH, Website, Products, Use Cases, *The Federal University of Rio de Janeiro*, available at https://www.h2coresystems.com/en/h2c_usecase/universidade-federal-do-rio-green-hydrogen-decarbonizing-the-amazon/.

[34] Furnas, Website, News*, Renewable Hydrogen Plant of Eletrobras in Itumbiara Receives Certification from the Electric Energy Commercialization Chamber - The Itumbiara Plant was*

an 800 kWp (kilowatt peak power capacity) photovoltaic system alongside a hydroelectric power station.[35] Its Hydrogen Energy Storage System consists of three main components: an electrolyzer with a maximum capacity of 51 Nm^3/h at 27.5 barg for hydrogen production, a pressurized reservoir with a 30 m^3 volume and 27.5 barg pressure (storing up to 825 Nm^3 of hydrogen), and a fuel cell assembly that generates 300 kW of electricity.[36]

Inaugurated in December 2021, it is a pilot project aimed at advancing hydrogen technologies for decarbonizing agriculture, industry and transportation.[37] Initially, it evaluated and analyzed hydrogen production, storage and conversion to electricity and integrated this energy into the National Interconnected System (SIN).[38] Its subsequent Operation and Maintenance (O&M) phase has focused on developing procedures and conducting continuous efficiency tests for hydrogen production and conversion.[39] Since its launch, it has produced over 3 tons of hydrogen, with a daily capacity of 100 kg.[40] The project aims for scalability and in November 2023 received Brazilian Electric Energy Commercialization Chamber (CCEE) certification.[41]

The Portuguese EDP Group is also progressing on a pilot project at the Pecém Port in São Gonçalo do Amarante, Ceará. Collaborating with the German NEA Group company Hytron Energy and Gas, the Federal University of Rio de Janeiro Electric Sector Study Group (GESEL), the Advanced Institute of Technology and Innovation (IATI) in Recife and ANEEL, the project utilizes wind potential, a 3 MW solar PV unit, and an electrolyzer to produce 250 Nm^3/h of hydrogen as part of a broader initiative within the Pecém Thermal Complex aimed at advancing scalable renewable hydrogen production.[42]

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the First to Start Operating in Brazil, (Nov. 8, 2023), available at https://www.furnas.com.br/noticia/103/noticias/3052/planta-de-hidrogenio-renovavel-da-eletrobras-em-itumbiara-re.

[35] MDPI, Open Access Article, Anna Beatriz Barros Souza Riedel et. al., *Technical-Economic Analysis of Renewable Hydrogen Production from Solar Photovoltaic and Hydro Synergy in a Pilot Plant in Brazil*, (Sept. 9, 2024), available at https://www.mdpi.com/1996-1073/17/17/4521.

[36] Id. (A normal cubic meter is defined as 1,000 liters at a temperature of 0 degrees Celsius and a pressure of 1 bar gauge, which corresponds to an absolute pressure of 2 bar.).

[37] Id. supra note 34.

[38] Id.

[39] Id.

[40] Id.

[41] Id. Parenthetically, the CCEE issued its first hydrogen certification in December 2022.

[42] Companhia de Desenvolvimento do Complexo Industrial e Portuário do Pecém - CIPP S/A, Website, Industrial Area, News, *The First Green Hydrogen Molecule Produced in Brazil is Launched in Ceará*, (Jan. 20, 2023), available at

Likewise evolving is the CH2V Green Hydrogen Center, a green hydrogen production and refueling station developed by the Federal University of Itajubá (UNIFEI) in Itajubá, Minas Gerais. The facility features a 300 kW PEM (Polymer Exchange Membrane) electrolyzer, hydrogen storage vessels a refueling dispenser and a fuel cell assembly, designed to produce green hydrogen at a rate of 60 Nm^3/h, and which collaborators include the German Agency for International Cooperation (GIZ) and the German Federal Ministry for Economic Cooperation and Development (BMZ).[43]

Feasibility Assessment and Initial Planning of Major Future Projects

The feasibility and early planning of major future projects include a 2021 Memorandum of Understanding (MoU) between Fortescue Future Industries Pty Ltd (FFI) and the state of Ceará,[44] which was extended in 2022 for an additional 20 years to develop a green hydrogen production facility in the Pecém Industrial and Port Complex. This project aims to potentially launch large-scale production by 2027, targeting the production of 837 tons of green hydrogen daily using 2,100 MW of renewable energy, with an anticipated investment of USD 5 billion and a final investment decision expected this year 2024.[45] The thermoelectric Pecém II

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https://www.complexodopecem.com.br/primeira-molecula-de-hidrogenio-verde-produzida-no-brasil-e-lancada-no-ceara/#:~:text=A%20planta%20de%20Hidrog%C3%AAnio%20Verde,250%20Nm3%2Fh%20do%20g%C3%A1s.

[43] Universidade Federal de Itajubá (UNIFEI), CH2V, Website, *The CH2V*, available at https://ch2v.unifei.edu.br/o-ch2v/.

[44] As of January 1, 2024, over 30 agreements have been established by Ceará with national and international partners, signaling investments exceeding USD 30 billion. Of these, four pre-contracts have been signed, with projected investments totaling USD 8 billion. The Government of Ceará has already signed Memoranda of Understanding with the following entities: Enegix Energy, White Martins/Linde, Qair, Fortescue (pre-contract), Eneva, Diferencial, Hytron, H2helium, Neoenergia, Engie, Transhydrogen Alliance, Total Eren, AES Brasil (pre-contract), Cactus Energia Verde (pre-contract), Casa dos Ventos (pre-contract), H2 Green Power, Comerc Eficiência, Enel Green Power, HDF, Mitsui, ABB, Gold Wind, Alupar, Mingyang Smart Energy, Spic, Gansu Science & Technology Investment, PowerChina, Platform Zero (Pecém Complex + 13 institutions from five countries), Green Hydrogen Corridor (Pecém Complex, AES Brasil, Casa dos Ventos, Comerc Eficiência, Havenbedrijf Rotterdam, Fortescue, and EDP), Voltalia, Lightsource bp, EDF Renewables, GoVerde, Hitachi and Jepri. Government of the State of Ceará, Website, Renewable Energies, Joanna Cruz, *With Great Potential in Renewable Energies, Ceará is Becoming the House of Green Hydrogen*, (Jan. 1, 2024), available at https://www.ceara.gov.br/2024/01/01/com-grande-potencial-em-energias-renovaveis-o-ceara-esta-se-tornando-a-casa-do-hidrogenio-verde/.

[45] Fortescue Future Industries, Website, News, *Fortescue Future Industries and the State of Ceará Reinforce Joint Commitment to Develop Green Hydrogen Project at COP27*, (Nov. 10, 2022), available at https://fortescue.com/news-and-media/news/2022/11/14/fortescue-future-industries-and-the-state-of-cear%C3%A1-reinforce-joint-commitment-to-develop-green-hydrogen-project-at-cop27; Empresa Brasil de Comunicação - EBC, Agência Brasil, General, *Australian Company to Produce Green Hydrogen in Brazil - Fortescue Plans to Invest $5 Billion in an Industrial Complex in Ceará*, (Oct. 11, 2023), available at

Substation shall connect renewable electricity from the National Grid to support Fortescue's green hydrogen facility.[46] Most likely similar to Fortescue's Brisbane Australia Gibson Island Green Hydrogen and Ammonia Project, the facility shall generate green hydrogen through electrolysis and supply it to a nearby ammonia plant to produce green ammonia for storage and export, with water for the operation shall be sourced from a mix of desalinated (in this case) and purified recycled sources.[47]

Also in 2021, Qair Brasil, a subsidiary of the French company Qair Internacional, signed a Memorandum of Understanding with the state of Ceará to invest USD 6.95 billion in a green hydrogen initiative. This initiative includes the development of the 1,216 MW Dragão do Mar offshore wind park, with a USD 3 billion investment, and a 2,240 MW electrolysis plant, which shall account for the remaining USD 3.95 billion, together aiming to produce 296,000 tons of green hydrogen annually.[48]

On June 6, 2023, Petrobras announced that it has signed a non-binding, two-year confidentiality agreement with Unigel Participações S.A., a key player in the chemical sector and Brazil's largest nitrogen fertilizer producer. The agreement aims to explore joint ventures in fertilizers, green hydrogen and low-carbon projects, in line with Petrobras's revised Strategic Plan for 2024-2028.[49]

TECHNOLOGICAL AND INFRASTRUCTURAL CHALLENGES TO GREEN HYDROGEN PRODUCTION

Brazil is strategically positioned to emerge as a prominent player in the global green hydrogen market, owing to its substantial renewable energy potential, particularly from solar energy and wind potential resources. However, unlocking this promise necessitates meeting a host of formidable technological and infrastructural obstacles headfirst. In this respect, it is necessary to first understand the fundamental problems

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https://agenciabrasil.ebc.com.br/en/geral/noticia/2023-11/australian-company-produce-green-hydrogen-brazil.

[46] Megawhat Energy, News, Hydrogen, Maria Clara Machado, *Fortescue and Solatio's Hydrogen Projects Receive Approval for Grid Access*, (Aug. 16, 2024), available at https://megawhat.energy/destaques-do-diario/projetos-de-hidrogenio-da-fortescue-e-solatio-recebem-aval-para-aceso-a-rede/.

[47] Fortescue Future Industries, Website, What We Do, *Gibson Island Green Hydrogen and Ammonia Project*, available at https://fortescue.com/what-we-do/our-projects/gibson-island.

[48] Renewables Now, News, Wind, *Qair Brasil Signs Pact for USD 7bn Offshore Wind-based H2 Project in Ceará*, (Jul. 8, 2021), available at https://renewablesnow.com/news/qair-brasil-signs-pact-for-usd-7bn-offshore-wind-based-h2-project-in-ceara-746988/.

[49] Petrobras, Announcement, *Petrobras on Unigel*, (Jun. 6, 2023), available at https://api.mziq.com/mzfilemanager/v2/d/25fdf098-34f5-4608-b7fa-17d60b2de47d/e64543c8-470b-e604-f365-374aff0ffdaa?origin=2.

to be addressed, explore the various avenues by which the issues can be addressed and then rationally evaluate the merits and faults of relevant proposals.

Addressing the Central Problem of the Climate Crisis and the Urgent Need for Sustainable Solutions

The obvious central problem to be addressed is that of the potentially catastrophic global impact of world climate change due to the environmental pollution and damage caused by human activity.[50] The indicator that is usually quoted is the production of carbon dioxide (CO2) that is produced by the burning of fossil fuels. A ground-based observation weather station on Mauna Loa (Hawaii) established by the U.S. National Oceanic and Atmospheric Administration (NOAA) first started consistently measuring atmospheric CO2 levels in 1974. Its data show a steady increasing curve from around 330 ppm (parts per million) in 1984 to around 420 ppm in 2022.[51]

Climate change deniers often claim that there are massive natural CO2 emissions from the oceans and land. This is true, but they also uptake it. The oceans are effective sinks of CO2 and absorb approximately 31% of fossil fuel emissions.[52] The only net sources of steadily increasing CO2 are therefore due to fossil fuel emissions, and this is what is measured. The CO2 emissions into the atmosphere are rapidly rising.

In 1960, the CO2 emission into the atmosphere was reported by NASA as being over 9 billion metric tons (one ton, also known as a metric ton, is equal to 1,000 kilograms).[53] In 2023, NASA data indicated 36.8 billion tons from fossil fuel

[50] "The climate crisis has passed the point of no return – even though we had plenty of warning and could have acted earlier." United Nations, Press Release, Secretary-General Statements and Messages, No. 21173, *Climate Crisis Past Point of No Return, Secretary-General Says, Listing Global Threats at General Assembly Consultation on 'Our Common Agenda' Report*, (Mar. 10, 2022), available at https://press.un.org/en/2022/sgsm21173.doc.htm.

[51] National Oceanic and Atmospheric Administration (NOAA), Global Monitoring Laboratory, Monthly Trends in Atmospheric Carbon Dioxide (CO2), Average Mauna Loa CO2, *Atmospheric CO2 at Mauna Loa Laboratory* (Chart), available at https://gml.noaa.gov/ccgg/trends/.

[52] National Oceanic and Atmospheric Administration (NOAA), National Centers for Environmental Information, Website, Home, News, *Quantifying the Ocean Carbon Sink - Database Provides Access to Vital Quality-controlled Observations*, (Updated Jul. 19, 2024), available at https://www.ncei.noaa.gov/news/quantifying-ocean-carbon-sink.

[53] NASA, Website, Article, Matthew Conlen, *How Much Carbon Dioxide Are We Emitting?,* (Jul. 15, 2021), available at https://science.nasa.gov/science-research/earth-science/climate-science/how-much-carbon-dioxide-are-we-emitting/.

emissions, and a total emission estimate of 40.9 billion tons in 2023, when including other sources such as deforestation and extreme wildfire seasons.[54]

The thermally reflective (heat-trapping) CO2 concentration in the atmosphere raises the global temperature, and therefore of everything global, such as the oceans. The global surface temperature in 2023 was 1.2 degrees Celsius warmer than the NASA baseline level for the period 1951 to 1980, and 2023 was the hottest year on world record. Polar ice-cap melting has increased, with corresponding sea level rise. The global mean sea level has risen 9.4 cm since 1993, with a current rate of 0.42 cm/yr. This puts low-lying cities and communities at sea level at considerable storm risk.[55]

The effects of all this are well known. Recent weather conditions have been extreme, with severe floods and extended droughts and dry conditions leading to extensive forest fires. The warm sea in the Gulf of Mexico has led to the generation of hurricanes from seasonal tropical storms and has recently (October 2024) caused two severe hurricanes hitting the west coast of state of Florida in the United States within just over 1 week, with extensive flooding and hurricane damage, and at a level not seen previously.[56] The effects were severe, and with failure of insurance in many cases to cover losses.[57]

This is anticipated to be an increasingly common pattern of events worldwide and represents the fundamental worldwide problem that has to be addressed. There is no longer any dispute of this global crisis.

There is also the added problem of methane emission. Methane (CH4) is a powerful greenhouse gas, estimated to be around 80 times more influential than CO2 in trapping heat in the atmosphere over a 20-year period.[58]

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[54] NASA, Earth Observatory, *Emissions from Fossil Fuels Continue to Rise*, (Feb. 2021), available at https://earthobservatory.nasa.gov/images/152519/emissions-from-fossil-fuels-continue-to-rise.

[55] NASA, Jet Propulsion Laboratory, News, Sea Level Change, Observations From Space, Jane J. Lee, *NASA Analysis Sees Spike in 2023 Global Sea Level Due to El Niño*, (Mar. 27, 2024), available at https://sealevel.nasa.gov/news/270/nasa-analysis-sees-spike-in-2023-global-sea-level-due-to-el-nino/.

[56] World Weather Attribution, Website, Home, Storms, *Yet Another Hurricane Wetter, Windier and More Destructive Because of Climate Change*, (Oct. 11, 2024), available at https://www.worldweatherattribution.org/yet-another-hurricane-wetter-windier-and-more-destructive-because-of-climate-change/.

[57] The Guardian, Hurricane Milton, Lauren Aratani, Insurance Is Failing Hurricane Survivors: *"People Thought They Were Covered" - Flooding Is Separate From Typical US Home Insurance and Many Homeowners Are Not Adequately Covered*, (Oct. 12, 2024), available at https://www.theguardian.com/us-news/2024/oct/12/flood-insurance-hurricane-milton-helene.

[58] United Nations, Environment Programme, Story, Climate Action, *Methane Emissions Are Driving Climate Change. Here's How To Reduce Them*, (Aug. 20, 2021), available at

Fortunately, methane only lasts for around 7 to 12 years in the atmosphere, breaking down eventually as a result of hydroxyl oxidation to water and, unfortunately, CO_2 – which can persist in the atmosphere for hundreds of years.[59] Therefore, although methane emission is also a significant concern, the large overriding and long-term problem is related to the production of CO_2 in the atmosphere, which will have catastrophic consequences and which must be addressed seriously and as a top priority.

An estimated 60% of the methane emitted in the atmosphere at present comes from human activities, with the major sources being fossil fuels, agriculture and decomposition of landfill waste.[60] Methane is the essential ingredient of natural gas produced in oilfields across the world. NASA has satellite programs, and also instrumentation on the international space station, to identify the spectral signature of methane in the infrared and these programs have detected large methane emitters including large leaks from oil fields and refineries in many parts of the world, and which were subsequently fixed.[61]

The burning of natural gas in industrial processes for the generation of electricity, although considerably less polluting than the use of coal, is still producing CO_2 in large amounts. Also, the combustion of oil based and petroleum-based products in transportation and industrial processes generates enormous amounts of CO_2. Electrical energy production and transportation and the commercial burning of methane are therefore the key sources of CO_2 emission, and these are therefore the key problems that have to be urgently addressed.[62]

This article deals with the question of using hydrogen as a clean fuel that does not emit CO_2, and describes how this could be used, and outlines the production methodology for hydrogen, and the many problems that are involved in its practical use, in the context of Brazil.

Current Hydrogen Production Method Technological Challenge

Hydrogen production currently predominantly relies on three methodologies: steam methane reforming (SMR), coal gasification and electrolysis. Of these three, SMR remains the most prevalent method, utilizing high-temperature (up to 1,000 °C)

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https://www.unep.org/news-and-stories/story/methane-emissions-are-driving-climate-change-heres-how-reduce-them.

[59] NASA, Website, Climate, Vital Signs, *Methane,* available at https://climate.nasa.gov/vital-signs/methane/?intent=121#:~:text=Methane%20Basics&text=A%20molecule%20of%20methane%20traps,natural%20sources%20and%20human%20activities.

[60] Id.

[61] Id.

[62] United States Environmental Protection Agency, Website, Home, Greenhouse Gas Emissions, *Sources of Greenhouse Gas Emissions*, available at https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions.

steam to react with methane (CH4) under pressure (up to 25 bar)[63] in the presence of a catalyst, yielding hydrogen alongside carbon monoxide and carbon dioxide. While the SMR process is relatively efficient – having an energy conversion efficiency ranging between 74% and 85% – it is energy intensive and generates significant carbon dioxide emissions, raising serious environmental concerns.[64] Keep in mind that the whole reason for producing and using hydrogen is to eliminate CO2 emission.

Coal gasification transforms coal into electricity, hydrogen and other energy forms through partial oxidation rather than direct combustion. In this process, coal is combined with hot steam and controlled amounts of air or oxygen in a high temperature (up to 1,427 °C) highly pressurized (up to 1,200 psig (pounds per square inch gauge)) gasifier, producing synthetic gas (syngas) that contains carbon dioxide, hydrogen, methane, nitrogen and carbon monoxide. The syngas is purified to remove pollutants and the cleaned gas can be used to generate electricity or converted into pipeline-quality natural gas for residential use.[65] This process also significantly contributes to global CO2 emissions.[66]

Steam methane reforming (SMR) and coal gasification are the two processes employed by the fossil fuel industry. The hydrogen produced in these processes is referred to as “brown” or “black” hydrogen as compared to the production of “green” hydrogen from the electrolysis of water.[67]

The production of an overall cleaner syngas fuel by the above-described processes, although representing a very worthwhile improvement, still produces huge amounts of CO2 emission to the atmosphere that is not acceptable. It is essential that, at the point of electrical energy and natural gas production, serious efforts must be made

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[63] Elsevier B.V., ScienceDirect, Engineering, *Methane Stream Reforming*, Comprehensive Energy Systems Reference Work, Ibrahim Dincer et. al. (eds.), (2018), available at https://www.sciencedirect.com/topics/engineering/methane-steam-reforming#:~:text=Steam%20methane%2. See also supra note 32.

[64] Elsevier B.V., ScienceDirect, Energy Reports, Vol. 8, Research Paper, Hannah Hyunah Cho et. al., *Environmental Impact Assessment of Hydrogen Production Via Steam Methane Reforming Based on Emissions Data*, (Nov. 2022), available at https://www.sciencedirect.com/science/article/pii/S2352484722019874.

[65] Pepperl+Fuchs, Inc., Website, Process Automation, Technical White Paper, *The Challenges and Benefits of Coal Gasification*, available at https://files.pepperl-fuchs.com/selector_files/navi/productInfo/doct/tdoctb0d4__eng.pdf.

[66] Elsevier B.V., ScienceDirect, International Journal of Hydrogen Energy, Vol. 77, *Adoption of Advanced Coal Gasification: A Panacea to Carbon Footprint Reduction and Hydrogen Economy Transition In South Africa*, (Aug. 5, 2024), available at https://www.sciencedirect.com/science/article/abs/pii/S036031992402398X.

[67] MDPI, Open Access Article, Jose M. Marín Arcos and Diogo M. F. Santos, *The Hydrogen Color Spectrum: Techno-Economic Analysis of the Available Technologies for Hydrogen Production*, (Feb. 3, 2023), available at https://www.mdpi.com/2673-5628/3/1/2.

to capture and sequester the emitted CO2. Such efforts would make a significant contribution to solving the fundamental problem of dangerous levels of CO2 in the atmosphere.

There is extensive literature on sequestration systems developed by major energy companies. The most common method is called "carbon capture and storage" (CCS), where the CO2 is captured from the emission stacks of power plants or other industrial sources and compressed into liquid CO2 form and then deep injected underground into porous rock formations where it is trapped and stored. This is referred to as "geological carbon sequestration."[68] This type of sequestration facility involves serious capital investment, and is not a trivial undertaking, and is an undertaking for a major power plant or industrial user.[69]

For small regional power plants (as perhaps in regions of Brazil) burning fossil fuel or perhaps using natural gas (methane) to generate electrical power, the emissions (containing CO2) could be extracted and driven through scrubbers. This is familiar aeration column technology, with random structure packing material.[70] The CO2 is absorbed into down-streaming thin-layer water films to form carbonic acid which is then constantly recirculated through the scrubbers and through a filtration bed of crushed limestone to form calcium bicarbonate.[71] This represents a simple form of CO2 sequestration that would capture the CO2 emission to the atmosphere and would make a valuable contribution given that it is essential to reduce CO2 emissions by all means possible. Methane (natural gas) is a nonpolar molecule and does not dissolve in water so, unfortunately, methane cannot be trapped with such water-based scrubbers and would instead require the separate use of appropriate chemical scrubbers for effective capture.

Hydrogen production currently relies mainly on three key processes (the first two aforementioned) and Brazil is prioritizing the third method, electrolysis, to produce green hydrogen, leveraging its vast renewable energy resources, including hydropower, wind potential and solar energy. Electrolysis involves splitting water (H2O) into hydrogen (H2) and oxygen (O2) through the application of electrical energy. However, the inefficiency of this direct process presents a major obstacle.

There is ongoing effort in the development of high efficiency electrolyzers to produce hydrogen using electrolysis. Because water is not a good conductor of electricity,

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[68] FAS Project on Government Secrecy, Congressional Research Service, *Carbon Capture and Sequestration (CCS) in the United States*, (Updated Oct. 5, 2022), available at https://sgp.fas.org/crs/misc/R44902.pdf.

[69] Id.

[70] Id.

[71] U.S. Department of the Interior, USGS Publications Warehouse, Conference Paper, Abstract, W.H. Langer et. al., *Accelerated Weathering of Limestone for CO2 Mitigation Opportunities for the Stone and Cement Industries*, (2009), available at https://pubs.usgs.gov/publication/70037039.

alkaline electrolytes are used, such as KOH – potassium hydroxide, with water. This permits the transport of the hydroxyl ion (OH-) to the anode to form oxygen and hydrogen. This technology is well established, and hydrolyzer cells can be stacked to obtain capacity.[72]

The main drawbacks include the use of corrosive electrolytes, low operating current densities, low operating pressures and gas crossover. The capacity can be increased by the stacking of hydrolyzer cells, into the MW range – which represents the operational power of the electrolyzer.[73]

As an example, assuming 50kWh to produce 1kg of Hydrogen, a 10 MW electrolyzer produces 200 kg of hydrogen in an hour. Actual hydrogen production depends critically on the electrolyzer design and performance.[74]

The Polymer Electrolyte Membrane (PEM) electrolyzer design uses a solid polymer electrolyte and pure (mineral free) water instead of an alkaline liquid electrolyte. Hydrogen ions (H+) pass through the membrane, combining with electrons to form molecular hydrogen (H2) at the cathode side. There is no corrosive electrolyte and the units can operate at high current density, increasing the hydrogen production.[75] The cited efficiency of PEM electrolyzers is around 80% in working applications.[76]

One of the concerns with such PEM systems is the use of platinum and iridium, which are rare and expensive materials (particularly iridium).[77] These are rare heavy elements in the universe that are actually produced as a result of supernova events in stars[78] and it therefore seems totally unacceptable that they would be just used as electrodes in batteries, but platinum and iridium are used as catalysts in the electrolyzer. The anode is typically a catalyst made of iridium oxide with carbon black (a particulate form of carbon characterized by its black color, structure and ability to

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[72] Scielo Brasil, Quimica Nova, Diogo M. F. Santos et. al., *Hydrogen Production by Alkaline Water Electrolysis*, (2013), available at https://www.scielo.br/j/qn/a/KyQvF9DMHK6ZJXyL5zQNy7N/?lang=en.

[73] Id.

[74] Id.

[75] Senza, Website, *PEM Hydrogen Generator vs Alkaline Hydrogen Generator*, available at https://senzahydrogen.com/pem-hydrogen-generator-vs-alkaline-hydrogen-generator.

[76] Id.

[77] John Cockerill, Website, Press and News, Blog Post, *Alkaline or PEM Electrolyzers: Which Should You Choose?*, (Jul. 23, 2024), available at https://hydrogen.johncockerill.com/en/press-and-news/news/alkaline-or-pem-electrolyzers-which-should-you-choose/.

[78] University of Guelph, Website, News, Top Stories, *Earth's Heavy Metals Result of Supernova Explosion, U of G Researcher Discovers*, (Updated Jun. 18, 2019), available at https://news.uoguelph.ca/2019/06/earths-heavy-metals-result-of-supernova-explosion-u-of-g-researcher-discovers/.

conduct electricity). The oxygen evolution reaction occurs at the anode. The cathode is typically platinum supported on carbon black.[79] The concern about the use of platinum and iridium also applies to fuel cells which also utilize the PEM process approach, and this use seriously raises the system cost.

An ultra-high 95% efficiency is recently claimed for Hysata electrolyzers (Australia).[80] The Hysata capillary-fed electrolysis (CFE) cell electrolyzer is not a PEM (Polymer Electrolyte Membrane) type, is made from earth-abundant materials and does not require any platinum group metals.[81] The CFE cell concept enables direct production of hydrogen and oxygen gasses in collection chambers by using spontaneous capillary action to supply an aqueous electrolyte to the electrodes through a porous hydrophilic separator immersed in a reservoir. The gas diffusion electrodes, positioned above the electrolyte level, draw liquid from the separator and are covered by a thin electrolyte layer. When voltage is applied, water undergoes electrolysis, continuously replenished by the upward movement of water. This design allows for bubble-free electrolysis, as the generated gasses migrate through the electrolyte layer without forming bubbles, enhancing efficiency.[82]

If the planned 5 MW Hysata demonstration unit in Australia is successful, this could indicate a major cost breakthrough.[83] The Hysata project seems to be well funded and supported.[84] If successful, and acceptable in other related aspects, the Hysata electrolyzer could be a significant game changer in the large-scale production of green hydrogen at low cost.

The present installed capital cost of average PEM electrolyzers is around USD 2,000 per kW, and the current cost of hydrogen is stated to be USD 5 to USD 7 per kilogram (kg), or USD 5,000 to USD 7,000 per ton (1,000 kg).[85] On the basis of 50 kWh to

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[79] Wiley, Online Library, Open Access Article, Ajay Kumar et. al., *Surface Functionalization of Carbon Black for PEM Fuel Cell Electrodes*, (Jul. 26, 2024), available at https://onlinelibrary.wiley.com/doi/10.1002/macp.202400092?af=R.

[80] Hysata, Website, Technology, *Hysata Will Deliver the World's Lowest Cost Green Hydrogen*, available at https://hysata.com/our-technology/.

[81] Nature Communications, Article, Aaron Hodges et. al., *A High-Performance Capillary-Fed Electrolysis Cell Promises More Cost-Competitive Renewable Hydrogen*, (Mar. 15, 2022), available at https://www.nature.com/articles/s41467-022-28953-x.

[82] Id.

[83] Australian Renewable Energy Agency (ARENA), Website, Home, Projects, *Hysata "Capillary-fed" Electrolyser Commercial-Scale Demonstration Project*, available at https://arena.gov.au/projects/hysata-capillary-fed-electrolyser-commercial-scale-demonstration-project/.

[84] Id.

[85] In year 2002 USD and without subsidies. U.S. Department of Energy, DOE Hydrogen Program Record, Record #: 24005, McKenzie Hubert et. al., *Clean Hydrogen Production Cost Scenarios with PEM Electrolyzer Technology*, available at

produce 1 kg hydrogen gas per hour (the theoretical value is 39.4 kWh) a typical 5MW PEM electrolyzer would produce 100 kg per hour, or 2.4 metric tons of hydrogen per day. A typical passenger size hydrogen fuel cell powered car (Toyota Mirai – mentioned later) has fuel tank capacity of 5 kg hydrogen weight, for an operating range of 500 km (310 miles).

Energy Storage and Management

Brazil possesses favorable geographical conditions, characterized by seasonal and daily patterns of wind and solar sources and over recent years wind potential and solar energy have been integrated into the Brazilian electrical matrix, showing promising expansion capacity. Brazil has exhibited significant growth in wind and solar photovoltaic (PV) power, with installed capacities reaching 14.4 GW for wind power and 2.3 GW for solar PV. Additionally, certain regions in Brazil exhibit strong complementarity between wind potential, solar energy and water resources, which can be effectively utilized.[86]

It makes optimum long-term sense to link green hydrogen production with a green source of electrical energy. The intermittent nature of solar energy and wind potential, however, complicates stable hydrogen production. The fluctuations in electrical energy availability can disrupt hydrogen production processes, necessitating the development of hybrid systems that incorporate energy storage solutions, such as batteries, pumped hydro storage or even hydrogen storage itself. One of the significant advantages of hydrogen is that it can be stored as an available energy source. Advanced power management systems will be essential for synchronizing hydrogen production with renewable energy availability and stored energy to ensure an overall stable and reliable hydrogen supply.[87]

Capital Investment and Scalability

One of the most significant impediments to implementing a green hydrogen production strategy in Brazil is the high initial capital investment required for infrastructure and technology. The primary cost driver for on-site green hydrogen production is the present expense of renewable electricity. The upfront costs associated with electrolyzers and renewable energy production are substantial, as

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https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/24005-clean-hydrogen-production-cost-pem-electrolyzer.pdf?sfvrsn=8cb10889_1.

[86] Elsevier B.V., ScienceDirect, Utilities Policy, Vol. 67, *Combining Wind and Solar Energy Sources: Potential for Hybrid Power Generation in Brazil*, (Dec. 2020), available at https://www.sciencedirect.com/science/article/abs/pii/S0957178720300795.

[87] Elsevier B.V., ScienceDirect, Fuel, Vol. 371, Part A, Zahra Saadat et. al., *Integration of Underground Green Hydrogen Storage in Hybrid Energy Generation*, (Sept. 1, 2024), available at https://www.sciencedirect.com/science/article/pii/S0016236124010470.

has been discussed here previously. The cost of electrolysis facilities constitutes the second-largest expense in green hydrogen production.[88]

Transitioning from small-scale pilot projects to industrial-scale production will require overcoming scalability challenges. An encouraging estimation is that enhancing electrolyzer design and construction to allow for larger module sizes could cut costs by over 30% when scaling from 1 MW to 20 MW. Economies of scale could be achieved through automated production (decreasing electrolyzer stack costs from 45% to 30% at higher production rates). Addressing the scarcity of critical materials such as iridium and platinum is vital for scaling, with alternative electrolyzer technologies possibly offering solutions, as stated earlier. Additionally, learning rates (cost reductions or efficiency gains in technology as production increases and manufacturers gain experience) for electrolyzers are projected to be between 16-21%, potentially reducing costs by over 40% by 2030. Collectively, these efforts could lower green hydrogen production costs by up to 85% in the long term.[89]

Transportation and Storage

Given Brazil's vast geographic expanse, establishing an efficient transport network presents considerable challenges. The successful commercialization of hydrogen necessitates a safe and reliable delivery infrastructure. A promising prediction is that compressed gaseous hydrogen can be transported via pipelines, rail, tanker trucks or ships. However, this optimism needs to be considerably modified by cost and distance because, relatedly, high-pressure tanks and pipelines must be specifically engineered to withstand hydrogen at extreme pressures, and cryogenic storage of hydrogen (considered to be below -150°C (-238°F)) also requires cryostat design and the use of energy-intensive cooling processes.[90] The temperature of liquid hydrogen is -252.8 °C (-423.04 °F).[91]

As of 2021, the national natural gas pipeline network in Brazil spans 9,409 km and is distributed across all regions. It includes natural gas produced nationally at 16 Processing Poles, as well as imports via three international transmission pipelines and five regasification terminals for liquefied natural gas (LNG). The network consists of 265 pipelines totaling approximately 4,564 km, with 146 transfer pipelines

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[88] International Renewable Energy Agency (IRENA), Website, Publication, *Making the Breakthrough Green Hydrogen Policies and Technology Costs*, (Nov. 2020), available at https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Nov/IRENA_Green_Hydrogen_breakthrough_2021.pdf.

[89] Id.

[90] Elsevier B.V., ScienceDirect, International Journal of Hydrogen Energy, Vol. 52 Part A, Javier Sánchez-Laínez et. al., *Enabling the Injection of Hydrogen in High-pressure Gas Grids: Investigation of the Impact on Materials and Equipment*, (Jan. 2, 2024), available at https://www.sciencedirect.com/science/article/abs/pii/S0360319923025880.

[91] See supra note 32.

accounting for at least 1,765 km. These pipelines primarily serve hydrocarbon-producing regions, including the North (2 outflow pipelines), Northeast (235 outflow and transfer pipelines) and Southeast (174 pipelines of both types).[92]

The presumed intention is then to generate hydrogen (which does not emit CO2 on combustion) to significantly complement, or ideally replace, the general use of natural gas (methane) which does emit CO2 on combustion. The commercial and home consumption and burning of natural gas is a major emitter of CO2 to the atmosphere. Retrofitting existing natural gas pipelines to transport hydrogen could allow large volumes of green hydrogen to reach end users while ensuring compatibility with the infrastructure. Two transport options could then include blending hydrogen with natural gas or transporting 100% hydrogen, each requiring specialized injection facilities.

However, in reality, there are specific problems with hydrogen. Hydrogen is the smallest atom in the universe and can wind its way through lattice structures of materials. There is the very real risk of hydrogen embrittlement (whereby hydrogen permeates the metal lattice structure so that metals become brittle and fracture) especially within the high-pressure transmission network of the Bolivia-Brazil Natural Gas Pipeline,[93] as well as the direct porosity leakage risks due to hydrogen's high diffusivity (penetration capacity). Pipework and tanks therefore need to be specially epoxied or polymer lined to prevent hydrogen porosity and to be reinforced for extremely high pressures. This is all based on the assumed use of hydrogen as a fuel instead of natural gas (methane). Hydrogen therefore is not a simple direct substitution for methane. Furthermore, if the main intention is to blend hydrogen as a green gas together with methane natural gas, separation technologies might also be required in blending scenarios to ensure that end users receive appropriate energy balanced fuel mixtures.[94]

Industrial Transition

Industries such as steel, cement and chemicals are prime candidates for adopting green hydrogen, however they face significant hurdles in transitioning from fossil fuels. When comparing energy density by mass, hydrogen has a significantly higher

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[92] Ministry of Mines and Energy (MME), 2031 Ten-Year Energy Expansion Plan (English version), (Apr. 6, 2022), available at https://www.gov.br/mme/pt-br/assuntos/secretarias/sntep/publicacoes/plano-decenal-de-expansao-de-energia/pde-2031/english-version/relatorio_pde2031_cap07_eus.pdf.

[93] The Bolivia-Brazil Natural Gas Pipeline transports up to 30 million cubic meters per day of natural gas from Brazil and Bolivia through a 2,593 km pipeline that traverses the states of Mato Grosso do Sul, São Paulo, Paraná, Santa Catarina and Rio Grande do Sul. It operates at high pressure, reducing pressure near cities to facilitate delivery to Local Distribution Companies (LDC) and consumers through designated Delivery Points. Transportadora Brasileira Gasoduto Bolívia-Brasil S.A. - TBG, Website, *Our Operations*, available at https://www.tbg.com.br/en/operations.

[94] Id. supra note 90.

energy density than methane or even gasoline.[95] However, when comparing by volume (due to the low hydrogen density) hydrogen has an energy density which is only one-third that of natural gas.[96] This presents challenges in repurposing existing infrastructure. Its lower boiling point of -252.8 °C[97] says that it is a gas at all working temperatures, and this necessitates the desirability of converting hydrogen into higher-density forms, such as liquefied hydrogen (green hydrogen), ammonia, or the use of liquid organic hydrogen carriers (LOHC) or synthetic hydrocarbons, which are more suitable for long-distance transport and trade.[98]

To enable the transition to hydrogen, it is essential to significantly retrofit existing natural gas networks (see Transportation and Storage above) and develop new dedicated infrastructure, including constructing special pipelines, ports and terminals as well as cargo ships and trains for hydrogen transport. Additionally, large-scale hydrogen storage, conversion technologies and refueling stations for hydrogen-powered vehicles – such as trucks, ships, planes and trains – need to be addressed individually, but will all be necessary, along with required upgraded supply networks.[99]

Automotive Industry Transition

The automotive industry in Brazil faces its own set of challenges in transitioning to hydrogen fuel cell technology. Looking to the United States as a case study example, there are only approximately 17,000 hydrogen-powered fuel cell electric vehicles (such as the Toyota Mirai and Hyundai Nexo) currently on U.S. roads, all concentrated in California.[100] They are designed with high-pressure carbon-fiber tanks that can withstand crashes without leaking, making them comparable in safety

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[95] ResearchGate, Renewable and Sustainable Energy Reviews, Article, Kaveh Mazloomi and Chandima Gomes, *Table 2 (Volumetric and Gravimetric Energy Densities of Common Fuels), Hydrogen as an Energy Carrier: Prospects and Challenges*, (Jun. 2012), available at https://www.researchgate.net/figure/olumetric-and-gravimetric-energy-densities-of-common-fuels_tbl2_235777492.

[96] Id.

[97] See supra note 32.

[98] United Nations Industrial Development Organization (UNIDO), Green Hydrogen for Sustainable
Industrial Development - A Policy Toolkit for Developing Countries, (Dec. 2023), available at https://www.unido.org/sites/default/files/unido-publications/2024-02/Green%20hydrogen%20for%20Sustainable%20Industrial%20Development%20A%20Policy%20Toolkit%20for%20Developing%20Countries.pdf.

[99] Id.

[100] Car and Driver, Website, Essential Reads: Stories and Features, John Voelcker, *Hydrogen Fuel-Cell Vehicles: Everything You Need to Know - They're related to electric cars but have pros and cons that make them very different*, (Updated Apr. 29, 2024), available at https://www.caranddriver.com/features/a41103863/hydrogen-cars-fcev/.

to conventional vehicles, and fueling takes approximately only 5 minutes.[101] However, the hydrogen fueling infrastructure in California is limited, with fewer than 60 stations.[102]

It can basically be stated that the use of hydrogen as a fuel for the family car is totally new as far as the USA general public is concerned. California is traditionally the progressive state in the USA where the new ideas, such as hydrogen fueled vehicles, are first introduced.[103] Not unexpectedly, in California the cost of hydrogen fuel is high and there is an absence of any network of hydrogen filling stations in comparison to electric vehicles (EVs), which have a well-established charging infrastructure in California, though not across the USA as a whole. Therefore, EV's are far more appealing for most consumers there.[104]

The initial premise for EVs is also fairly straightforward. The cars use an electric motor, powered from a battery bank. There is a basic network of electrical charging stations, powered from the electricity grid, and there are also charging kits that can be used in the home garage for overnight charging of the battery bank. The cars have exceptionally good acceleration and use a large lithium-ion battery bank located underneath the car in a sealed compartment. A major manufacturer is Tesla. The popular base model Tesla Model 3 has a driving range of 272 miles (438 km) and the long-range Model 3 version has an estimated range of 363 miles (584 km).[105] The required infrastructure for the EV is built around providing a functioning network of charging stations, powered from the electrical grid. This all seems very feasible. On this basis the idea was supported that EVs are the cars of the future, with zero CO2 emission. The other car manufacturers all started providing electric vehicles in competition.

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[101] Id.

[102] Id.

[103] The state of California is firmly dedicated to decarbonizing its industries employing hydrogen. On July 17, 2024, the Alliance for Renewable Clean Hydrogen Energy Systems (ARCHES) initiative officially launched a renewable hydrogen hub, following a USD 12.6 billion agreement with the U.S. Department of Energy (DOE). Of this amount, USD 1.2 billion is specifically allocated to advance clean hydrogen projects throughout the state. The ARCHES hub is the first of seven national hydrogen hubs to formalize its partnership with the DOE, establishing a network aimed at reducing reliance on fossil fuels and supporting California's objective of achieving a carbon-neutral economy by 2045. Arches, Website, Latest News, *California´s Renewable Hydrogen Hub Officially Launches*, (Jul. 18, 2024), available at https://archesh2.org/arches-officially-launches/.

[104] Id. supra note 100.

[105] First Motors, Website, News, *400 Miles Range? New Tesla Model 3 Long Range RWD Launched -*
The Model 3 Long Range RWD is Now the Second-cheapest, Value-for-money Variant of the Popular EV, (Jul. 13, 2024) available at https://f1rstmotors.com/news/tesla-model-3-long-range-rwd.

This was expected to bring the initial high cost of EVs down, but it has not. In 2024, the Tesla Model 3 starting price is USD 38,990, and the long-range Sedan 4D Model 3 starting price is USD 42,490.[106] These vehicles are just too expensive for the average customer. EVs in the USA are now being significantly discounted and some manufacturers have stopped EV production.[107]

The main cost item is the lithium-ion battery bank. Lithium is a rare metal, with limited availability, and is expensive.[108] A replacement battery bank for a mid-sized sedan (Toyota bZ4X) costs around USD 20,000 before labor installation costs.[109] The lithium-ion battery units are expensive, and although they might last for around 10 years before total replacement is required[110] (and which may be the average vehicle life) the EV is not a product that is suitably priced for the average consumer market.

This is all mentioned in detail because it can also equally apply to hydrogen fueled vehicles, where the required infrastructure is much more complicated and difficult. That is why the previous discussions here of the very high electrolyzer costs and also fuel cell costs are all very relevant. To analyze this situation further, the Toyota Mirai hydrogen car is a good example.

Sales of the Mirai began in the USA in 2015 at a price of USD 57,500.[111] There were some later government incentives for it (a USD 8,000 federal credit and a USD 5,000 rebate for California residents) in support of the carbon free initiative.[112]

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[106] Id.

[107] CNBC, Website, Autos, *EV Euphoria is Dead. Automakers are Scaling Back or Delaying Their Electric Vehicle Plans*, (Updated on Mar. 13, 2024), available at https://www.cnbc.com/2024/03/13/ev-euphoria-is-dead-automakers-trumpet-consumer-choice-in-us.html.

[108] MDPI, Open Access Article, Shriram S. Rangarajan et. al., *Lithium-Ion Batteries - The Crux of Electric Vehicles with Opportunities and Challenges*, (Sept. 21, 2022), available at https://www.mdpi.com/2571-8797/4/4/56,

[109] Top Speed, Website, Nikesh Kooverjee, *Here's How Much It Costs To Replace A Toyota EV Battery*, (Oct. 20, 2024), available at https://www.topspeed.com/how-much-costs-replace-toyota-ev-battery/.

[110] Car and Driver, Website, Essential Reads: Stories and Features, Brendan McAleer, *Electric Car Battery Life: Everything You Need to Know, Including How Long They Last - The Battery Packs of Electric Vehicles are Quite Resilient, with the Lithium-ion type Used in Most Modern EVs Capable of Lasting at Least a Decade Before Needing Replacement*, (May 10, 2024), available at https://www.caranddriver.com/features/a31875141/electric-car-battery-life/.

[111] Green Light National, News, *Toyota's Mirai Hydrogen Fuel Cell Vehicle Priced from $57,500 in the U.S.*, available at https://www.greenlightnational.com/toyotas-mirai-hydrogen-fuel-cell-vehicle-priced-57500-u-s/.

[112] Id.

The Mirai is a small sedan and has composite fiberglass high pressure storage tanks for hydrogen. It feeds hydrogen to a fuel cell that produces electricity to drive an electric motor. There is no lithium-ion battery. It is therefore running with the hydrogen gas generating electricity from a fuel cell. Toyota has recently been promoting a supposedly new engine that is a normal-type piston (or perhaps rotary) engine that runs directly on hydrogen gas,[113] but the Mirai uses an electric motor system. This future possibility would be extremely desirable and very significant because it would eliminate the expensive fuel cell. However, preliminary tests have indicated that direct hydrogen injection engines are not as efficient as the fuel cell alternative at present,[114] and there are associated technical issues to be solved – for instance, the fact that hydrogen combustion produces water in the combustion chambers.

The Mirai´s features and specifications are quite impressive. It features a cruising range of approximately 550 km (310 miles) and a maximum speed of 178 km/h (110 mph). It is equipped with two hydrogen tanks operating at a maximum pressure of 700 bar (10,500 psi) and utilizes advanced fuel cell technology with a volume power density of 3.1 kW per liter of hydrogen, achieving a maximum output of 114 kW (155 hp). For those who need extended range, versions with three hydrogen tanks are also available.[115]

The Mirai passenger car demonstrates that hydrogen fuel cell electric vehicles (HFCEVs) are totally viable. The HFCEVs have failed in the USA at present because there is totally inadequate hydrogen supply infrastructure and the vehicle cost is too high for the average consumer – essentially for the reason already described above (the high cost of the fuel cell).

Brazil’s sugarcane-based ethanol infrastructure is well established and the industry is currently focused on ethanol-based flex-fuel vehicles (FFV)s, with over 90% of passenger cars being FFVs, which can run on either gasoline or ethanol.[116] The combustion of ethanol still produces CO2 emissions but the argument is that this is

[113] Toyota, European Website, News, *Prototype Corolla Cross Hydrogen Concept - Hydrogen Combustion is Another Important Path on the Journey to Zero Emissions*, available at https://www.toyota-europe.com/news/2022/prototype-corolla-cross-hydrogen-concept.

[114] U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy (EERE), Hydrogen and Fuel Cell Technologies Office (HFTO), H2IQ Webinar, Today’s Topic: Overview of Hydrogen Internal Combustion Engine (H2ICE) Technologies, Sandia National Laboratories, Aleš Srna, *Is There a Place for H2 Internal Combustion Engines?*, available at https://www.energy.gov/sites/default/files/2023-03/h2iqhour-02222023.pdf.

[115] Smart Circulair, Toyota Mirai FCV Poster, available at https://www.smartcirculair.com/wp-content/uploads/2020/06/Toyota-Mirai-FCV_Posters_LR.pdf.

[116] Stillwater Associates, Website, Insights, James Primrose, *Spotlight on Brazil: Global Biofuels Powerhouse*, (Sept. 19, 2014), available at https://stillwaterassociates.com/spotlight-on-brazil-global-biofuels-powerhouse/?cn-reloaded=1.

offset by the CO2 amount absorbed from the atmosphere when the crops are grown for ethanol production – namely that the emission is offset and is sustainable.[117]

There is rising controversy about this in practice. Growing crops (sugarcane in Brazil´s case) to produce ethanol is energy intensive and involves using fertilizers produced with fossil fuels.[118] The claimed benefit of ethanol flex vehicles in reducing CO2 emissions to the atmosphere is therefore rather dubious.

Brazil has also developed FFVS that operate on methane gas. These vehicles are used in taxi fleets in the major cities,[119] and there are also buses using natural gas (syngas).[120] They are operating with stored methane gas at high pressure.

Methane has a liquid boiling point of -161.49 °C and below which it is in liquid form at one atmosphere pressure.[121] Cooling methane to -161.49 °C turns it to liquid methane, and above this temperature methane is a gas – which can still be liquified at high pressures at temperatures, below -82.1 °C, which is the critical temperature of methane.[122] Above -82.1 °C there is no liquid phase, regardless of pressure – it is always gas. The required pressure at -82.1 °C to liquify methane is 46.4 bar (673.1 psi).[123]

It is necessary to cool methane to low (cryogenic) temperatures below -82.1 °C to liquify it, and methane liquifies at 1 bar when at -161.49 °C. The taxi vehicles operating on methane gas use gas stored in high pressure fuel tanks (180 to 220

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[117] U.S. Department of Energy, Energy Efficiency and Renewable Energy, Alternative Fuels Data Center, Fuels & Vehicles, *Ethanol*, available at https://afdc.energy.gov/vehicles/flexible-fuel-emissions.

[118] Renewable Fuels Association, Media & New, Blog Post, Geoff Coope, *The Truth About Ethanol and Carbon Emissions*, (Oct. 4, 2022), available at https://ethanolrfa.org/media-and-news/category/blog/article/2022/10/the-truth-about-ethanol-and-carbon-emissions.

[119] Compressed natural gas (CNG) vehicles are commonly used as taxicabs in Brazil, retrofitted from gasoline or ethanol flexible-fuel vehicles and refilled at commercial pumping stations with compressors and specialized fueling pumps in major cities such as São Paulo and Rio de Janeiro. The Regional and Urban Economics Lab of the University of São Paulo (NEREUS), Roberto Amaral-Santos et. al., *Natural Gas Vehicles: Consequences to Fuel Markets and the Environment*, (Jul. 13, 2023), available at http://www.usp.br/nereus/wp-content/uploads/TD_NEREUS_07_2023.pdf.

[120] State of Paraná Government News Agency, *Bus Powered 100% by Natural Gas Will Serve the Metropolitan Transport Line in Curitiba*, (Feb. 28, 2023), available at https://www.aen.pr.gov.br/Noticia/Onibus-movido-100-gas-natural-vai-atender-linha-do-transporte-metropolitano-de-Curitiba.

[121] Compressed Gas Association (CGA), Handbook, CH4 Methane, (Updated May 9, 2024), available at https://handbook.cganet.com/monographs/Methane.

[122] Id.

[123] One psi is equivalent to 0.0689475729 bar.

bar, 2,610 to 3,190 psi)[124] which are refilled at specifically designated filling stations that use high pressure pumps and may have supplies of stored methane in the form of liquified natural gas (LNG). Unfortunately, the use of methane gas in all these flex vehicles, as with the use of ethanol or regular gasoline, still produces full CO2 emissions into the atmosphere. The capture and sequestration of emitted CO2 remains an essential requirement that is not addressed.

The storage and transport of large volumes of gas is best performed with the gas in the liquid state. In the case of methane gas this involves cryogenically cooling it below -161.49 °C which is quite achievable with Joule Thomson effect (J-T) cooling to generate liquid methane at atmospheric pressure (using the expansion of methane gas to lower its temperature, allowing it to turn into a liquid). This liquid methane can be supplied to a storage tank that needs to be extremely well insulated thermally. Such tank arrangements are called cryostats, and these are generally dual walled systems where the inner tank is thermally isolated from the outer one by use of supporting thin stainless steel wire support frames or tubing to minimize heat transfer to the stored liquid. The space between the tanks is vacuum pumped and sealed at a high vacuum level to minimize heat transfer to the inner tank. This is the same approach as used in the familiar thermos containers for transporting hot liquids. These are cryostats. Very often there are several concentric thermally insulated tanks, some of them also cooled, to prevent external heat transferring to the inner tank containing the liquified gas. This permits liquid methane to be stored and shipped as LNG (liquified natural gas). Brazil is building the infrastructure to become an LNG exporter.[125] The major world exporters of LNG at present are the USA, Australia and Qatar.[126]

The storage and transport of liquid hydrogen is more difficult. To become liquid, hydrogen has to be at a very low temperature near the boiling point of -252.8 °C.[127] This can actually be achieved, and liquid hydrogen can be produced. The large-scale bulk storage and transport of hydrogen is then best achieved with liquid hydrogen, and this involves very effective and detailed cryogenic system design. A cryostat storage system for liquid hydrogen would require the inner storage tank to be

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[124] The pressure of CNG at fuel stations in Brazil is standardized and regulated by the National Agency of Petroleum, Natural Gas, and Biofuels (ANP) at 200 kgf/cm², with a tolerance of plus or minus 10%. National Institute of Metrology, Quality, and Technology (INMETRO), Frequent Questions, *What is the Storage Capacity of CNG in the Cylinder?*, available at https://www.gov.br/inmetro/pt-br/acesso-a-informacao/perguntas-frequentes/avaliacao-da-conformidade/servico-de-instalacao-de-gnv-em-veiculos/qual-a-capacidade-de-armazenamento-de-gnv-no-cilindro.

[125] See supra note 93 and accompanying text.

[126] Baker Institute, Edward P. Djerejian Center for the Middle East, Center for Energy Studies, Political Economy of the Arab Gulf, Conference Report, Christina Boufarah et. al., *Global Energy: Qatar's LNG Expansion*, (May 10, 2024) available at https://www.bakerinstitute.org/research/global-energy-qatars-lng-expansion.

[127] See supra note 32.

surrounded by the second tank at liquid nitrogen temperature (-196 °C)[128] and with further shieldings at low temperature and the use of high vacuum insulation between shields, and detailed thermal design to minimize heat transfer to the storage cryostat. Storage as a gas requires extremely high pressures of 350 to 700 bar (approximately 5,000 to 10,000 psi)[129] to get an adequate mass of hydrogen. Hydrogen fuel vehicles then need high pressure composite carbon fiber storage tanks to provide adequate vehicle operating range. The hydrogen fuel capacity is expressed in terms of weight (kg).

There is rising popularity of battery electric vehicles (BEVs) in Brazil – from January to June 2024, EV sales surged by 170%, driven by a 749% increase in the number of BEVs sold compared to the same period in 2023[130] – in contrast to present trends in the USA as earlier described here and is puzzling. The popularity of BEVs will pose stiff competition for potential use of hydrogen fuel cell vehicles – which in some ways is quite encouraging news, because BEVs are not emitting CO2 and other pollutants into the atmosphere – which is the primary concern with the use of all internal combustion motor vehicles. But the batteries being used are presumably lithium-ion type and the commodity price of lithium is high and the true battery manufacturing costs are difficult to hide. Also, the cars themselves are mostly small battery vehicles from China and they may be highly cost subsidized in a deliberate attempt to establish a market entry dominance in Brazil for Chinese made BEVs.[131]

That hydrogen refueling stations (HRSs) are, practically speaking, non-existent in Brazil is, however, notably, the most significant barrier to its adopting HFCEVs.[132] HFCEVs nonetheless could play an obviously important key role in decarbonizing road transport in Brazil, complementing BEVS by offering longer ranges and much greater energy density per kilogram (120 MJ/kg) than fossil fuels.[133]

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[128] Demaco, Cryogenics, Liquid Nitrogen: Characteristics, Production, and Application, available at https://demaco-cryogenics.com/cryogenics/liquid-nitrogen-characteristics-production-and-application/.

[129] See supra note 32.

[130] Adamas Intelligence Inc., Website, Frik Els, *Brazil's 2024 EV Market is a Tariff Test Case*, Sept. 3, 2024, available at https://www.adamasintel.com/brazils-2024-ev-market-is-a-tariff-test-case/.

[131] Id.

[132] Elsevier B.V., ScienceDirect, Journal of Energy Storage, Vol. 61, M. Genovese et. al., *Hydrogen Refueling Station: Overview of the Technological Status and Research Enhancement*, (May 2023), available at https://www.sciencedirect.com/science/article/pii/S2352152X2300155X.

[133] See supra note 95 and accompanying text.

In the USA there is growing interest in HFCEVs by the long-haul trucking industry.[134] The trucking industry tends to be based around trucking hubs and distribution centers, which are the perfect locations for the hydrogen refueling stations that are essential for supporting HFCEVs. The required nationwide network of HFCEV refueling stations in Brazil is therefore already largely located and defined by the existing trucking hubs that can become the sites of high-capacity hydrogen fueling stations.

The same rationale applies to other hub-based enterprises, such as public (bus and train) transportation that can locate hydrogen production and refueling facilities in hub locations.[135] The diesel engines and diesel fuel can be replaced by electric motors and fuel cells operating with hydrogen, and with no CO2 emission – exactly the same as the Toyota Mirai.[136]

REGULATORY CLARITY FOR GREEN HYDROGEN PRODUCTION IN BRAZIL

Regulatory clarity is crucial to green hydrogen production in Brazil. The promulgation of Federal Law No. 14.948, known as Legal Framework Regulating the Production of Green Hydrogen in Brazil, constitutes a considerable advancement in Brazil's regulatory landscape concerning low-carbon hydrogen production. Officially published on August 2, 2024, this legislation establishes a comprehensive legal framework designed to promote the sustainable production and utilization of hydrogen, laying the foundation for the ongoing growth and advancement of Brazil's green hydrogen sector.

Under this law, the National Agency of Petroleum, Natural Gas and Biofuels (ANP) is designated as the principal regulatory authority responsible for overseeing all

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[134] Clean Trucking, Hydrogen, David Cullen, *Hydrogen Fuel cells: Green Solution for Long-haul Trucks*, (Sept. 28, 2023), available at https://www.cleantrucking.com/hydrogen/article/15634996/hydrogen-fuel-cells-green-solution-for-longhaul-trucks.

[135] There has been a growing interest in developing a hybrid battery-dominant electric-hydrogen fuel cell plug-in city bus in Brazil, the first prototype of which was demonstrated in 2010 at the Michelin Challenge Bibendum competition in Rio de Janeiro, the second showcased during the Rio+20 conference in 2012 and the third unveiled at the Rio Olympic Games in 2016. Elsevier B.V., ScienceDirect, International Journal of Hydrogen Energy, Vol. 42, Issue 19, P.E.V. de Miranda et. al., *Brazilian Hybrid Electric-hydrogen Fuel Cell Bus: Improved On-board Energy Management System*, (May 11, 2017), available at https://www.sciencedirect.com/science/article/abs/pii/S0360319917300216. Set to begin operations in late 2024, an ethanol steam reformer (converting ethanol into hydrogen) is designed to produce 4.5 kg of hydrogen per hour for three buses and one light vehicle hydrogen refueling station at the University of São Paulo (USP). Hydrogen Industry Leaders - HIL, Website, Projects, *Brazil to Construct Ethanol-based Hydrogen Refueling Station*, available at https://hydrogenindustryleaders.com/brazil-to-construct-ethanol-based-hydrogen-refuelling-station/.

[136] See supra note 115 and accompanying text.

activities associated with the production, loading, packaging, transportation and marketing of hydrogen and its by-products. Hydrogen production and its associated by-products must be executed by companies or consortia incorporated under Brazilian law, necessitating ANP authorization. Further, the law delineates clear definitions for various types of hydrogen. “Low Carbon Hydrogen” is defined as hydrogen produced with greenhouse gas emissions levels of 7 kgCO2eq/kgH2 or lower, “Renewable Hydrogen” encompasses hydrogen derived from renewable sources and "Green Hydrogen" specifically refers to hydrogen produced via electrolysis employing renewable energy sources.

Additionally, Federal Law No. 14.948 lays the groundwork for the establishment of a National Low Carbon Hydrogen Policy, aimed at augmenting the role of low-carbon hydrogen within Brazil’s energy transition. This policy framework encompasses initiatives such as the National Hydrogen Program (PNH2), the Low Carbon Hydrogen Development Program (PHBC) and the Brazilian Hydrogen Certification System (SBCH2). The SBCH2, in particular, seeks to enhance the sustainable utilization of hydrogen through a voluntary certification process.

Moreover, the law introduces the Special Incentive Regime for Low Carbon Hydrogen Production (REHIDRO), which confers tax benefits for the sale or importation of machinery and construction materials designated for infrastructure projects related to hydrogen production.[137] Beneficiaries of the REHIDRO regime shall also be afforded the opportunity to issue incentivized debentures, thereby facilitating access to necessary capital for hydrogen projects.

A further regulatory decree shall detail the law's provisions. Additionally, the ANP will provide a definition of how it will effectively fulfill its expanded regulatory responsibilities.

CONCLUSION

Brazil has steadily advanced policies to incorporate hydrogen into its energy strategy, focusing on renewable energy and clean technologies since the early 2000s. Central to this strategy is the role of hydrogen in reducing emissions, enhancing energy security and diversifying the nation’s energy mix. With abundant renewable resources – particularly hydropower, wind potential and solar energy – Brazil is well-positioned to become a leader in green hydrogen production.

Domestically, hydrogen could serve a variety of sectors, including steel production, transportation and industrial heating. Internationally, Brazil has the potential to export millions of tons of green hydrogen by 2040, bolstering its position in the global market.

[137] The law's original provisions concerning tax credits were partially vetoed by President Lula. This was addressed in proposed Federal Bill No. 3.027/2024, sanctioned and converted into Federal Law No. 14.990 of September 27, 2024, which aims to restore and adjust the tax credit program, with a total of BRL 18.3 billion in credits to be allocated from 2028 to 2032, contingent on project qualifications and fiscal goals.

The green hydrogen sector in Brazil is progressing very practically through both operational and planned projects. Current initiatives include the Federal University of Rio de Janeiro's pilot project and the Itumbiara facility, both of which utilize solar energy and hydropower for hydrogen production, with the latter already producing over 3 tons of hydrogen. Other emerging projects, such as those at Pecém Port and the CH2V Green Hydrogen Center, aim to further harness wind potential and solar energy for hydrogen production. Looking ahead, major projects, such as Fortescue Future Industries' planned facility in Ceará, and Qair Brasil's investments in offshore wind and electrolysis plants, signal robust growth in Brazil's hydrogen sector. Petrobras is also exploring partnerships to expand production, further underscoring the sector's potential.

While Brazil is well-positioned to become a global player in the green hydrogen market, significant challenges must, however, be necessarily faced and overcome. These include high production costs, the need for technological advancements and the development of essential infrastructure. Scaling up production will require overcoming material shortages and substantial initial investments in electrolyzers and renewable energy infrastructure. Additionally, addressing the intermittency of wind potential and solar energy will necessitate the addition of stored energy capability, while the possible future transportation of hydrogen across Brazil's vast geography presents logistical challenges, including retrofitting natural gas pipelines and mitigating the actual physical risks of hydrogen embrittlement and leakage. Industries such as steel and chemicals, as well as the automotive sector, face significant hurdles in transitioning to hydrogen, with updating of infrastructure and, relative to the automotive industry, a lack of widespread individual hydrogen refueling stations that hinders and perhaps may prevent the full-scale adoption of hydrogen fuel cell vehicles. These are the initial challenges and are to be expected and overcome.

In this context, the enactment of Federal Law No. 14.948 of August 2, 2024, represents a major regulatory milestone, setting the stage for the growth and development of Brazil's green hydrogen sector. The law establishes a clear legal framework, designating the National Agency of Petroleum, Natural Gas, and Biofuels (ANP) as the primary regulatory body overseeing hydrogen activities, including production, transportation and marketing. It defines the "Low Carbon Hydrogen," "Renewable Hydrogen" and "Green Hydrogen" key types of hydrogen and introduces several initiatives, including the National Low Carbon Hydrogen Policy and the Brazilian Hydrogen Certification System (SBCH2), aimed at promoting sustainability and fostering investor confidence. The law also creates the Special Incentive Regime for Low Carbon Hydrogen Production (REHIDRO), offering tax benefits and financial incentives for infrastructure development.

Currently, the prevailing discourse surrounding green hydrogen reflects a marked tendency toward over-optimism. While Brazil's green hydrogen sector stands poised for growth, buoyed by its abundant renewable resources, realizing its full potential is no small feat and significant technological, financial and logistical real-world hurdles must be confronted head on. This being said, the new legal framework regulating the production of green hydrogen in Brazil is considered to be a significant step forward towards fostering sustainable development and attracting the investment that is essential to achieving its implementation within the Country's energy transition goals.