Challenges and Solutions for Low-Carbon Hydrogen Production in Brazil: An Analysis of Business Models and Contractual Structures

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***Abstract*— Green and low-carbon hydrogen production in Brazil faces several challenges, chiefly stemming from policy and regulatory uncertainty, dependency on external technology, market unpredictability, and necessity for infrastructure expansion. This article explores business models and contractual structures that could tackle these obstacles and foster the growth of green and low-carbon hydrogen in Brazil. By thoroughly reviewing current literature, international experiences, and practices from other sectors, the study focuses on risk mitigation strategies and the feasibility of producing green and low-carbon hydrogen and its derivatives in the national context. The results underscore the necessity for innovative business models and supportive policy measures to overcome economic barriers to green and low-carbon hydrogen production. By addressing such challenges, Brazil can position itself as a leader in the global renewable hydrogen economy, strengthening its energy resilience while contributing to international decarbonization efforts.**

Index Terms **- Green hydrogen, Electricity market, Decarbonized economy, Contracts, Renewable energy**

I. Introduction

THE energy transition aims to transform the way energy is produced, distributed, and consumed, moving away from a heavy reliance on fossil fuels and promoting the expanded use of renewable sources. One of the crucial milestones in the energy transition was the Paris Agreement, an international treaty signed by 196 countries in 2015. The goal was to limit the increase in global average temperature to below 2° Celsius above pre-industrial levels, and if possible, to 1.5° Celsius, to avoid the worst impacts of climate change.

Hydrogen is considered a key element in the energy transition, serving as a versatile energy carrier. It can be stored and transported for use as fuel for transportation and power generation, for heating buildings and industrial process, and as a feedstock for chemicals and many other products, such as those in metallurgy, steel, food, and glass industries.

Globally, in 2020, 70% of the hydrogen produced came from natural gas, while another significant part comes from coal. Only about 0.1% of hydrogen were produced by electrolysis. Of the total global production, only 10% is estimated to have had carbon capture and storage (CCUS) technologies associated with it. By 2050, the International Energy Agency (IEA) estimates 60% of hydrogen production coming from electrolysis, 38% from fossil fuels associated with CCUS, and the remain from fossil with no CCUS [1]

Numerous studies highlight Brazil as one of the most competitive countries for green and low carbon hydrogen production. By 2030, the projected cost of Brazilian green hydrogen is estimated to be between US$1.00 and US$1.50/kg of H_2. This makes it more competitive than gray hydrogen, produced from natural gas, expected to cost at the same period US$2.25/kg of H_2. For blue hydrogen, produced from natural gas with carbon capture, costs of production are approximately US$3.00/kg of H_2.[2] [3]

However, green and low-carbon hydrogen production in Brazil faces several challenges, chiefly stemming from policy and regulatory uncertainty, dependency on external technology, market unpredictability, and necessity for infrastructure expansion. [4] This article explores business models and contractual structures that could tackle these obstacles and foster the growth of green and low-carbon hydrogen.

By thoroughly reviewing current literature, international experiences, and practices from other sectors, the study focuses on risk mitigation strategies and the feasibility of producing green and low-carbon hydrogen and its derivatives in the national context.

Hydrogen Purchase Agreements (HPAs), Contracts-for-Difference (CfDs), Take-or-Pay (ToP) and Take-and-Pay (TaP) are commonly used contract structures in many sectors to address and share counterparties' risks, in order to make capital-intensive and innovative investments feasible. This article aims to explore these structures discussing their pros and cons for the feasibility of renewable hydrogen investments. Also, it is explored the latest global experience on auctions and subsidies for renewable hydrogen and the importance of the Book-and-Claim (BaC) to foster the initial investments in different parts of the world.

II. Contracts

A. Hydrogen Purchase Agreements

A Power Purchase Agreement (PPA) is a contract between two parties commonly used in the power sector. However, its structure is also appliable to many other sectors such as agriculture, real state, technology, transportation, infrastructure development, etc. They are commonly a medium or long-term agreement providing a stable revenue for sellers and price certainty for buyers. The price agreed in a PPA can be fixed or variable, and the responsibilities and obligations of each party are tailored to address the risk appetite accordingly. These contracts ensure regulatory compliance and legal clarity between the parties and are an important instrument for securing funds for new investments.

For example, for Variable Renewable Sources, PPAs can have various configurations. Recently, these contracts are shifting from delivering a fixed annual amount of energy to providing real-time on-demand, with buyers accepting some levels of intermittency. [5]

Because of the possibility of being completely tailored, Hydrogen Purchase Agreements (HPAs) negotiations can be complex and time-consuming, requiring from the parties a deep knowledge of the market, legal, and regulatory framework. Another drawback is its lack of flexibility to adapt to future changes in market and technology, which will probably occur during its lifetime.

Given the characteristics of the low-carbon hydrogen economy, HPAs, while an interesting option, could face challenges due to early stage of market maturity, pricing complexity and evolving regulations and policies. Additionally, the developing technologies for production and distribution coupled with associated uncertainties create additional layers of complexity and risk in Hydrogen Purchase Agreements.

B. Contracts-for-Difference

CfD has its origin in financial hedging, being an agreement between two parties to exchange the difference between the current price of an underlying asset (shares, currencies, commodities, indices, etc.) and its price when the contract is closed. In CfDs, there is no physical delivery of the assets. [6]

CfDs have been largely used in the energy sector in the past decades. For the electricity sector, a two-way contract for difference is a contract signed between an electricity generator and a public entity, typically the State, which sets a strike price, usually by a competitive tender. The generator sells the electricity in the market but then settles with the public entity the difference between the market price and the strike price. [7] [9]

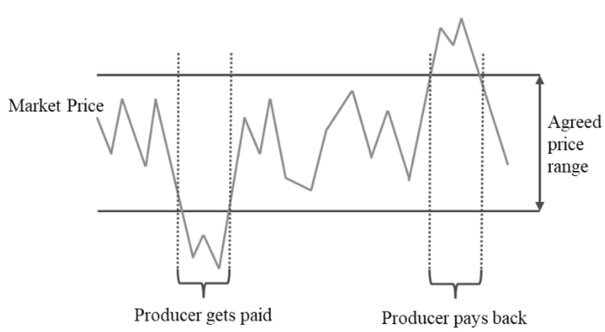

Fig. 1. CfD dynamic in the electricity market

In the electricity market, CfDs are used as a mechanism of price support for innovation and emerging technologies. In the case of offshore wind projects, for example, on average between 33% and 50% of new capacity in Europe has been financed through this mechanism over the past 15 years, in several countries bordering the North Sea. [8] [9]

CfDs can offer advantages for the low-carbon hydrogen economy development by providing price stability and revenue predictability. These contracts would set a "strike price" for low-carbon hydrogen, ensuring that producers receive consistent income even when market prices fluctuate below this threshold. This predictability could increase low-carbon hydrogen projects attractiveness to investors, thus facilitating access to financing and potentially reducing the cost of capital.

By making prices more stable, CfDs could also foster innovation and technological advancements needed to scale up production and reduce costs over time. In addition, by reviewing the use of CfDs in other markets, such as the electricity market, its use for low-carbon hydrogen markets could easily align with government policies aimed at promoting clean energy, providing a structured and scalable approach to support the hydrogen economy.

However, the use of CfDs can also present some challenges. The extensive of such mechanism can distort market dynamics, potentially crowding out other mechanisms like private HPAs or limiting financing options. [10]

Implementing and managing CfDs schemes requires significant administrative oversight, and their heavy reliance on government support means that changes in political or economic conditions can impact their sustainability. Besides, CfDs can be inflexible and lead to misalignment between set strike prices and actual market values in rapidly changing conditions. Lastly, the costs associated with CfDs payments are often passed on to consumers, then being considered a subsidy, resulting in higher energy costs or requiring substantial public funding, which could impact public acceptance and economic feasibility.

C. Take-or-Pay

ToP agreements are widely used in energy markets to address risks associated with the supply and demand of energy resources. Usually, these contracts determine the buyer to either take a predetermined amount of a product (such as natural gas, coal, or electricity) and pay for it, or, if they do not take the product, pay a specified amount as a penalty. Although these contracts clauses vary from one contract to another, its essential characteristic is the risk transfer from the seller to the buyer, in exchange of a production commitment on the seller's side. [11]

Therefore, ToP provides a level of financial security to the seller, ensuring that this part will receive payment regardless of whether the buyer takes delivery of the product. Similarly to HPAs and CfDs, ToPs are especially beneficial in infrastructure investments with significant upfront capital expenditure and operating costs, helping stabilizing revenue streams, and mitigating the financial risks associated with fluctuating demand. In the context of the energy market, ToP contracts are critical for ensuring the financial viability of large-scale projects, such as those in the natural gas and electricity sectors. [12] [13]

ToPs contracts provide significant advantages for the development of the low-carbon hydrogen market by ensuring revenue assurance and financial stability for producers by guaranteeing these would receive a fixed income, either through the sale of hydrogen or penalty payments if the buyer does not take the agreed quantity. This stability is crucial for attracting investors and securing funding for large-scale hydrogen projects, which require substantial upfront investments. Additionally, these contracts help mitigate demand fluctuation risks, enabling producers to plan and scale their operations more effectively.

However, ToPs contracts also present challenges, particularly for buyers. Buyers are obligated to pay for the low-carbon hydrogen even if their demand forecasts are inaccurate, leading to potential financial strain. This inflexibility can result in inefficiencies and wasted resources if market conditions change unexpectedly. The penalties for not taking the agreed quantity can be substantial, which may deter smaller companies from participating in the hydrogen market and limit its competitiveness and diversity.

Similarly to HPAs, the complexity of negotiating ToP contracts can pose additional hurdles. These contracts require detailed forecasting and careful balancing of interests between buyers and sellers, making the negotiation process time-consuming and costly. This complexity can delay the initiation of projects and increase transaction costs, potentially hindering the rapid development and scaling of the low-carbon hydrogen market.

D. Take-and-Pay

In a TaP contract, the buyer is obligated to take and pay for a specified quantity of goods or services. If the buyer does not take the goods or services, they must still pay a predetermined amount as damages. This ensures the seller receives payment regardless of whether the buyer accepts delivery. The contractual guarantee of delivery and payment reduces sellers' risk and provides them with a more predictable revenue stream, thus improving their ability to attract financing to develop or expand projects. [14]

One of the advantages of TaP is that buyers have a greater enforcement to accurately forecast their needs to avoid unnecessary costs. While both ToP and TaP agreements have the obligation to pay, TaPs have specific clauses to address damages if the buyer does not accept the delivery, making the acceptance and obligation and not an option.[15]

TaP clauses have been used in PPAs in the electricity sector, particularly in transitioning markets like those in Kenya and Ghana, where they help stabilize the energy supply and demand dynamics.[14]

TaP agreements can offer advantages for the development of the low-carbon hydrogen market by providing revenue stability and mitigating financial risks for suppliers, by ensuring that hydrogen producers receive payment even if the buyer does not take delivery. This predictability in cash flow encourages infrastructure investment and helps overcome initial market barriers, fostering the development of a robust clean hydrogen economy. The risk allocation between buyers and sellers can increase market confidence and support the scaling up of hydrogen production and distribution infrastructure.

However, TaP agreements can also present challenges, particularly for buyers because of the obligation to pay for hydrogen that is not used, thus imposing a significant financial burden, especially if demand forecasts are inaccurate. This risk may discourage particularly smaller buyers from entering the market, potentially limiting overall demand. There are also regulatory and policy challenges that need to be addressed to support a wider adoption of TaP in the low-carbon hydrogen market. The success of these contracts will depend on careful design and supportive policy frameworks that balance the interests of both buyers and sellers.

E. SWOT Analysis of Contract Models

Contracts, especially HPAs, CfDs, ToP, and TaP, are more than just financial tools—they are critical mechanisms for overcoming the inherent challenges in developing Brazil's low-carbon hydrogen economy. Each contract type addresses specific risks and barriers. In order to better evaluate and compare the applicable contract models, table I brings a SWOT analysis of the Contract Models discussed.

III. AUCTIONS

Globally, auctions are commonly used in the electricity sector address the procurement of several products such as supply adequacy, fostering renewables and grid services. [16] By 2020, about 116 countries had adopted auctions to support renewable energy deployment in the power sector. [17] Auctions serve as an effective mechanism for achieving price discovery, especially under conditions of uncertainty regarding the valuation of renewables-based generation. Therefore, this mechanism can be meticulously tailored to align with specific contexts or policy objectives, incorporating a range of design elements. Key components include defining auction demand, establishing qualification requirements, determining winner selection criteria, and structuring the allocation of liability and risk for sellers. [18]

Auctions have the capacity to attract both domestic and foreign private investment through their clear and transparent processes. These attributes have made auctions one of the most widely adopted instruments in the energy transition, even in countries with no prior experience in supporting renewable energy. [18] [19]

To foster investments in innovative net-zero technologies, the European Commission created in 2023 the Innovation Fund, with an estimated budget of €40 billion from the revenues of auctioning allowances under the EU Emissions Trading System (EU ETS) between 2020 and 2030. [20]

TABLE I
SWOT ANALYSIS OF CONTRACT MODELS

Strengths	Weaknesses
- **HPAs (Hydrogen Purchase Agreements):** Offer price certainty and stable revenue for hydrogen producers.	- **HPAs:** Complex and time-consuming negotiations, lacking flexibility for future market changes.
- **CfDs (Contracts for Difference):** Provide price stability, which attracts investment and reduces capital costs.	- **CfDs:** Can distort market dynamics and require significant government support.
- **ToP (Take-or-Pay Agreements):** Ensure financial security for hydrogen producers by guaranteeing revenue.	- **ToP:** Financial strain on buyers if demand forecasts are inaccurate, leading to inefficiencies.
- **TaP (Take-and-Pay Agreements):** Encourage accurate demand forecasting and provide predictable revenue streams for producers.	- **TaP:** Inflexibility and potential burden on buyers, especially in rapidly changing market conditions.

Opportunities	Threats
Global Experience: Potential to adapt successful contract structures from the energy and gas sectors to hydrogen.	Market volatility and the evolving regulatory landscape can complicate contract execution.
Government Support: Auctions and subsidies can be designed to support long-term hydrogen contracts.	Heavy reliance on government support (e.g., CfDs) may be unsustainable in changing political climates.
Scalability: Contracts can help scale hydrogen production and attract significant infrastructure investments.	Complexity of contracts may delay project initiation and increase transaction costs.

The EU ETS operates on the 'cap and trade' principle. A cap is established on the total amount of greenhouse gases that can be emitted by the installations and aircraft operators covered by the system. This cap is reduced annually to align with the EU’s climate targets, ensuring a gradual decrease in emissions over time. The diminishing cap also determines the revenues generated by the EU ETS from the sale of allowances. [21]

Since 2013, the EU ETS has generated over EUR 152 billion in revenues. The ETS Directive provides that Member States should use at least 50% of auctioning revenues or the equivalent in financial value for climate and energy-related purposes. Based on the most recent information available, around 78% of revenues in 2013-2019 were used for climate and energy related purposes. [21] [22]

The European Hydrogen Bank (EHB), introduced by the President of the European Commission in 2022, is designed to enhance the EU's renewable hydrogen production and imports. Its objectives include unlocking private investment in the EU and third countries by addressing investment barriers, bridging the funding gap, and connecting future renewable hydrogen supplies with consumers. The financial support for the EHB is channeled through the Innovation Fund.

The first auction by the EHB garnered 132 bids from 17 European countries, with demand surpassing the available €800 million budget by more than 15 times. In April 2024, the Commission allocated nearly €720 million to seven renewable hydrogen projects in Europe, selected through a competitive bidding process. These projects will collectively support 1.5 gigawatts electric (GWe) of electrolyser capacity and generate 1.58 million tons of Renewable Fuels of Non-Biological Origin (RFNBO) hydrogen over the next decade. [23]

The seven selected projects submitted bids between €0.37 and €0.48 per kilogram of RFNBO hydrogen produced and based on the pay-as-bid design of the pilot auction, will receive an Innovation Fund grant ranging between €8 million and €245 million. [23] The results of the winning bids were significantly lower than previously anticipated, presenting an unexpectedly favorable outcome for the projected green premium costs. This outcome suggests a promising future for the economic feasibility of renewable hydrogen production, indicating that market conditions and technological advancements may reduce costs more rapidly than originally forecasted.

Upon signing the grant agreement, selected projects must begin renewable hydrogen production within five years and will receive a fixed premium subsidy for up to ten years, subject to certification and verification. Additionally, Germany's "Auctions-as-a-Service" mechanism provides €350 million in national funding for top-ranked projects that meet eligibility criteria but did not qualify for EU support. [23]

The United Kingdom is developing a Hydrogen Production Business Model to support clean hydrogen projects, allocating over $2.53 billion in subsidies to 11 projects across England, Wales, and Scotland in the first auction round. These 125MW projects will receive a strike price of £241/MWh for 15 years, with subsidies varying based on natural gas prices under a CfD-style scheme. [24]

In the US, the White House Council of Economic Advisers house has issued a report addressing “The Economics of Demand-Side Support for the Department of Energy’s Clean Hydrogen Hubs,” where several initiatives are mentioned and analyzed, also mentioning the UK and EU initiatives, which are focusing on a demand-pull mechanism.[25]

In August 2023, the Interior Department's Bureau of Ocean Energy Management (BOEM) promoted the first offshore wind auction to foster the Gulf of Mexico region's green hydrogen push. [26]

Auctions present a strategic approach to foster competition and drive down costs for low-carbon hydrogen market development. Because of the competitive nature of auctions, policymakers can achieve price discovery, ensuring that the true market value of low-carbon hydrogen is established. Additionally, the transparency and fairness inherent in auction processes can attract significant private investment, both domestic and international, that are crucial for scaling up production capabilities.

However, the success of auctions in promoting low-carbon hydrogen depends on their careful design and implementation. It requires meticulous consideration of tariffs, qualification criteria, and risk allocation to ensure broad participation and competitive bidding. Moreover, auctions need to be complemented by robust policy frameworks that address infrastructure needs, as the production, storage, and transportation of hydrogen require substantial investments that auctions alone may not incentivize adequately. Policymakers must be vigilant against potential market manipulation and ensure that the regulatory framework supports the long-term sustainability and scalability of hydrogen infrastructure.

IV. Book-and-Claim

Book-and-claim is a flexible model that facilitates the transfer of verified emissions savings. It allows producers of clean fuels or materials to record (or "book") the emissions reductions of their products, while customers in different locations can then claim these reductions for their own climate disclosures. This system helps in connecting producers and consumers to decarbonize value chains, even when direct physical supply chain connections are not feasible. The approach promotes investment in sustainable fuels and materials, encouraging the production and scalability of low-emission alternatives. [27]

In the aviation industry, the book-and-claim system enables corporate consumers to purchase Sustainable Aviation Fuel (SAF) certificates, referred to as SAFc. These certificates document the verified lifecycle emissions reductions from flights using sustainable fuels, which corporations can then include in their emissions reporting. This process ensures a transparent and verifiable ownership trail. [27] [28]

Companies like Microsoft and Alaska Airlines, as well as organizations participating in initiatives like the Sustainable Aviation Buyers Alliance (SABA), use SAF certificates to meet their emissions reduction goals. [29] Logistics and Shipping Companies such as DHL use the book and claim system to purchase sustainable fuel certificates, which allows them to claim reduced emissions for their logistics operations without being limited by the physical availability of sustainable fuels at all locations. [30]

In the maritime sector the *Zero Emission Maritime Buyers Alliance* (ZEMBA) and other stakeholders in the maritime industry are exploring book-and-claim systems to pool corporate demand for decarbonized shipping and support the transition to sustainable marine fuels. [27]

The European Union is assessing the viability of a book and claim system to manage SAF and hydrogen supplies across airports. This approach aims to increase flexibility and market access while ensuring adherence to sustainability standards. The system can help airlines achieve carbon reduction targets mandated by initiatives like the European Union's RefuelEU Aviation program. [31]

Companies like Shell are pioneering blockchain-powered digital book-and-claim solutions. These systems enhance transparency and traceability, ensuring that environmental claims are credible and verifiable. Such digital platforms could be adapted to manage hydrogen transactions as well, ensuring robust and transparent reporting of sustainability attributes. [32]

The book and claim system allow enterprises to acquire carbon credits for utilizing low-carbon hydrogen, even if the hydrogen they physically use is not low-carbon. This mechanism can enhance participation in the hydrogen market by eliminating the logistical challenges associated with transporting low-carbon hydrogen to every user.[27]

By facilitating the trade of carbon credits, the book and claim system can stimulate demand for low-carbon hydrogen and mitigate investment risk for producers. This system enables producers to engage with a broader, global pool of potential buyers, thereby improving market liquidity and stability.[33]

This system reduces the necessity of physically transporting hydrogen over long distances, which can be both costly and contribute to additional carbon emissions. Through the trading of credits, the environmental benefits of low-carbon hydrogen can be realized without the emissions associated with its transportation.[34]

The book-and-claim approach are readily scalable as it relies on a virtual market for carbon credits rather than the physical infrastructure required for hydrogen transportation. This can facilitate the swift expansion of low-carbon hydrogen utilization.[27]

Industries and companies that are geographically distant from hydrogen production facilities can still participate in the low-carbon hydrogen market, thereby increasing overall demand and supporting market growth.[14]

Ensuring that carbon credits accurately represent actual reductions in carbon emissions can be challenging. Robust verification mechanisms are essential to maintain the system's integrity, though they can be complex and costly to implement.

The virtual nature of book and claim systems can lead to potential market manipulation or fraud if not adequately regulated. Companies might claim more credits than justified by their actual hydrogen usage or production.

Given that the hydrogen used by companies under this system might not be low-carbon, there may be less incentive for companies to invest in local low-carbon hydrogen production and infrastructure. This could impede the development of the necessary physical hydrogen economy.[31]

Certain stakeholders may perceive the book and claim system as less credible compared to the direct utilization of low-carbon hydrogen, potentially leading to skepticism and decreased acceptance among consumers and investors.[32]

Developing and implementing the necessary regulations to support a book and claim system can be challenging. Governments must ensure that the system is equitable, transparent, and effective in reducing emissions, which can involve significant administrative and legal efforts.

In summary, the book-and-claim system is an invaluable tool for scaling the adoption of sustainable fuels, such as hydrogen and other low-carbon products, particularly in sectors where direct procurement is challenging. By decoupling the environmental benefits from the physical products, it enables companies to support and benefit from sustainability initiatives irrespective of geographic and logistical constraints.

V. What would fit for Brazil?

Numerous studies highlight Brazil as one of the most competitive countries for green and low carbon hydrogen production. By 2030, the projected cost of Brazilian green hydrogen is estimated to be between US$1.00 and US$1.50/kg of H_2. This makes it more competitive than gray hydrogen, produced from natural gas, expected to cost at the same period

US$2.25/kg of H_2. For blue hydrogen, produced from natural gas with carbon capture, costs of production are approximately US$3.00/kg of H_2.[2] [3] Beyond the production of the hydrogen molecule itself, many other hydrogen derivatives can be produced, adding value to export products and fostering the development of green national industries, such as feedstocks (ammonia, chemicals, fertilizers, etc.) and steel, for example.

On August 2, 2024, the Law 14.948 was enacted, setting up a regulatory framework for low-carbon hydrogen production and introducing incentive mechanisms for the sector in Brazil. The new law establishes three classifications of hydrogen, which can be combined, and introduces definitions for hydrogen derivatives and carriers:

- Low-carbon hydrogen: Hydrogen fuel or industrial input with greenhouse gas (GHG) emissions, according to a life cycle analysis, of 7 kg of CO2 or less per kg of H2. Originally, the bill set the limit at 4 kg of CO2/kg of H2, but this was increased to 7 kg;
- Renewable hydrogen: Hydrogen that meets the criteria for low-carbon hydrogen and is collected as natural hydrogen or produced from renewable sources such as biofuels or through electrolysis powered by renewable energy like solar, wind, hydro, geothermal, or biomass;
- Green hydrogen: Hydrogen produced through the electrolysis of water using renewable energy sources, including solar, wind, hydro, geothermal, biomass, or other sources recognized as renewable;
- Hydrogen derivatives: Industrial products that use hydrogen, collected or produced as described above, as an input in their production process;
- Hydrogen carriers: Substances or materials that transport hydrogen for storage, conditioning, transport, or transfer purposes and release it in its original form at the destination.

The National Policy for Low-Carbon Hydrogen has been established, which provides for the granting of tax credits amounting to R$ 18.3 billion and will have its technical and economic parameters defined by the National Council for Energy Policies (CNPE) based on proposals from the Ministry of Mines and Energy (MME), with guidelines being set by the Management Committee of the National Hydrogen Program (Coges-PNH2). The National Agency of Petroleum, Natural Gas, and Biofuels (ANP) will be the competent authority for regulation and authorization. The law establishes the Brazilian Hydrogen Certification System (SBCH2), tasked with accrediting certifying companies. These companies will issue certificates for produced hydrogen, indicating the greenhouse gas emissions associated with its life cycle.

The newly enacted law, once regulated, will help foster the creation of low-carbon HPA, as well as the mechanisms previously mentioned in this work. Among the mechanisms, that are options that can be privately agreed upon between parties as well as structures for public procurement. Regarding private procurement, Brazilian industries have substantial experience in engaging in contracts with ToP and TaP clauses. These clauses, as previously discussed, could enhance the attractiveness of low-carbon hydrogen agreements by balancing risk-sharing between parties. Additionally, the internal development of certification standards for the SBCH2 may be a key driver in fostering bilateral agreements by providing clear guidelines and regulations for the emission compensation of buyers.

The early stage of infrastructure development may constrain the initial capacity for both exporting and internally transporting low-carbon hydrogen and its derivatives over long distances. Smaller-scale projects are anticipated to become more viable when situated proximate to their end-users. Conversely, larger-scale projects, owing to their significant scale, have the potential to catalyze investments in distribution and transportation infrastructure. This, in turn, is expected to enhance the dynamism and liquidity of the market in the future.

Studies shows that the domestic market is the largest opportunity, potentially generating revenue of USD 10-12 billion by 2040, primarily driven by trucking and steel, as well as other industrial energy uses. Exports to the US and Europe could add another USD 4-6 billion as the landed cost of Brazilian green hydrogen in these regions should be competitive vis-à-vis the main potential competitors. [33]

It is important to emphasize that Brazilian projects could seek access to international auctions through partnerships with foreign companies and the establishment of supply contracts with enterprises located in these markets. International alignment and the consolidation of partnerships between countries and economic blocs could facilitate this access, potentially providing subsidies. Furthermore, the book-and-claim structure discussed in Section IV may serve as another critical enabler for projects during the interim period before the infrastructure is fully developed, also potentially easing access to national and international funding mechanisms. To facilitate the implementation of the book-and-claim system, as well as to access subsidies and international mechanisms, it is crucial to establish the regulations of Law 14.948 and define the parameters and requirements of the SBCH2.

The financing of low-carbon hydrogen projects and their derivatives, including by development banks, may encounter certain challenges. Typically, the financing of capital-intensive infrastructure projects relies on medium- and long-term agreements with buyers, as discussed in Section II. Unlike the electricity and oil and gas sectors, the purchase of low-carbon hydrogen and its derivatives in today's market is usually based on shorter-term contracts and involves a more fragmented group of buyers.

Using the Brazilian fertilizer market as an example, despite Brazil's economy being heavily reliant on agricultural exports, approximately 80% of the fertilizers used domestically are imported. [34] This presents a significant opportunity for the Brazilian government to promote green fertilizers within the national agricultural sector. However, the typical short-term contracts for these products, coupled with a more fragmented client base, complicate the structuring of project finance. This divergence from standard long-term, stable-contract financing models poses a unique challenge for developing a robust financial framework to support the growth of this low-carbon hydrogen derivative in Brazil.

Although the current market design for low-carbon hydrogen does not include the execution of public auctions for the purchase of HPAs or CfDs, these structures should not be entirely dismissed in the national context. Brazil has extensive experience in conducting public auctions in the electricity sector, which have enabled the development of significant infrastructure and ensured supply adequacy. Depending on the market's evolution under the initially proposed framework, new products and structures may emerge to support its development. The primary concern with centralized contracting is the potential for cross-subsidies with other sectors. In the electricity sector, many subsidies provided in the past to promote new technologies, ensure supply security, and achieve other goals have ultimately increased tariffs excessively and reduced the competitiveness of domestic industries.

VI. Summarizing the Main Challenges and Solutions

Based on all the topics presented and discussed, a summary of the main challenges and proposed solutions for Low-Carbon Hydrogen Production in Brazil are presented below:

A. Policy and Regulatory Uncertainty

Brazil's regulatory framework for hydrogen production is still in its early stages, leading to uncertainty for investors. Without clear and cohesive regulations, there is a significant risk of project delays, unclear tax incentives, and inconsistent policies. For instance, while *Law 14.948* provides a foundation, it lacks the detailed guidelines that would foster confidence in the market.

Solution: To overcome this, Brazil needs to establish a comprehensive National Hydrogen Strategy. This strategy should provide clear guidelines for tax incentives and, eventually, subsidies, and long-term regulatory commitments. Additionally, the establishment of the Brazilian Hydrogen Certification System (SBCH2) will be crucial in standardizing emissions metrics and making the market more transparent. Contract types discussed previously can help bridge the gap during this uncertain phase by providing price and revenue stability, even in a fluctuating policy environment. By locking in long-term agreements with stable prices, HPAs can offset regulatory risks and give producers the confidence to invest in hydrogen production.

B. *Technological Dependency*

Brazil currently depends heavily on imported technologies, such as electrolysis systems and carbon capture solutions, to produce low-carbon hydrogen. This reliance increases production costs, exposes projects to global supply chain risks, and limits Brazil's ability to scale production independently.

Solution: A shift towards technological innovation and domestic strengthening of supply chain is necessary. Promoting local production for electrolysis and carbon capture solutions will not only reduce reliance on international economy dynamics but also decrease production costs in the long run. This can be facilitated through government grants, tax incentives, and partnerships with Brazilian research institutions. Furthermore, contractual structures discussed previously can encourage this innovation by providing more financial security for early adopters of new technologies. These structures ensure that hydrogen producers have a more balanced financial risk associated with adopting untested, locally developed technologies. This would incentivize local companies to invest in Research & Development while guaranteeing stable returns.

C. Infrastructure Gaps

Brazil’s infrastructure for low-carbon hydrogen storage, transportation, and distribution is insufficient to support the expected growth in production. The lack of infrastructure limits the ability to meet international demand and hinders the development of a liquid, competitive market.

Solution: A strategic prioritization of infrastructure development is crucial. The government could foster Public-Private Partnerships (PPPs) to build hydrogen corridors and storage facilities. By sharing investment risks, these partnerships can swiftly advance the establishment of vital infrastructure. Additionally, co-locating hydrogen production near industrial hubs can reduce transport needs and allow for faster scaling of projects.

D. Market Uncertainty and Financial Risks

The hydrogen market in Brazil is still in its infancy, with no established demand, especially for low-carbon hydrogen. Producers might face high upfront costs, while fluctuating global hydrogen and its derivatives prices create significant market risks. The lack of certainty in demand and price stability deters investors, who are hesitant to commit to long-term projects without guaranteed returns.

Solution: To mitigate these financial risks, Brazil can leverage initial projects based on the commercialization of carbon credits associated with the green production, similarly to the Book and Claim system used for SAF. The stability associated to a medium/long-term revenue linked to a green-premium might give producers the confidence to invest in larger-scale projects and facilitating the bankability of those projects. CfDs add an extra layer of protection by setting a “strike price” that ensures producers receive a guaranteed income even if market carbon credit prices fall. These contracts can be particularly effective when paired with subsidies and government auctions, as they provide both financial stability for producers and price predictability for buyers.

Additionally, Brazil should focus on creating a competitive domestic market for low-carbon hydrogen and its derivatives. Encouraging local industries, such as steel production, feedstock and heavy transportation, to adopt low-carbon hydrogen can create a steady internal demand. By fostering domestic demand, Brazil can reduce its reliance on volatile export markets and ensure a more consistent revenue stream for producers.

VII. Conclusions

This paper thoroughly examines the landscape of low-carbon hydrogen production in Brazil, focusing on the diverse business models and contractual frameworks necessary to overcome challenges and stimulate sector growth. Significant obstacles identified include policy and regulatory uncertainty, technological dependency, market volatility, and infrastructure expansion issues. These factors collectively impede the development and scalability of low-carbon hydrogen production.

Key business models and contractual frameworks include HPAs, CfDs, ToP, and TaP contracts. Each model presents unique advantages and limitations. HPAs offer price certainty and stable revenue but are complex and inflexible. CfDs provide price stability and revenue predictability, encouraging investment despite potential market distortion and substantial government support requirements. ToP contracts ensure financial security for producers by guaranteeing revenue, although they may impose financial strain on buyers. Take-and-Pay contracts mitigate financial risk for investors and enhance financing options, though they can lead to inefficiencies if not well managed.

The paper highlights effective global and local initiatives, such as auctions and subsidies, which have successfully promoted renewable hydrogen investments in regions like the EU, UK and the US. The book-and-claim system is presented as a flexible approach to support hydrogen market development by enabling carbon credit trading without physical hydrogen transport.

Establishing consistent and supportive regulatory frameworks at both national and international levels is crucial. Continued investment in R&D is necessary to develop and scale efficient, cost-effective hydrogen production technologies. Building a stable and predictable hydrogen market requires coordinated efforts among stakeholders, including government, industry, and financial institutions. Significant investments in infrastructure are also needed to support the production, storage, and distribution of hydrogen.

Addressing these challenges through coordinated policy measures, innovative business models, and international cooperation is essential for Brazil to emerge as a leader in the global low-carbon hydrogen economy. Such efforts will enhance energy resilience and contribute significantly to global decarbonization initiatives.

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IX. Biographies

Clarissa Petrachini Gonçalves has accumulated a decade of experience in electricity markets. Currently, she holds the position of Power Generation Manager at Czarnikow while pursuing her Ph.D. in Electrical Engineering at the University of São Paulo. She also obtained a degree and master's in electrical engineering from USP. Earlier in her career, she spent four years at EDP Brasil, focusing on Energy Planning, Risk, and Regulation. Subsequently, she worked as an Associate for Utilities' Equity Research at Citibank for 1.5 years. Later, she served as a market consultant at MRTS Consultancy for three years. Clarissa's journey reflects a consistent commitment to the dynamic field of electricity markets.

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