ERRA REPORT:

GUARANTEES OF ORIGIN & CERTIFICATION FOR HYDROGEN AND RENEWABLE GASES

ERRA GASEOUS FUELS MARKETS AND ECONOMIC REGULATION COMMITTEE

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September 2024

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ERRA Report: Guarantees of Origin & Certification for Hydrogen and Renewable Gases

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September 2024

Publishing by ERRA Secretariat

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LIST OF ABBREVIATIONS

EU	European Union
CP	Contracting Parties
EC	Energy Community
IR	International Review
P	Part

EXECUTIVE SUMMARY

This paper explores hydrogen as a visionary energy solution, focusing on its production methods, logistics, and the role of Guarantees of Origin (GO) in ensuring environmental integrity and market viability.

The introduction highlights hydrogen's growing importance in the global energy transition and the need for certification mechanisms like GOs to verify the sustainability of hydrogen production.

Hydrogen is a versatile energy carrier capable of decarbonizing various sectors, including industry, transportation, and residential energy use, while enhancing energy security.

The production section examines various methods, such as electrolysis using renewable energy and steam methane reforming with carbon capture and storage (CCS).

The paper distinguishes between "dirty" hydrogen from fossil fuels without CCS and "clean" hydrogen from renewable sources. While dirty hydrogen dominates due to cost advantages, the shift towards clean hydrogen is essential for sustainability.

Effective logistics, including storage and transportation, are critical for hydrogen's success. The paper addresses challenges and solutions for hydrogen storage, such as high-pressure tanks, underground storage, and transportation methods, including pipelines and liquefied hydrogen transport.

The importance of certification for hydrogen is emphasized, with GOs playing a pivotal role in providing transparency and credibility. GOs verify hydrogen's renewable or low-carbon nature, building consumer and investor confidence.

The paper identifies four critical attributes of GOs: traceability, ensuring that hydrogen's origin and production details are accurately tracked; tradability, allowing GOs to be bought and sold independently of the physical hydrogen; transparency, providing clear information about hydrogen's environmental credentials; and credibility, maintaining rigorous standards and independent verification.

The conclusion underscores that transitioning to a sustainable hydrogen economy requires robust infrastructure, transparent certification processes, and international cooperation. GOs ensure hydrogen's environmental integrity, supporting its adoption as a clean energy solution.

In summary, this paper highlights the transformative potential of hydrogen and the crucial role of GOs in fostering a transparent, credible, and efficient hydrogen market. Hydrogen can significantly contribute to global sustainability and energy security goals through strategic investments and collaborative efforts.

INTRODUCTION

In the modern world, the process of decarbonization is actively underway. Developed countries are increasingly taking steps to reduce fossil fuel consumption and seeking effective ways to replace it. One of the feasible and sustainable alternatives to fossil fuels is hydrogen and other types of renewable gases. The transition from fossil fuels to hydrogen and other renewable gases represents one of the crucial components of the ongoing energy transition.

The modern economy's financial burden is a significant challenge associated with the energy transition. This is unsurprising, given that transitioning from conventional fossil fuels to renewable energy requires substantial financial resources.

Therefore, in the energy transition context, the existing environmental problems related to fossil fuel use and the significant economic and financial challenges associated with replacing fossil fuels intersect. Achieving a balance between these integral aspects of the energy transition is possible through hydrogen, a "clean" fuel that, unlike fossil fuels, only produces water and heat and does not emit greenhouse gases (GHGs) into the atmosphere.[1]

Hydrogen production is not a new concept in the energy sector, as discussions on this topic have been ongoing for decades. However, recent discussions and studies on hydrogen's potential in the energy sector and the development of policies related to its integration are taking place worldwide. It is noteworthy that the European Union is particularly proactive in this regard. Various stakeholders within the European Union, including representatives from the private sector, member state governments, and relevant EU institutions, engage in active discussions. These discussions involve planning and implementing essential reforms and steps to achieve climate neutrality by 2050.

However, achieving climate neutrality is highly dependent on using only renewable hydrogen, the production of which, unlike the "dirty hydrogen", does not result in GHG emissions. Otherwise, introducing or using hydrogen will not effectively mitigate the impacts of global warming. Developing a renewable hydrogen economy requires establishing a regulatory framework that fosters the growth of this sector and attracts potential investors' interest in investing. An essential aspect of developing the renewable hydrogen economy is hydrogen certification and its guarantees of origin, which is the key focus of the preceding research.

The certification of hydrogen and the issuance of its guarantees of origin cannot be discussed without considering the various means of hydrogen production and analyzing the characteristics of these processes. The issuance of the guarantees of origin for hydrogen primarily depends on the type, form, and means of production. Therefore, Chapter 2 of this paper delves into issues related to hydrogen production, discussing the primary forms and methods of hydrogen production.

Given that the primary purpose of the certificate of origin is to inform the end user about the proportion of pure hydrogen in the hydrogen consumed, it is equally important to analyze the modes of transportation used to convey hydrogen from the production point to the end user. Non-renewable energy sources can be employed in transportation, potentially affecting the purity and quality of the hydrogen supplied to the end user. Therefore, Chapter 3 of this paper explores issues related to hydrogen transportation from the production to the final consumption point.

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[1] *Fitch G., Barbero M., Wasylenchuk K.,* Hydrogen Roadmap: Policy, Regulation and Prospect for Future Development in Alberta, 60 ALTA. L. REV. 2022, 436.

1. HYDROGEN: A VISIONARY ENERGY SOLUTION FOR TOMORROW

The imperative to increase the utilization of renewable energy sources is not a novel challenge for the modern world. However, this paper's focus is not to dwell on reiterating this necessity or emphasizing its significance. Instead, the scope of this paper needs to underscore that the transition towards renewable energy primarily aims to mitigate global warming by using carbon-neutral energy sources.

A significant hurdle in harnessing traditional renewable sources, such as solar and wind energy, is their inherent instability attributable to weather fluctuations.[2] Consequently, it is essential to explore energy sources that are characterized by stability and are simultaneously capable of meeting the demands of decarbonization. In essence, the search is for energy alternatives that remain consistent in their output, unlike solar and wind energy and do not emit greenhouse gases, like solar and wind energy. Therefore, the critical challenge to fight against global warming from the beginning was to find energy sources that possess stability, environmental friendliness, and efficiency. It is within this context that hydrogen emerged as a promising option. Hydrogen stands out due to its stable nature and lack of greenhouse gas emissions - these qualities position hydrogen as a frontrunner in pursuing sustainable energy solutions.

In the modern world, hydrogen is perceived as a highly effective alternative to replace fossil fuels, which is crucial in ensuring sustainable development for humankind.[3] Unlike fossil fuels, hydrogen consumption does not release greenhouse gases (GHGs), making it a key player in achieving carbon neutrality goals. Hydrogen is a clean energy carrier that does not emit GHGs when utilized, making it an attractive option for various applications, including transportation, heating, and electricity generation. Its versatility positions it favorably as a fuel in the automotive sector, especially for long-distance trucking.[4]

Hydrogen finds its niche in sectors where electricity or electric alternatives are currently impractical due to technological limitations.[5] Notably, it can replace fossil fuels in hard-to-abate sectors, such as heavy industries (e.g., cement, steel, and chemicals production) and heavy-duty transport (e.g., shipping, aviation). These sectors contribute to over 30 percent of global CO_2 emissions, a figure expected to double given current economic development rates.

Moreover, hydrogen stands out in energy storage, overcoming constraints linked to electricity storage.[6] Unlike conventional electricity storage methods, such as lithium-ion batteries, hydrogen offers a cost-effective solution for storing energy over extended periods. For instance, excess electricity generated from solar panels during peak production seasons, like summer, can be utilized to produce hydrogen. This hydrogen can then be stored and used to generate electricity or heat during high-demand periods,

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[2] *Lavrijssen S., Vitez B.,* Make Hydrogen whilst the Sun Shines: How to Turn the Current Momentum into a Well-Functioning Hydrogen Market, Carbon & Climate Law Review (CCLR), Vol. 14, Issue 4 (2020), pp. 266-280, 270.

[3] *Lengyel A.,* EU and domestic regulation on the production of renewable hydrogen, constitutional issues related to the domestic regulation, Journal of Agricultural and Environmental Law, 30/2021, 123.

[4] *Fitch G., Barbero M., Wasylenchuk K.,* Hydrogen Roadmap: Policy, Regulation and Prospect for Future Development in Alberta, 60 ALTA. L. REV. 2022, 437.

[5] Proposal for a Regulation of the European Parliament and of the Council on the internal markets for renewable and natural gases and for hydrogen (recast) COM/2021/804 final, 1.

[6] *Lengyel A.,* EU and domestic regulation on the production of renewable hydrogen, constitutional issues related to the domestic regulation, Journal of Agricultural and Environmental Law, 30/2021, 125.

such as winter.[7] Therefore, hydrogen facilitates energy storage and enables the utilization of renewable energy generated in one season during increased energy demand, ensuring a continuous and reliable energy supply.[8]

In addition, governments in developed countries see hydrogen as a potential driver of economic growth and a green alternative within the European Union.

In addition to the benefits linked to hydrogen use, its appeal also stems from the versatility of its production. Specifically, hydrogen can be generated through various methods and approaches, as elaborated in detail in the subsequent chapter of this paper.[9]

2. PRODUCTION OF HYDROGEN

Hydrogen is one of the most abundant elements in the universe. However, it is exceedingly rare to find pure hydrogen in its elemental form on Earth without being combined with another chemical element.[10] Typically, hydrogen only exists on Earth in combination with other elements, forming various substances. A prime example is water (H2O), which consists of Hydrogen and Oxygen. Consequently, producing hydrogen from water entails separating hydrogen from oxygen. This process of hydrogen extraction is a crucial aspect of hydrogen production.[11] Additionally, Methane can serve as an essential source of hydrogen, as one of its constituent elements is hydrogen.

Hydrogen is present in various substances, so its production necessitates separating hydrogen from other elements. This separation process can be achieved through multiple mechanisms and means. The literature indicates the existence of at least 22 different hydrogen production methods, 19 of which involve direct hydrogen production, while the remaining three yield hydrogen as a by-product during the production of other industrial goods.[12] As of 2021, Europe's hydrogen production amounted to 11.5 million metric tons, with 80 percent (9.2 million metric tons per year) being directly created for hydrogen production purposes and 20 percent (2.3 million metric tons per year) as a by-product of various industrial processes.[13]

Considering the context mentioned above, this chapter will identify the primary means and mechanisms of hydrogen production employed in modern times. This exploration is crucial because the method of hydrogen production determines the purity of the hydrogen produced and its suitability for contributing to energy transformation and achieving the net zero carbon emission goal.

In modern reality, hydrogen is mainly produced using fossil fuels such as natural gas or coal. The production of hydrogen in this way is associated with the emission of a large amount of CO_2, which is

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[7] https://www.pagerpower.com/news/green-hydrogen/

[8] *Lengyel A.,* EU and domestic regulation on the production of renewable hydrogen, constitutional issues related to the domestic regulation, Journal of Agricultural and Environmental Law, 30/2021, 125.

[9] Hydrogen – A Regulatory Approach, March 2023 (Chapter II: Production classification)..

[10] *Fitch G., Barbero M., Wasylenchuk K.,* Hydrogen Roadmap: Policy, Regulation and Prospect for Future Development in Alberta, 60 ALTA. L. REV. 2022, 436; EC, Study on the potential for implementation of hydrogen technologies and its utilization in the Energy Community, P. I: IR, June 2021, 15.

[11] *Glachant J. M., Reis P. C.,* A Snapshot of Clean Hydrogen Costs in 2030 and 2050, Florence School of Regulation, April 2021, 2.

[12] *Glachant J. M., Reis P. C.,* A Snapshot of Clean Hydrogen Costs in 2030 and 2050, Florence School of Regulation, April 2021, 3.

[13] EC, Study on the potential for implementation of hydrogen technologies and its utilization in the Energy Community, P. I: IR, June 2021, 14.

why the hydrogen obtained in this manner is referred to as high-carbon Hydrogen.[14] A common method of hydrogen production based on these primary resources is Steam Methane Reforming (SMR).

SMR involves reacting Methane with steam to produce CO_2 and Hydrogen. In most existing models using this mechanism, the separated CO_2 is completely dispersed into the atmosphere, which is why the hydrogen produced by this method is undoubtedly considered high-carbon hydrogen.[15]

SMR is the most common method of hydrogen production in modern times. As of 2021, approximately 96 percent of hydrogen was produced through SMR.[16]

Although this method is associated with relatively low costs and is characterized by cost-effectiveness, a large amount of CO_2 is released.[17] Therefore, hydrogen produced by this method is considered 'grey hydrogen' if the CO_2 released is dispersed into the atmosphere. If this process is combined with CO_2 recapture, it is called 'blue hydrogen'.[18]

Along with SMR technologies, other similar technologies also produce hydrogen using fossil fuels. Such technologies include Partial Oxidation of Hydrocarbons, Autothermal Reforming (ATR), and Gasification. These methods are well-established and widely used but come with the drawback of emitting CO_2 and other greenhouse gases during the process.

Some technologies ensure zero environmental impact when producing hydrogen using non-fossil fuels by avoiding CO_2 emissions. The leading such technology is Water Electrolysis. As of the end of 2021, there were around 500 MW of electrolysers installed worldwide for dedicated hydrogen production.[19]

In this technology, water molecules are split using electricity, producing oxygen and hydrogen. Therefore, electricity is the fundamental element of this technology. The renewable nature of the hydrogen produced through Water Electrolysis depends on the renewable nature of the electricity used in the process. Specifically, suppose the electricity used to split water molecules is produced using fossil fuels. In that case, the hydrogen cannot be considered renewable. Thus, hydrogen produced using electricity from non-renewable sources cannot be classified as green hydrogen. Hydrogen from low-carbon electricity, such as nuclear energy, is termed Low Carbon Hydrogen.

The use of electrolysis technology is associated with the principle of additionality, which implies that the creation of additional electricity generation capacity from renewable sources should accompany the production of green hydrogen through electrolysis. This is because the transition to hydrogen loses its environmental benefit if the energy used in its production generates greenhouse gases. Therefore, the additionality principle requires that the increased demand for green electricity, driven by green hydrogen production, be met by electricity generated from renewable sources, necessitating the development of additional renewable energy production capacities.

Moreover, advancements in renewable energy technologies, such as solar, wind, and hydropower, play a crucial role in the viability and sustainability of green hydrogen production. Integrating energy storage

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[14] EC, Study on the potential for implementation of hydrogen technologies and its utilization in the Energy Community, P. I: IR, June 2021, 25.

[15] EC, Study on the potential for implementation of hydrogen technologies and its utilization in the Energy Community, P. I: IR, June 2021, 29.

[16] *Erbach G., Jensen L.,* Briefing towards climate neutrality, EU hydrogen policy, 2021, 2.

[17] *Erbach G., Jensen L.,* Briefing towards climate neutrality, EU hydrogen policy, 2021, 2.

[18] *Erbach G., Jensen L.,* Briefing towards climate neutrality, EU hydrogen policy, 2021, 2.

[19] International Energy Agency (IEA), Energy Technology Perspective 2023

systems, such as batteries and pumped hydro storage, ensures a stable and reliable supply of renewable electricity for electrolysis, even during low renewable energy generation periods.

Additionally, governments and industries worldwide recognize green hydrogen's potential as a critical component of the energy transition. Policies and incentives are being implemented to support hydrogen infrastructure development, including production facilities, transportation networks, and refueling stations. International collaborations and partnerships also foster the global hydrogen economy, promoting the sharing of knowledge, technology, and best practices.

In conclusion, while traditional hydrogen production methods using fossil fuels remain prevalent, shifting towards green hydrogen through technologies like Water Electrolysis is essential for achieving a sustainable and low-carbon future. By leveraging renewable energy sources and adhering to the principle of additionality, green hydrogen can significantly contribute to reducing greenhouse gas emissions and combating climate change. Continued innovation, investment, and policy support are crucial to realizing the full potential of green hydrogen in the global energy landscape.[20]

3. "DIRTY" VS. "CLEAN" HYDROGEN

According to the means of hydrogen production or the primary energy resource used in its production, different types of hydrogen are distinguished. The approach developed in the literature distinguishes between "dirty" and "clean" hydrogen for a general classification.[21]

"Dirty" Hydrogen, often called grey or brown hydrogen, is produced using fossil fuels such as natural gas or coal without capturing the carbon emissions generated. This method, known as steam methane reforming (SMR) or coal gasification, is the most common and cost-effective way to produce hydrogen but results in significant greenhouse gas emissions. Gray Hydrogen, specifically made from natural gas, contributes substantially to global CO_2 emissions. Brown Hydrogen, derived from coal, is even more carbon-intensive, further exacerbating environmental concerns.

"Clean" Hydrogen, on the other hand, includes green Hydrogen and blue Hydrogen. Green Hydrogen is produced through water electrolysis using renewable energy sources like wind, solar, or hydropower, resulting in zero carbon emissions. This process splits water into hydrogen and oxygen, with the only by-product being oxygen, making it an environmentally friendly option. Blue hydrogen is also produced from natural gas.[22] Still, it includes carbon capture and storage (CCS) to reduce emissions, making it a lower-carbon alternative to grey hydrogen. While blue hydrogen is not entirely emission-free, it represents a transitional solution, balancing economic feasibility with environmental considerations.

Unfortunately, in modern reality, it is unanimously recognized that dirty hydrogen dominates clean hydrogen production due to its lower cost and established infrastructure. As of 2021, the vast majority of hydrogen produced across Europe is dirty, with only about 1 percent being clean.[23] This disparity highlights the economic and infrastructural challenges of scaling clean hydrogen production. The predominance of dirty hydrogen is primarily driven by the existing industrial processes and the

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[20] EPICO & Aurora Energy Research (2022). „Herkunftsnachweise für grüne Energie – Granulare Grünstromvermarktung für eine marktbasierte Energiewende", Berlin, 9.

[21] *Glachant J. M., Reis P. C.,* A Snapshot of Clean Hydrogen Costs in 2030 and 2050, Florence School of Regulation, April 2021, 2.

[22] https://www.transitionhero.nl/how-green-is-hydrogen/

[23] EC, Study on the potential for implementation of hydrogen technologies and its utilization in the Energy Community, P. I: IR, June 2021, 14.

availability of cheap fossil fuels, which have historically been prioritized over cleaner alternatives due to cost efficiency.

The transition from dirty to clean hydrogen is crucial for achieving global climate targets and reducing dependence on fossil fuels. Significant investments in renewable energy infrastructure, advancements in electrolysis technology, and supportive policies and incentives are necessary to make clean hydrogen more competitive and widespread. Governments and industries must collaborate to create a favorable economic environment for clean hydrogen. This includes subsidies for renewable energy projects, tax incentives for green hydrogen production, and stringent regulations on carbon emissions to disincentivize the continued use of dirty hydrogen.

Moreover, developing efficient and cost-effective carbon capture, utilization, and storage (CCUS) technologies is vital for the blue hydrogen pathway. By capturing and storing the CO_2 emissions generated during hydrogen production, blue hydrogen can serve as a bridge towards a fully renewable hydrogen economy. Research and development in this area are essential to improve the scalability and economic viability of CCUS technologies.

Public awareness and consumer acceptance also play a crucial role in the transition to clean hydrogen. Educating the public about the environmental benefits of green hydrogen and the long-term economic advantages of investing in sustainable energy sources can drive demand and support for clean hydrogen initiatives. International cooperation and standardization of hydrogen production, storage, and transportation methods are also necessary to create a global hydrogen market. Harmonized standards and certifications can ensure the traceability and reliability of hydrogen, promoting its adoption across different regions and industries.

In conclusion, while the current hydrogen production landscape is heavily skewed towards dirty hydrogen, efforts are underway to increase the share of clean hydrogen. Addressing economic, technological, and policy barriers aims to create a sustainable and low-carbon hydrogen economy. Transitioning to clean hydrogen is an environmental imperative and a financial opportunity, paving the way for innovation, job creation, and energy security in a decarbonized future.

4. THE LOGISTICS OF HYDROGEN

4.1 COMMENCING REMARKS

One of the main foundations for developing the hydrogen economy is the creation of appropriate infrastructure to ensure hydrogen's practical storage and transportation. The classification of hydrogen as "clean" should be influenced not only by the production methods but also by the technologies used in its storage and transportation. In other words, clean hydrogen production loses its significance if CO_2 is released into the atmosphere due to the technologies or methods employed in its storage and transportation.

The logistics of hydrogen encompass a wide range of activities and considerations, from the initial production site to the end user. This includes the development of robust and efficient storage solutions, establishing a reliable transportation network, and implementing technologies that minimize environmental impact throughout the supply chain. Additionally, hydrogen logistics play a crucial role in maintaining the integrity and transparency of Guarantees of Origin (GO) for hydrogen.

Guarantees of Origin are essential for certifying the source of hydrogen and verifying its environmental credentials. They assure consumers and stakeholders that their hydrogen is produced from renewable or low-carbon sources. Effective logistics are vital in ensuring the GO system remains reliable and trustworthy. This involves accurate tracking and documentation of hydrogen from production to end use, ensuring that the hydrogen's origin and the associated emissions are transparent and verifiable.

Proper hydrogen logistics are essential for several reasons. First, they ensure hydrogen's continuous and reliable supply to meet demand across various sectors, including industry, transportation, and energy generation. Second, efficient logistics reduce the overall cost of hydrogen, making it more competitive with conventional fossil fuels and other renewable energy sources. Third, the hydrogen supply chain can maintain its low-carbon credentials by employing environmentally friendly storage and transportation methods, essential for meeting global climate targets.

Furthermore, integrating advanced tracking and monitoring systems within the logistics framework can enhance the GO system. These systems can provide real-time data on hydrogen production, storage, and transportation, ensuring the environmental impact is minimized and accurately recorded. Blockchain technology, for example, can create immutable records of hydrogen transactions, enhancing transparency and trust in the GO system.

For this paper, it is necessary to consider issues related to hydrogen logistics comprehensively. This includes examining state-of-the-art storage technologies that can safely and efficiently store hydrogen for extended periods and innovative transportation methods that deliver hydrogen over long distances with minimal energy loss and environmental impact. The following subchapters will delve into these critical areas, providing insights into the current challenges and potential hydrogen storage and transportation solutions, focusing on how these logistics processes support and uphold the Guarantees of Origin for Hydrogen.

4.2 STORAGE

The importance of hydrogen storage is underscored by the European directive on the internal market of electricity, highlighting the necessity of storing electricity in another form of energy that can be converted back to electricity when needed. This directive implicitly acknowledges the role of hydrogen as a critical energy storage medium. During periods of excess electricity production, this surplus can be utilized to produce hydrogen through electrolysis. The hydrogen produced in this manner can then be stored and used to generate electricity when the supply is limited. (*See* ***Figure 1***)

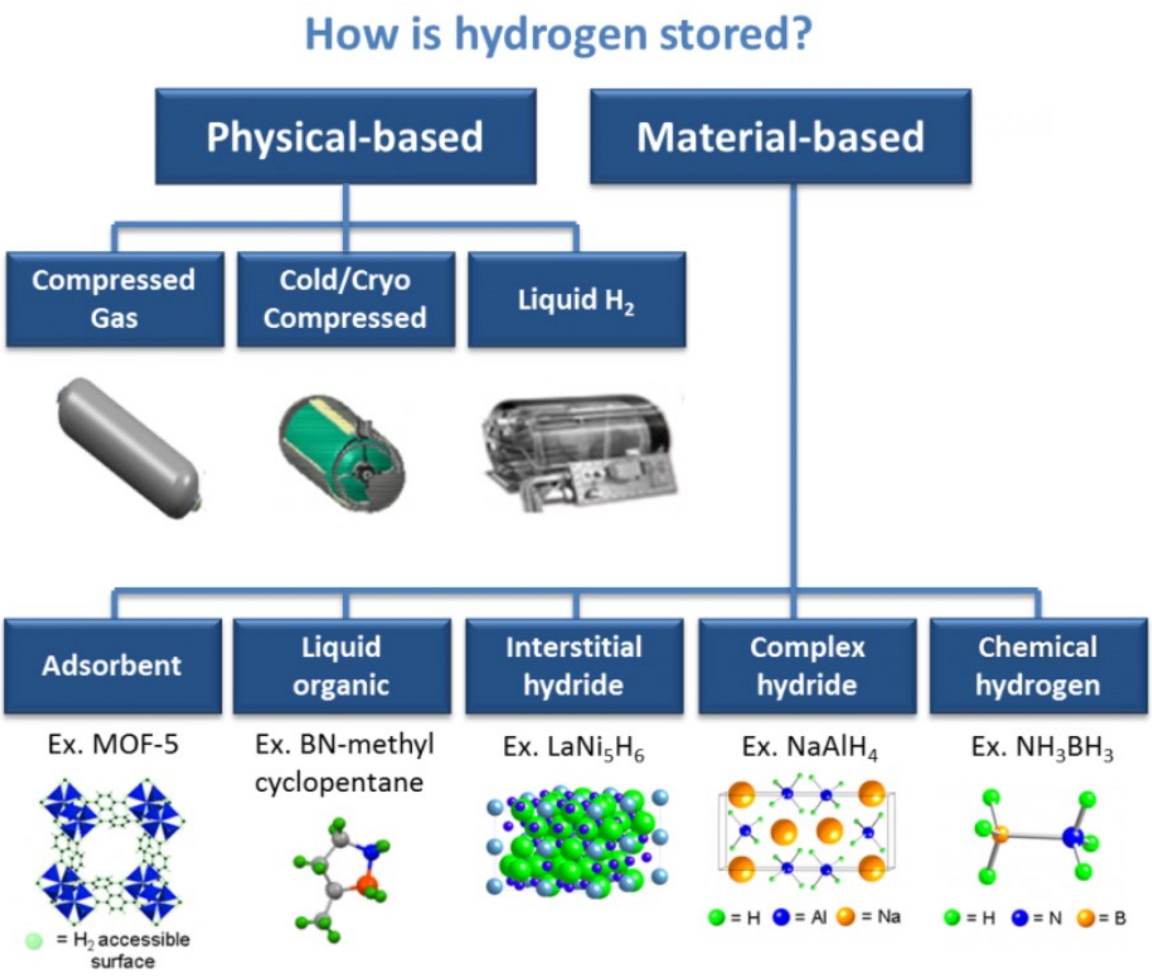

Figure 1. How is Hydrogen Stored? - Compressed Gas Storage[24]

Hydrogen storage is a cornerstone of the hydrogen economy, providing a versatile solution for balancing supply and demand in the energy market. There are several methods for storing hydrogen, each with advantages and challenges. The most common storage methods include:

1. Compressed Gas Storage: Hydrogen can be stored as a compressed gas in high-pressure tanks. This method is relatively straightforward and widely used, particularly for transportation and small-scale applications. However, it requires robust and safe storage systems due to the high pressure, typically up to 700 bar.[25]

2. Liquid Hydrogen Storage: Hydrogen can be stored as a cryogenic liquid at extremely low temperatures (-253°C). Liquid hydrogen storage has a higher energy density than compressed gas storage, making it suitable for applications requiring large amounts of hydrogen in a compact form. However, the energy-intensive liquefaction process and the need for specialized insulation to maintain low temperatures are significant challenges.[26] (*See **Figure 2***)

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[24] https://www.energy.gov/eere/fuelcells/hydrogen-storage

[25] https://www.energy.gov/eere/fuelcells/hydrogen-storage

[26] https://ig.linde-gas.com/hydrogen-distribution-storage?elqTrackId=297ca8c96309478e9d6d469939f5f263&elq=00000000000000000000000000000000&elqaid=1052&elqat=2&elqCampaignId=

Figure 2. Liquid Storage - Cryogenic Tank[27]

3. Metal Hydrides: Hydrogen can be stored in solid-state materials known as metal hydrides, which absorb and release hydrogen through a chemical reaction. This method offers the advantage of lower storage pressures and improved safety. However, the weight and cost of the materials and the kinetics of hydrogen absorption and desorption require further development.[28]

4. **Underground Storage**: Hydrogen can be stored in subterranean caverns, depleted oil and gas fields, or aquifers. This method is suitable for large-scale, long-term storage and can leverage existing geological formations. However, significant initial investment and thorough geological assessments are required to ensure safety and feasibility.[29] (*See **Figure 3***)

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[27] The image is used from: https://ig.linde-gas.com/hydrogen-distribution-storage?elqTrackId=297ca8c96309478e9d6d469939f5f263&elq=00000000000000000000000000000000&elqaid=1052&elqat=2&elqCampaignId=

[28] *Billur Sakintunaa, Farida Lamari-Darkrimb, Michael Hirscher*, Metal hydride materials for solid hydrogen storage: A review, 2007.

[29] https://www.sciencedirect.com/topics/engineering/hydrogen-underground-storage

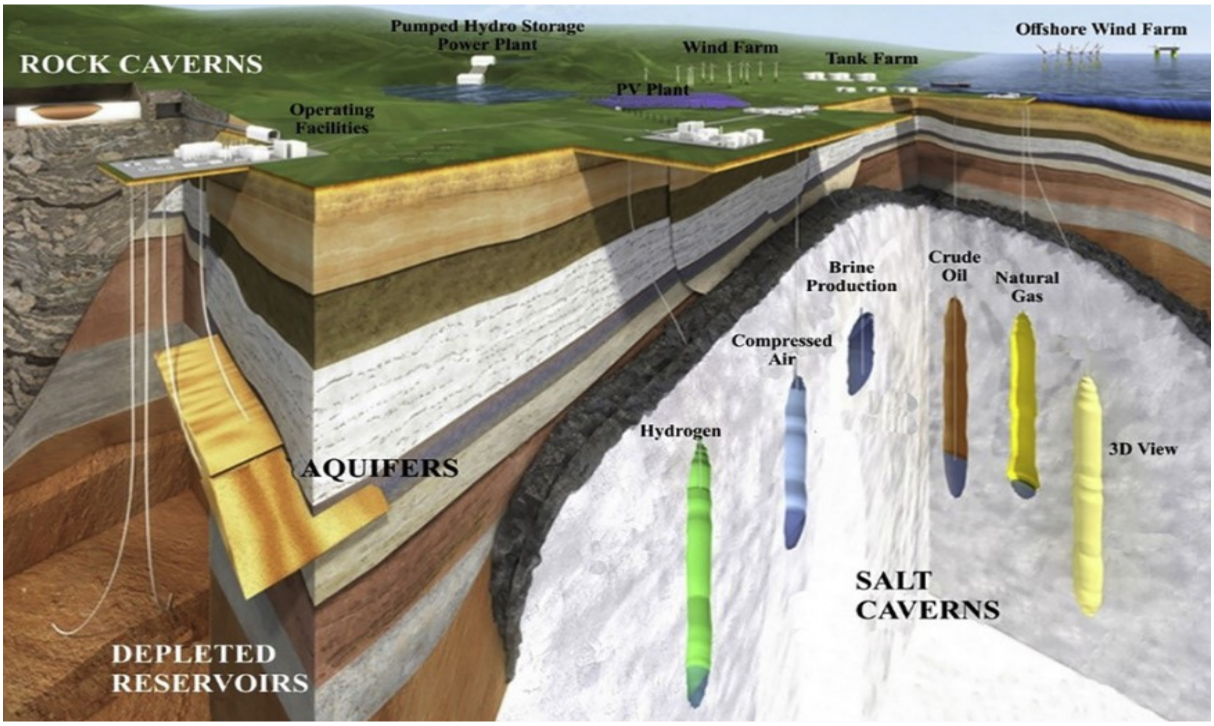

Figure 3. Potential Underground Storage Reservoir[30]

The role of hydrogen storage extends beyond electricity grid balancing. It also includes industry, transportation, and heating applications, where hydrogen can serve as a clean fuel or feedstock. Efficient hydrogen storage systems are essential for deploying hydrogen refueling infrastructure for fuel cell vehicles, providing a practical solution for zero-emission transportation.

Storage is critical regarding Guarantees of Origin (GO) for hydrogen. The integrity and traceability of clean hydrogen must be maintained throughout its lifecycle, from production to end-use. Advanced monitoring and verification technologies are necessary to ensure that the hydrogen stored and subsequently utilized retains its certification as green or low-carbon Hydrogen. This includes tracking the conditions under which hydrogen is stored, the energy sources used in storage processes, and the potential emissions associated with these activities.

Innovative technologies and materials are continually being developed to enhance hydrogen storage's efficiency, safety, and cost-effectiveness. Research and development in this field aim to overcome current limitations and pave the way for the large-scale adoption of hydrogen as a critical component of a sustainable energy system. Collaborative efforts between industry, academia, and government agencies are crucial to drive these advancements and implement effective hydrogen storage solutions.

In conclusion, hydrogen storage is a vital aspect of the hydrogen economy, enabling the flexible use of hydrogen across various sectors. By addressing the challenges associated with different storage methods and ensuring the integrity of hydrogen Guarantees of Origin, we can unlock the full potential of hydrogen as a clean and versatile energy carrier.

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[30] *Billur Sakintunaa, Farida Lamari-Darkrimb, Michael Hirscher*, Metal hydride materials for solid hydrogen storage: A review, 2007.

4.3 TRANSPORTATION OF HYDROGEN

The development of modern technological advancements has introduced various mechanisms for hydrogen transportation, enhancing the potential for hydrogen to become a cornerstone of sustainable energy systems. Hydrogen can be transported via the natural gas grid,[31] leveraging existing infrastructure to facilitate distribution. However, one of the main obstacles and most pressing challenges in promoting the use of hydrogen and its deployment is the connection between hydrogen producers and end-users. These challenges are both infrastructural and logistical, requiring significant investment and innovation.[32]

Primarily, logistical issues surrounding hydrogen transportation must be addressed. Hydrogen, due to its high energy density in small volumes, requires specialized transport solutions.[33] It can be transported as a gas through pipelines or in a high-pressure liquefied state by trucks, ships, or railroads.[34] Each method has its own set of technical and economic considerations. For instance, pipelines offer a continuous supply but require substantial upfront investment and maintenance. In contrast, liquefied hydrogen transport offers flexibility but involves high energy costs for liquefaction and handling.

As of 2021, there were approximately 5,000 kilometers of hydrogen pipelines globally. A significant portion of these pipelines is located in the United States of America, which boasts 2,600 kilometers of hydrogen pipelines. Substantial networks exist in Belgium (600 kilometers) and Germany (400 kilometers). These pipelines are primarily used for industrial applications, supplying hydrogen to refineries, chemical plants, and other industrial users.[35]

Blending hydrogen into natural gas pipelines is another method to facilitate the transition to hydrogen as a primary energy source.[36] This approach utilizes the existing natural gas infrastructure, making the transition smoother and more cost-effective. Blending hydrogen with natural gas can reduce greenhouse gas emissions and help decarbonize the natural gas supply. However, there are technical challenges associated with this method, such as ensuring the compatibility of existing infrastructure and end-use equipment with hydrogen-enriched natural gas.

To overcome these challenges, several technological and policy initiatives are being pursued. The development of dedicated hydrogen pipelines, specifically designed to handle the unique properties of hydrogen, is a crucial area of focus. These pipelines can help to reduce energy losses and improve the efficiency of hydrogen transport. Additionally, advancements in hydrogen storage technologies, such as high-pressure tanks and underground storage facilities, are being explored to provide reliable and efficient storage solutions.

The role of policy and regulation is also critical in shaping the future of hydrogen transportation. Governments and regulatory bodies are working to establish standards and guidelines for hydrogen transport and storage, ensuring safety, reliability, and interoperability across different regions and

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[31] *Chatzimarkakis J., CLevoyannis C., Wouters F. W.,* Towards the Creation of the European Hydrogen Economy, prepared by Hydrogen Europe, April 2021, 12.

[32] Energy Community, Study on the potential for implementation of hydrogen technologies and its utilization in the Energy Community, P. III: CP assessment, June 2021, 11.

[33] EC, Study on the potential for implementation of hydrogen technologies and its utilization in the Energy Community, P. I: IR, June 2021, 14.

[34] EC, Study on the potential for implementation of hydrogen technologies and its utilization in the Energy Community, P. I: IR, June 2021, 14.

[35] *Erbach G,, Jensen L.,* Briefing towords climate neutrality, EU hydrogen policy, 2021, 2.

[36] *Erbach G,, Jensen L.,* Briefing towords climate neutrality, EU hydrogen policy, 2021, 2.

markets. Incentives and subsidies for infrastructure development, research and development, and pilot projects are being introduced to accelerate the deployment of hydrogen technologies.

In conclusion, hydrogen transportation is a complex but essential aspect of the hydrogen economy. Addressing the infrastructural and logistical challenges is crucial for widely adopting hydrogen as a sustainable energy source. The future of hydrogen transportation will likely involve a combination of pipelines, liquefied hydrogen transport, and blending with natural gas, supported by technological advancements and proactive policy measures. Hydrogen can play a pivotal role in achieving a low-carbon, sustainable energy future by overcoming these challenges.

5. UNDERSTANDING CERTIFICATION FOR HYDROGEN

In decarbonization, hydrogen cannot perform its functions fully if the consumption process does not separate dirty and clean hydrogen from each other. This means providing the user with specified and confirmed information regarding the fact that the hydrogen purchased or consumed by them is green hydrogen.[37] Accordingly, it is necessary to create appropriate high standards of transparency in this regard.

Along with the growth of hydrogen production and consumption, it is necessary to establish transparency standards regarding the origin of the hydrogen consumed in individual cases. Various circumstances can drive the need to guarantee this approach. In particular, the transparency of the origin of hydrogen creates an appropriate information field for its users, enabling them to determine what production mechanisms were used to produce hydrogen and to what extent the consumption of a specific amount of hydrogen can impact the environment.

Overall, using Guarantees of Origin (GOs) for green hydrogen is effective, especially in disclosing the renewable nature of hydrogen by suppliers. It shows the end user that a certain proportion or amount of hydrogen has been produced from renewable sources. GOs are used for demonstration (disclosure) either by suppliers demonstrating the share of renewable hydrogen in their supply or by end users confirming the use of green hydrogen for energy audits.

GOs can be used to demonstrate the supplier's and end users' hydrogen mix. The GO system also serves as a support mechanism for producers who do not receive public support, helping to stimulate renewable hydrogen production. Additionally, GOs can be used to demonstrate the share of renewable energy sources (RES) in total hydrogen consumption and to certify sustainability initiatives, thereby enabling GO users to demonstrate their commitment to a sustainable and green course.

For green hydrogen, the primary purpose of GOs is to disclose the supplier's hydrogen mix, ensuring transparency and accountability in the supply chain. There may also be an obligation for suppliers of hydrogen for transport to demonstrate through GOs that they have supplied the required proportions of advanced green hydrogen in their total hydrogen supply. The purpose of GOs extends to the disclosure of end-use and demonstration of the share of RES in transport, ensuring compliance with national and international renewable energy targets. (*See* ***Figure 4***)

Government	Name	Purpose	Product	Status	Criteria
Australia	Guarantee of Origin Certificate Scheme	Voluntary	Hydrogen, hydrogen carriers	Under development	No eligibility criteria. The only requirement is to implement an emissions accounting methodology for the hydrogen produced.
Canada	Clean Hydrogen	Regulatory, access	Hydrogen, ammonia	Under development	Production below certain emissions intensity levels (<0.75, 0.75-2,

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[37] EPICO & Aurora Energy Research (2022). „Herkunftsnachweise für grüne Energie – Granulare Grünstromvermarktung für eine marktbasierte Energiewende“, Berlin, 9.

	Investment Tax Credit	to tax credits			2-4 g CO2-eq/g H2). For ammonia, only one emissions intensity level is defined (<4 g CO2-eq/g H2-eq).
Denmark	Guarantee of Origin Certificate Scheme	Voluntary	Hydrogen, Hydrogen-based fuels	Operational	Production from renewable electricity.
European Union	Renewable Energy Directive III	Regulatory, count against renewable energy targets	Hydrogen, Hydrogen-based fuels	Operational (certification under development)	Production from renewable electricity (or grid electricity with <65 g CO2-eq/kWh) meeting criteria on temporal and geographical correlation and additionality of renewable generation.
France	France Ordinance No. 2021-167	Regulatory, access to public support programmes	Hydrogen	Under Development	"Low-carbon hydrogen": production with emissions intensity <3.38 g CO2-eq/g H2. "Renewable hydrogen": production with emissions intensity <3.38 g CO2-eq/g H2 and renewable sources.
Japan	Basic Hydrogen Strategy	Regulatory, access to public support	Hydrogen, Hydrogen-based fuels	Under development	Production with emissions intensity <3.4 g CO2-eq/g H2.
Korea	Clean Hydrogen Certification Mechanism	Regulatory, access to public support	Hydrogen	Under development	Production with emissions intensity <4 g CO2-eq/g H2.
India	Green Hydrogen Standard for India	Regulatory, access to public support	Hydrogen	Under development	Production with emissions intensity <4 g CO2-eq/g H2.
Italy	Guarantee of Origin Certificate Scheme	Voluntary	renewable gases (incl. hydrogen)	Operational	Production from renewable sources.
Netherlands	Guarantee of Origin Certificate Scheme	Voluntary	Hydrogen	Operational	Production from renewable electricity.
Spain	Guarantee of Origin Certificate Scheme	Voluntary	Renewable gases (incl. hydrogen)	Operational	Production from renewable electricity.
United Kingdom	Low Carbon Hydrogen Standard; Certification Scheme	Regulatory, access to public support	Hydrogen	Operational (Certification under development)	Production with emissions intensity <2.4 g CO2-eq/g H2.
United Kingdom	Renewable Transport Fuel Obligation	Regulatory, access to public support	Hydrogen (used in transport)	Under development	Production from renewable energy (excluding bioenergy) with emissions intensity <4.0 g CO2-eq/g H2.
United States	Clean Hydrogen Production Standard; Tax Credit	Regulatory, access to public support	Hydrogen	Under development	Production below certain emissions intensity levels (<0.45, 0.45-1.5, 1.5-2.5, 2.5-4 g CO2-eq/g H2) eligible for different levels of investment tax credits support.

Figure 4. Overview of Existing and Planned Regulatory Frameworks and Certification Systems for Hydrogen and Hydrogen-Based Fuels[38]

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[38] International Energy Agency (IEA), Global Hydrogen Review 2023. More details on the certification systems established by governments can be found on pg. 165-166.

6. CRITICAL ATTRIBUTES OF GUARANTEES OF ORIGIN

6.1 TRACEABILITY / TRACKABILITY

For the Hydrogen GO to serve its functions and purpose effectively, it must meet specific prerequisites and possess various characteristics. One crucial characteristic of the Hydrogen GO is its traceability/trackability, which allows it to provide specific details about the hydrogen, such as its source (green or non-renewable energy) and the volume and percentage of renewable Hydrogen in the delivered mixture. This makes it possible to differentiate between renewable and non-renewable hydrogen in the hydrogen supplied to the market.

Additionally, the traceability/trackability of the hydrogen GO enables users to have a comprehensive view of the production, transportation, and delivery processes of specific hydrogen to its final destination. This transparency assures consumers that their hydrogen is produced from renewable sources and provides them with detailed information about the origin of the hydrogen, aiding them in making informed decisions.

Furthermore, the traceability/trackability feature of the Hydrogen GO supports the goals related to creating a green economy. The certificate allows for imposing favourable regulatory conditions on entities using green hydrogen, which would only be effective and enforceable with such certificates. Additionally, the hydrogen GO helps producers gain a competitive advantage by distinguishing the green hydrogen they supply from other hydrogen not produced using renewable energy resources.

Traceability also enables the assessment of the environmental impact of hydrogen production and consumption, as stakeholders can track the life cycle of hydrogen and quantify emission savings and other sustainability metrics to support global efforts to combat climate change.

The process of determining the traceability of Hydrogen in Guarantees of Origin (GOs) involves several key steps:

1. Hydrogen producers must obtain certification confirming their hydrogen's renewable nature, issued by recognized bodies based on standardized criteria.
2. Detailed records must be maintained at all stages of the hydrogen supply chain, including information on production methods, transportation, storage, and distribution.
3. Advanced digital platforms can enhance the traceability of hydrogen GOs, providing secure, tamper-proof records to ensure information integrity.
4. Regular verification and auditing by an independent third party ensure that the traceability system functions correctly and that the information provided is accurate and reliable.

In summary, the traceability of Hydrogen Guarantees of Origin is essential for fostering a transparent, sustainable, and accountable hydrogen economy. It enables consumers to make informed choices, helps manufacturers highlight their green credentials, ensures regulatory compliance, and supports the overall goal of rising hydrogen production.

6.2 TRADABILITY

The traceability of Hydrogen Guarantees of Origin (GO) is a critical attribute underpinning clean hydrogen's market dynamics and economic viability. Guarantees of Origin serve as a certification mechanism that verifies the source of hydrogen production, ensuring that it meets specified environmental criteria. These certificates are pivotal in fostering transparency, trust, and accountability within the hydrogen market.

Tradability refers to the ability to buy and sell these certificates independently of the physical hydrogen itself. This separation allows for greater flexibility and efficiency in the hydrogen market, enabling various stakeholders to meet their regulatory and sustainability commitments more effectively.

The tradability of hydrogen GO operates through a structured system where certificates are issued for every unit of hydrogen produced from renewable or low-carbon sources. These certificates can be traded on dedicated platforms like carbon credits or renewable energy certificates. Establishing standardized GO frameworks ensures uniformity and comparability across different regions and markets. Standardization involves defining the criteria for hydrogen production, including the type of renewable energy used, the carbon footprint, and other relevant environmental factors.

Independent certification bodies are responsible for verifying the production processes and issuing GOs. These bodies ensure that the hydrogen meets the established standards and that the associated data is accurate and reliable. Digital registry systems track the issuance, ownership, and transfer of GOs. These systems provide a transparent and secure platform for trading, reducing the risk of fraud and double-counting. Dedicated trading platforms facilitate the buying and selling of hydrogen GOs. These platforms connect producers, consumers, and intermediaries, providing a marketplace for the efficient exchange of certificates.

The traceability of hydrogen GO offers several benefits that enhance the overall value proposition of clean hydrogen. Tradable GOs increase market liquidity by enabling the participation of a wide range of stakeholders. This includes hydrogen producers, consumers, investors, traders, and policymakers. Trading platforms facilitate price discovery, allowing the market to determine the value of clean hydrogen based on supply and demand dynamics. This transparent pricing mechanism helps in the formation of a robust hydrogen market.

Tradability provides additional revenue streams for hydrogen producers, incentivizing investment in renewable hydrogen production. Producers can offset some of the costs of clean hydrogen production by selling GOs. Tradable GOs help companies and governments meet their regulatory and sustainability targets. Organizations can purchase GOs to demonstrate their commitment to renewable energy and carbon reduction goals. The ability to trade GOs enhances consumer confidence in the authenticity of green hydrogen claims. It provides a verifiable mechanism to ensure that the hydrogen consumed is genuinely sourced from renewable or low-carbon production methods.

While the traceability of hydrogen GOs presents significant opportunities, it also faces several challenges. Achieving harmonization across different regions and regulatory frameworks is crucial for the seamless traceability of GOs. This requires international cooperation and the alignment of standards and certification processes. The hydrogen GO market is still in its nascent stages. Developing robust market infrastructure, including trading platforms and registry systems, is essential for supporting large-scale trading activities. Integrating hydrogen GOs with other environmental markets, such as carbon credits and renewable energy certificates, can enhance market synergies and provide comprehensive solutions for decarbonization.

In conclusion, the tradability of Hydrogen Guarantees of Origin is a crucial attribute supporting the hydrogen economy's growth and sustainability. By enabling transparent, efficient, and secure trading of GOs, the market can unlock the full potential of clean hydrogen, driving investments and innovation in renewable hydrogen production.

6.3 TRANSPARENCY

Transparency is a foundational principle in the hydrogen sector, crucial for building trust among stakeholders, ensuring accountability, and facilitating informed decision-making. Transparency in the context of hydrogen encompasses several vital aspects.

Transparency begins with the production processes of hydrogen. It involves disclosing the methods and technologies used to produce hydrogen, whether from renewable sources like wind, solar, or fossil fuels with carbon capture and storage (CCS). Clear documentation of these processes helps stakeholders understand the environmental impact and sustainability credentials of the hydrogen produced.

Guarantees of Origin (GO) play a pivotal role in enhancing transparency within the hydrogen market. GOs certify the origin of hydrogen and verify its environmental attributes, such as its renewable or low-carbon status. Transparency in GO issuance, tracking, and trading ensures that consumers and stakeholders can confidently verify the authenticity and sustainability of the hydrogen they purchase or invest in.

Transparency also extends to measuring and reporting emissions associated with hydrogen production, storage, and transportation. It involves disclosing the lifecycle of greenhouse gas emissions and other environmental impacts, allowing for comparisons between different hydrogen production pathways. This information is essential for making informed decisions regarding the adoption and deployment of hydrogen in various applications.

In addition to environmental transparency, disclosing the costs associated with hydrogen production, storage, and distribution is crucial for market participants. Transparency in cost structures enables stakeholders to assess hydrogen's economic feasibility and competitiveness compared to conventional fuels and other renewable energy options.

Transparency is fundamental in regulatory compliance and adherence to industry standards. Clear communication of regulatory requirements, adherence to safety protocols, and compliance with environmental regulations foster trust and confidence in hydrogen as a viable and safe energy carrier.

Effective public engagement and communication strategies enhance transparency by educating stakeholders about hydrogen's benefits, challenges, and future potential. Transparent communication helps build public trust and support for hydrogen initiatives, encouraging investment and policy development conducive to the sector's growth.

Ensuring the integrity and security of hydrogen production, distribution, and utilization data is essential for maintaining transparency. Robust data management systems and cybersecurity measures protect sensitive information, preventing unauthorized access and ensuring the reliability of reported data.

Enhancing transparency will be critical for addressing emerging challenges and opportunities as the hydrogen sector evolves. Advancements in digital technologies, such as blockchain and IoT (Internet of Things), promise to improve data transparency and traceability within the hydrogen supply chain. Collaborative efforts between industry stakeholders, governments, and international organizations will be essential for developing standardized reporting frameworks and enhancing transparency across global hydrogen markets.

In conclusion, transparency is not just a requirement but a catalyst for the sustainable growth of the hydrogen economy. By promoting openness, accountability, and clarity across all facets of hydrogen production and utilization, stakeholders can effectively navigate the complexities of the market, mitigate risks, and capitalize on the transformative potential of hydrogen as a clean energy solution.

6.4 CREDIBILITY

The credibility of Guarantees of Origin (GO) is fundamental to ensuring transparency, trustworthiness, and effectiveness within the hydrogen market. GOs serve as certificates that verify hydrogen's origin and environmental attributes, providing assurance to consumers, businesses, and regulatory authorities.

Credibility begins with the robustness of the certification process. Independent certification bodies are crucial in verifying that hydrogen production meets stringent environmental standards. These bodies conduct thorough audits and assessments to ensure compliance with defined criteria, such as the type of renewable energy used in production, carbon footprint calculations, and adherence to sustainability principles.

Transparency in GO issuance and tracking is essential for maintaining credibility. Clear documentation and digital registry systems enable stakeholders to trace the hydrogen journey from production to consumption, ensuring that GOs accurately reflect the environmental attributes of the hydrogen. This transparency reduces the risk of fraud or misrepresentation, enhancing the reliability of GOs as a certification mechanism.

Consistency and harmonization across GO frameworks are crucial to credibility. Standardized GO issuance and trading criteria promote uniformity and comparability across regions and markets. Harmonization efforts facilitate international trade in hydrogen and ensure that GOs retain their integrity and credibility regardless of geographic location or regulatory jurisdiction.

Robust governance and oversight mechanisms further bolster the credibility of GOs. Regulatory authorities and industry associations are vital in setting and enforcing GO certification and trading standards. Their involvement ensures GOs comply with regulatory requirements and industry best practices, enhancing market participants' trust.

Effective communication and education about the benefits and importance of GOs contribute to their credibility. Stakeholders, including consumers, investors, and policymakers, need to understand the role of GOs in promoting renewable and low-carbon Hydrogen. Transparent reporting on the environmental impact and lifecycle emissions associated with hydrogen production enhances credibility by providing evidence-based information for decision-making.

Technological advancements, such as blockchain and digital platforms, offer opportunities to enhance the credibility of GOs. These technologies provide secure, decentralized systems for recording and verifying GO transactions, reducing the risk of data manipulation or tampering. Blockchain, in particular, offers immutable records of GO ownership and transactions, ensuring transparency and trustworthiness in the hydrogen market.

In conclusion, Guarantees of Origin (GO)'s credibility is paramount for unlocking hydrogen's full potential as a clean and sustainable energy solution. By ensuring robust certification processes, promoting transparency in GO issuance and tracking, fostering consistency through harmonized frameworks, and leveraging technological innovations, stakeholders can build confidence in GOs and drive investment in renewable hydrogen production. Upholding the credibility of GOs strengthens market integrity, supports regulatory compliance, and accelerates the transition to a low-carbon hydrogen economy.

CONCLUSION

Hydrogen emerges as a versatile energy carrier capable of addressing diverse energy needs across industries, transportation, and residential sectors. Its potential to decarbonize various sectors while providing energy security underscores its pivotal role in achieving global climate goals.

The dichotomy between “dirty” and “clean” hydrogen production highlights the importance of transitioning towards sustainable production methods. While challenges persist, advancements in renewable energy integration and carbon capture technologies offer pathways to expand clean hydrogen production globally.

Adequate storage and transportation infrastructure are indispensable for the widespread adoption of hydrogen. Addressing logistical challenges, such as infrastructure development and mode diversification, is crucial for optimizing the efficiency and scalability of hydrogen deployment.

Certification frameworks, such as Guarantees of Origin (GO), play a pivotal role in verifying the environmental credentials of hydrogen. Ensuring robustness in GO issuance, transparency in tracking, and credibility in compliance are essential for building trust and facilitating international trade in hydrogen.

The attributes of GO – traceability/trackability, transparency, and credibility – form the foundation for a well-functioning hydrogen market. These attributes enable stakeholders to verify hydrogen's origin and environmental impact, promote market liquidity, enhance decision-making, and uphold integrity in certification processes.

In conclusion, the transition towards a sustainable hydrogen economy requires concerted efforts and strategic investments across all facets of the hydrogen value chain. By fostering innovation, promoting regulatory certainty, and enhancing international cooperation, we can unlock the full potential of hydrogen to drive economic growth and environmental stewardship.

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