Postgraduate Programme of Studies

Supply Chain Management (SCM)

Hellenic Open University

Dissertation

Analyzing the Potential of Green Hydrogen as a Game-Changer in Decarbonizing the Oil and Gas Industry's Supply Chain: A Focus on Green Certificates

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Athens, 2024

I would like to express my sincere and warm thanks to my supervisor, Prof. Stella Tsani, for her trust and support throughout the completion of my thesis. Additionally, I feel the need to thank my family, without whose understanding and love the completion of this work would not have been possible.

Abstract

The shift to a sustainable energy tomorrow is critical, especially to industries with a large carbon footprint, such as the oil & gas sector. This research investigates the function of Green Certificates (Guarantees of Origin) in greening the Oil & Gas Industry's supply chain, with a particular focus on the role of Green Hydrogen. The decision to explore this topic comes from the critical industry-wide desire for sustainable energy solutions, with the goal of addressing critical gaps in understanding how Green Certificates could encourage the adoption of Green Hydrogen and contribute to the industry's transition to a more sustainable and environmentally conscious future.

Green certificates, also known as Tradable Green Certificates (TGCs), Guarantees of Origin (GOs), or Renewable Energy certificates (RECs), are electronic certificates that verify that one MWh of energy has been produced from renewable energy sources. (Gkarakis & Dagoumas, 2016). Green Hydrogen is introduced as a prospective decarbonization alternative, investigating its properties, potential applications, benefits, and obstacles. Furthermore, the function of Green Certificates is investigated in encouraging renewable energy, explaining its purpose, regulatory frameworks, and market dynamics (Abad & Dodds, 2020)

The dissertation employs a multifaceted methodology, incorporating bibliometric analysis, a case study, and a SWOT analysis to comprehensively explore the chosen research area. Initially, a detailed analysis of the literature provides a comprehensive overview of the Oil and Gas Industry's transition to sustainability, highlighting the environmental problems it faces. Thus, 2,693 papers have been selected from the Web of Science database to examine publishing trends and highlight influential publications from 2000 to 2023.

In addition to bibliometric analysis, a case study approach was used, concentrating on Europe's largest green hydrogen endeavor, the NortH2-project. This real-world case study offers useful insights into the practical use and problems of incorporating green hydrogen and green certifications into the supply chain. The NortH2-project, led by Equinor, RWE, Shell, Groningen Seaports Gasunie, and the province of Groningen, is a thorough example of the problems and opportunities inherent in the shift to sustainable energy methods (north2, 2023). The data gathered from the document analysis have been thoroughly investigated utilizing qualitative methodologies in order to discover success drivers and impediments.

Furthermore, a SWOT analysis, based on the case study, was used to assess the multiple factors influencing the incorporation of green hydrogen and green certifications into the oil & gas industry's supply chain. This strategic analysis helps to identify internal and external variables influencing the industry's transition, offering a comprehensive understanding of the difficulties and opportunities involved with the implementation of sustainable energy solutions (Khan & Al-Ghamdi, 2023).

This research reveals major findings by conducting an in-depth investigation of the function of Green Hydrogen in decarbonizing the Oil and Gas Industry's supply chain. It evaluates Green Hydrogen's potential uses in several elements of the supply chain, such as transportation and energy storage, stressing its ability to cut carbon emissions and improve sustainability (Griffiths, et al., 2021). Moreover, the study addresses key questions, such as the role and environmental impact of Green Hydrogen, the operation of regulatory frameworks for Green Certificates, and the potential economic and environmental implications of integrating Green Hydrogen into the oil and gas supply chain. Finally, it also looks at the constraints of integrating Green Hydrogen into the supply chain, such as infrastructure requirements and financial considerations.

To sum up. the role of Green Certificates (Guarantees of Origin) in promoting the use of renewable energy, particularly Green Hydrogen (Azadnia, et al., 2023), within the Oil and Gas Industry is a primary focus of this research. The analysis shows how Green Certificates encourage the use of Green Hydrogen by offering transparency, traceability, and accountability in renewable energy sourcing (Abad & Dodds, 2020). It assesses the possible economic, environmental, and social consequences of incorporating Green Hydrogen and Green Certificates, with a focus on their innovative potential in the industry's sustainability practices. (Delardas & Giannos, 2023).

The present work combines significant findings from the case study and literature review to provide light on the implications for the oil and gas industry's transition to a sustainable supply chain. It recognizes the study's limitations, acknowledging the dynamic nature of the energy transition landscape, and makes recommendations for future research (Lee & Cheng, 2022). Finally, this research adds to the expanding body of knowledge on sustainable energy solutions while also providing practical recommendations to speed the use of Green Hydrogen and Green Certificates in the Oil and Gas Industry, thus allowing the decarbonization of its supply chain.

Keywords: Green Hydrogen, Oil and Gas Industry, decarbonization, supply chain, Green Certificates, Guarantees of Origin, sustainability, renewable energy, carbon emissions.

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I. Introduction

A. Background

For much more than a century, the oil & gas sector has been the fundamental component of the world's energy production (Wang, et al., 2023).

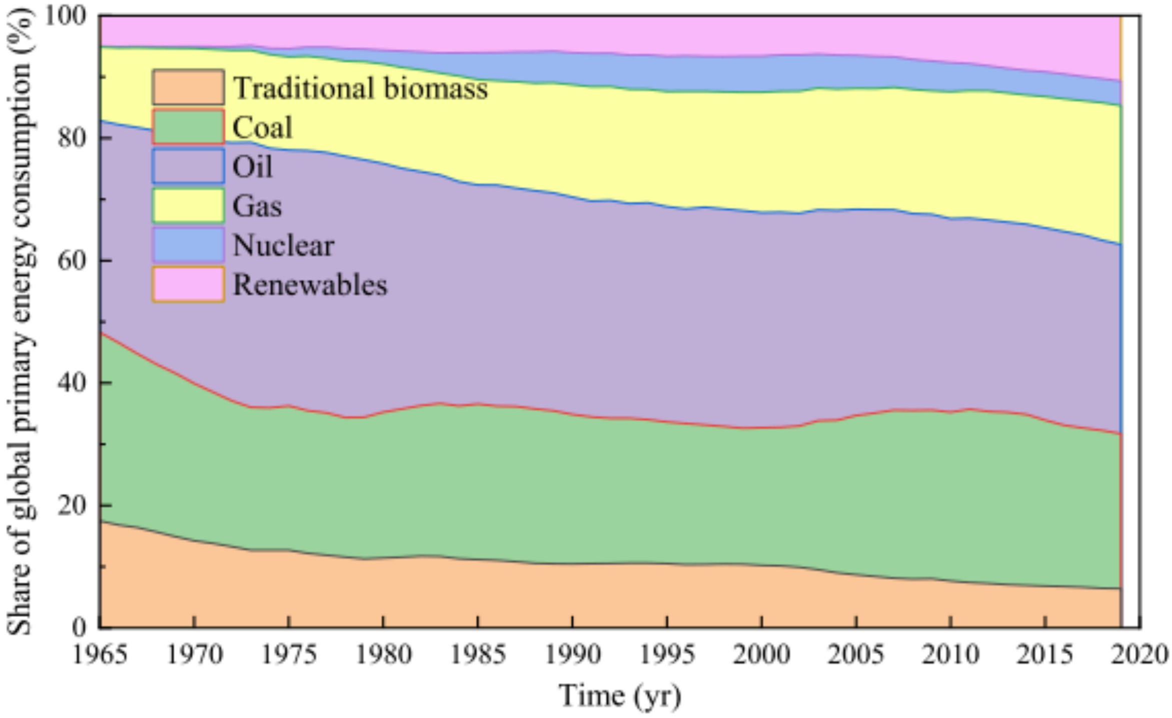


Figure 1: Source-specific share of global primary energy consumption (Wang, et al., 2023)

It supported transportation networks, stimulated economic expansion, and supplied raw materials to many businesses. However, the historical reliance on fossil fuels - natural gas and crude oil in particular - has presented a number of sustainability and environmental issues (Bennaceur, 2019).

The oil and gas sector has long been associated with worries about climate change, greenhouse gas emissions, and the depletion of scarce resources (Griffiths, et al., 2021). Discussions on carbon footprints and global environmental deterioration have focused heavily on the burning of hydrocarbons to satisfy the world's insatiable energy needs. Because of this, according to Abubakar (2014), it is becoming more and more obvious that the sector needs to completely change to responsibly contribute to the shift to a more environmentally conscious and sustainable energy landscape (Abubakar, 2014).

At the same time, there has been a global increase in interest and financial resources towards alternate energy sources. Green hydrogen is one of them that has shown promise and has the potential to completely transform the energy sector (Guarieiro, et al., 2022). It is made by separating water into hydrogen and oxygen using a method known as electrolysis, which uses renewable energy sources. When produced and used, green hydrogen emits no carbon dioxide, making it a clean and sustainable energy source. Its outstanding qualities have made it a desirable choice for a number of uses, such as industrial operations, energy storage, and transportation (Abad & Dodds, 2020).

B. Research Objectives and Questions

The primary aim of this research is to investigate the potential of Green Hydrogen as a game-changer in decarbonizing the oil and gas industry's supply chain, focusing on its integration with Green

Certificates (i.e. Guarantees of Origin). To achieve this overarching goal, the study sets out to address several specific research objectives and questions:

- Defining Green Certificates (Guarantees of Origin), and how do they incentivize the use of renewable energy sources, including Green Hydrogen, within the oil and gas industry's supply chain?
- Evaluating the role of green hydrogen in decarbonizing the oil and gas industry's supply chain (Eljack & Kazi, 2021). What environmental benefits and problems does Green Hydrogen integration provide, and how can it be integrated into various areas of the oil and gas supply chain?
- Analyzing regulatory frameworks and market mechanisms for Green Certificates within the oil and gas industry, exploring their role in promoting the adoption of Green Hydrogen.
- Furthermore, in what ways can Green Hydrogen be utilized for energy storage within the oil and gas supply chain, and what are the economic and environmental implications of such integration?
- Establishing correlations with the case study and
- Assessing the potential outcomes and impacts, both positive and negative, of adopting Green Hydrogen and Green Certificates in the oil and gas supply chain?

By addressing these research objectives, the dissertation aims to provide a comprehensive understanding of the broad relationship between Green Hydrogen, Green Certificates, and the supply chain of the oil and gas industry, providing insights into the possibilities, challenges, and implications of such integration.

C. Motivation and Methodology of the study

The main objective of this research lies at the intersection of crucial environmental imperatives, the imperative for energy transition, and the critical need for innovation within the oil and gas industry (Thorne & Mittal, 2019). In a world where the effects of climate change are becoming more obvious and the need to reduce carbon emissions has become a worldwide priority, the oil and gas sector takes priority due to its extensive record of greenhouse gas emissions and environmental degradation (Bennaceur, 2019).

This research employs a comprehensive and nuanced methodology to address the research questions, leveraging a combination of bibliometric analysis, a case study, and a SWOT analysis. Each method was strategically chosen to provide a comprehensive understanding of the selected field of study, offering distinct advantages in uncovering insights.

The first phase is to conduct a thorough bibliometric analysis, which will allow for a comprehensive examination of the oil and gas industry's transition to sustainability. This method entails gathering and evaluating 2,693 papers from the Web of Science database, which spans the years 2000–2023. The bibliometric study helps to find publishing patterns and highlight key publications, laying a solid foundation for comprehending the industry's evolution over time.

An important component of the study is the utilization of a case study approach. Thus, for the collection and analysis of primary data, the methodology predominantly employs a case study approach, with an emphasis on one of Europe's largest green hydrogen project, the NortH2-project (north2, 2023). This strategic case study selection aims to provide valuable insights into the practical applications and challenges of incorporating Green Hydrogen and Green Certificates into the supply chain. Finally, based on the case study, a SWOT analysis is used to systematically evaluate the strengths, weaknesses, opportunities, and threats connected with incorporating green hydrogen and green certifications into the oil and gas industry's supply chain. This strategic analysis offers a deep understanding of the internal and external elements that influence the industry's transition to sustainability. The bibliometric analysis provides a historical and globally perspective, the case study offers practical insights, and the SWOT analysis allows for a strategic assessment of the industry's shift. These methodologies, when combined, provide a solid foundation for investigating the study area's various aspects.

The oil and gas industry has been immensely significant since it is a major contributor to global carbon emissions (Flamme, et al., 2019). Thus, the study asserts that decarbonizing this sector is not merely an environmental necessity but a strategic move towards achieving broader climate goals (Schneider , et al., 2013). The research contributes to a better understanding of how a traditionally carbon-intensive business could shift to cleaner energy sources by examining the potential of Green Hydrogen and Green Certificates. Moreover, the study offers insights into how the industry can continue to fulfill energy requirements while minimizing its environmental impact. Aside from environmental concerns, the research delves into the economic viability of integrating Green Hydrogen.

Beyond mitigating the environmental impact, the exploration of Green Hydrogen and Green Certificates represents an acknowledgement that the oil and gas industry is on a path for transformation (Flamme, et al., 2019). Finally, the potential for technical innovation, notably in the field of Green Hydrogen, is viewed as a driving force for positive change in the oil and gas business. However, a critical assessment of its implementation across various areas of the supply chain, remains relatively unexplored (Rafie & Khalilpour, 2019). Further study should be conducted to examine its effectiveness in specific contexts like as transportation, energy storage, and industrial processes in order to provide targeted insights into the areas with the greatest potential for impact. Bridging this gap requires a more detailed analysis of the ongoing sustainability initiatives within the industry, providing a roadmap for companies seeking to align with global environmental goals.

D. Previous studies and research gaps

A thorough review of the current pool of literature gives an overview of the dynamics surrounding the integration of Green Hydrogen and Green Certificates within the supply chain of the oil and gas industry. Prior research has made progress in investigating the possible benefits, problems, and implications of implementing these sustainable technologies (Yan-yun, 2012). However, basic research gaps continue to exist, prompting scholars to explore further into hidden problems that require attention. Notably, studies have revealed the industry's transition to sustainability as well as Green Hydrogen's ability to reduce carbon emissions throughout the supply chain (Rafie & Khalilpour, 2019).

While existing research provides a solid framework, it also highlights recurrent gaps that necessitate more exploration into hidden concerns that require addressing. The integration process is complex and multidimensional, in keeping with the concept of a green supply chain, which prioritizes environmental protection and resource optimization. The oil and gas industry's embrace of renewable energy sources, particularly Green Hydrogen, is a viable avenue for lowering energy prices as well as greenhouse gas emissions (Flamme, et al., 2019).

Green Hydrogen, produced from renewable resources, represents a huge prospect for decarbonization in industrial operations within the oil and gas industry. Green supplier selection and green supply chain strategies such as reverse logistics and green design emerge as critical phases in this integration process. However, obstacles to the adoption of these techniques must be carefully considered and addressed (Hassan, et al., 2023).

In conclusion, while a limited amount of previous studies provide a solid foundation for understanding the integration of Green Hydrogen and Green Certificates in the oil and gas industry, significant research gaps exist (Rafie & Khalilpour, 2019). As the industry navigates this transformative journey, these insights contribute to a more holistic understanding of the integration dynamics, calling for continued exploration to bridge existing research gaps.

II. Literature Review

A. Overview of the Oil and Gas Industry's transition to sustainability

The oil and gas industry's transition to sustainability is a complex and ongoing process, as highlighted by (Schneider , et al., 2013) and (Pies, 2010). Furthermore, while the sector has made progress in addressing environmental, health, and safety (EHS) issues, there are still significant gaps in performance, particularly in compliance with regulations and spill management (Schneider, 2013). This underscores the complexity of the challenges faced by the industry in achieving comprehensive sustainability.

Moreover, Pies (2010) sheds light on the industry's voluntary commitments to ecological, social, and governance (ESG) standards, which play a pivotal role in steering the transition toward sustainability. These commitments signify a recognition within the sector of the broader responsibilities it holds toward the environment, society, and corporate governance. Such voluntary initiatives are integral to shaping the industry's ethical and responsible practices. (Pies, 2010).

In addition, Intykbayeva's contribution (2021) adds a forward-looking perspective, emphasizing the imperative for the industry to continue evolving in terms of sustainability, digitalization, and cultural innovation. This suggests that sustainability efforts are not static but must be continually developed and refined to maintain the industry's leadership position. The call for digitalization and cultural innovation underscores the need for a holistic transformation that goes beyond operational changes to encompass organizational and cultural shifts (Intykbayeva, 2021).

The impact of sustainable measures on the operational and business performance of the UK oil and gas supply chains is explored by Yusuf et al. (2013). Their findings underscore a positive correlation between the adoption of sustainable practices and improved performance metrics. This highlights the tangible benefits that sustainability measures can bring not only to environmental outcomes but also to the overall efficiency and effectiveness of supply chain operations (Yusuf, et al., 2013)..

In summary, the literature review reveals the intricate nature of the oil and gas industry's transition to sustainability. While progress has been made, challenges persist, particularly in areas like regulatory compliance and spill management. Voluntary commitments to ESG standards, as well as the ongoing development of sustainability, digitalization, and cultural innovation, are identified as crucial elements in this journey (Bennaceur, 2019).

B. Green Hydrogen, its potential in decarbonization and the role of Green Certificates

With 136 countries, representing a substantial portion of global GDP and population, committing to net-zero targets, the transition to net-zero requires decarbonization across all economic sectors. Green hydrogen, produced from renewable sources, emerges as an environmentally friendly solution to support these targets (Raman, et al., 2022).

Furthermore, extending the green certification system would be a crucial step since green hydrogen-produced from renewable energy sources—is a promising mean of decarbonizing the energy industry (Elshafei & Mansour, 2023). Therefore, the use of Green Certificates to encourage the production and use of green gases is considered a significant step toward diversification. (Abad & Dodds, 2020).

Green Certificates, also known as Guarantees of Origin (GOs), play a crucial role for the advancement of renewable energy. They play a crucial role in the integration of renewable energy support systems and the accomplishment of targets in national renewable energy plans (Linden, et al., 2004). The green certificate trading system, which is a mandated renewable energy quota, can help stimulate renewable energy development and respond to national energy conservation and emission reduction objectives (Mi, et al., 2019).

In addition, green hydrogen is a viable decarbonization solution that is created by electrolyzing water with renewable energy sources (Elshafei & Mansour, 2023). However, it currently faces difficulties becoming economically competitive with alternative technologies, therefore in order to become feasible, major cost reductions are required (Oliveira, et al., 2023). Notwithstanding these challenges, green hydrogen's potential for decarbonization is well known, and its adaptability and environmental sustainability make it a crucial component of the energy transition.

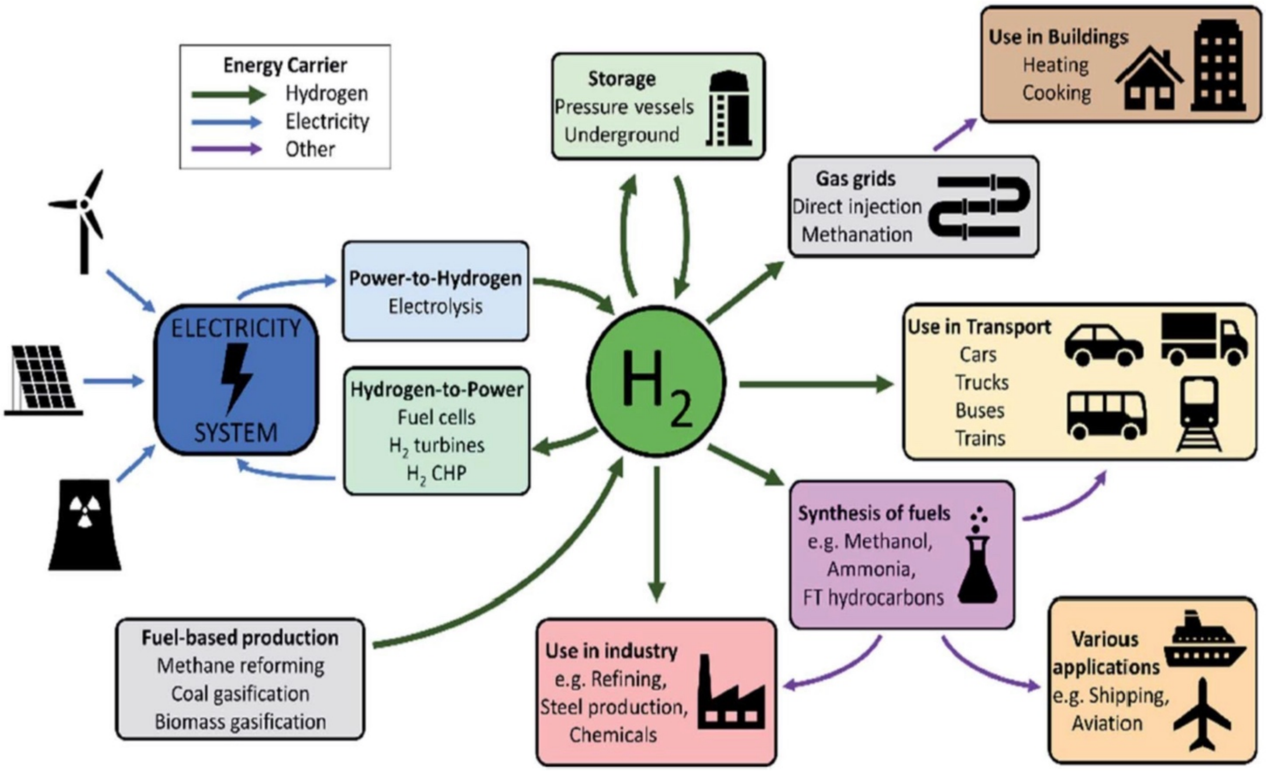


Figure 2:An overview of the hydrogen generation and consumption technologies (Griffiths, et al., 2021)

Because of its adaptability as a chemical reservoir of energy for application in the power, building, transportation, and industrial sectors, hydrogen is increasingly being positioned as an important energy vector (Griffiths, et al., 2021). However, innovation and research investments will need to be substantially raised in order to make the shift to a green hydrogen economy, and worldwide standards will need to be established (Scita, et al., 2020). The chemical sciences will play a crucial role in addressing the technological and economic aspects of green hydrogen, including production, storage, distribution, and final use (Guarieiro, et al., 2022).

C. Bibliometric overview

Numerous research have looked into the significance of green hydrogen in decarbonizing the oil and gas industry's supply chain. Over the next five years, policy decisions made in the US, EU, China, and India will have a major effect on the production and storage of green hydrogen. If implemented, these policies could be responsible for two-thirds of the anticipated growth, with Asia becoming the second-largest global producer. Therefore, there are research potentials for the future role of these regions, which will be crucial in shaping the future of green hydrogen. (Raman, et al., 2022).

For the bibliometric overview of Green Hydrogen, we accessed bibliographic data used in this research using the platform of Web of Science. The search for this summary began in early January 2024 to guarantee that full-year data of 2023 was included.

Following a broader search strategy using the combination of keywords “Green Hydrogen” OR “Guarantees of Origin” AND “oil and gas”, web of science initially revealed 43,826 journals since 2000. However, in order to acquire a clean data set, lot of manual work and refinement was required. Using the Web of Science platform, we included, only the relevant categories (energy fuels, Green sustainable Science technology, Engineering Environmental, Engineering Chemical, Environmental Science and studies etc), only articles in English Language and only articles as document types. At the same time irrelevant research areas, citation topics (Meso & Micro) and irrelevant publications were excluded.

Finally, we ended at **2,693** Web of Science results, which are relevant to our thematic area, which is green hydrogen and guarantees of origin across the oil and gas industry. (Web of Science query). The graph below depicts the growth trends in publications and citations per cited publication over a 23-year period (2000-2023).

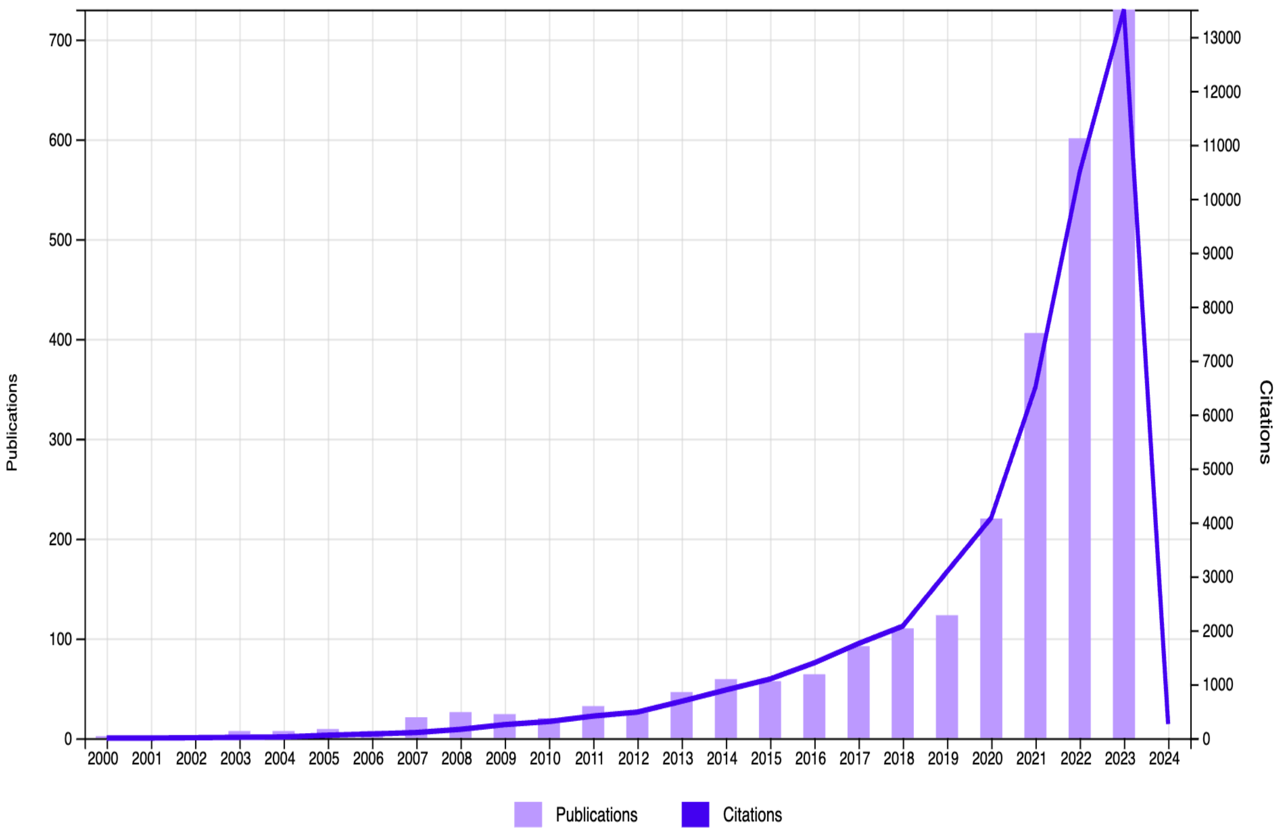


Figure 3: Publications with relevant Citations per year (2000-2023)

The overall amount of citations for every result in the data set is 47,711, with an average number of citing articles for all items in the results set 17.72 per item. With 730 articles and 13,577 total Citations, 2023 proved to be the most influential and productive year in terms of quantity, showing the field's present importance in light of the developing renewable energy situation. As we have already mentioned articles published in the year 2024 has been excluded.

Hamelinck’s et al (2004) article about clean transportation fuels production is the most cited in the field, with total 392 citations, averaging about 18.67 citations per year (Hamelinck, et al., 2004). Both Squaddrito (Squadrito, et al., 2023) and Kirchem (Kirchem & Schill, 2023) emphasize the environmental benefits of green hydrogen, with Sarker emphasizing advantages and drawbacks of various green hydrogen technologies and Kirchem evaluating its potential in Germany's power sector. Kazi (2021) emphasizes green hydrogen's potential in industrial decarbonization by offering a strategic framework for its application (Kazi, et al., 2021). Scita (2020) notes, however, that while green hydrogen shows potential, there are outstanding technological and geopolitical issues that must be addressed (Scita, et al., 2020).

Moreover, analyzing the leading countries we can assume that the majority of the 2,693 publications are associated with 98 countries. The 30 most prolific countries in our research are shown in the table below.

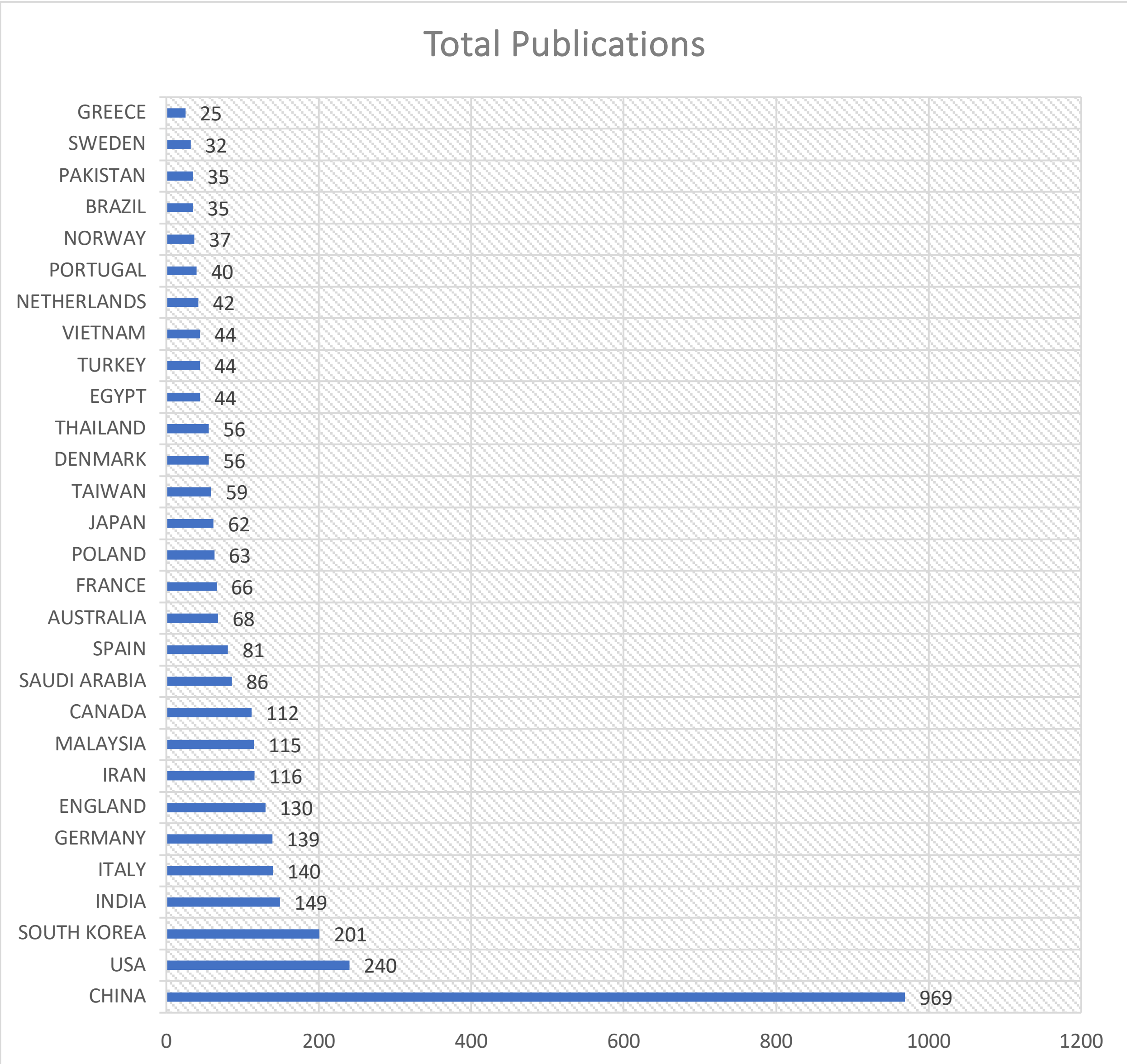


Figure 4: The leading countries in green hydrogen research (Web of Science)

As we can see from the figure above, China is the dominant county with 969 contributions (36% of the total). The USA holds is second with 240 publications. South Korea holds the third position, with 201 publications. The Netherland, homeland of project NorthH_2, is in number 24 with 42 publications and Greece is the last of the 30 countries, with 30 publications.

Moreover, following a broader search strategy using the combination of keywords "Green Hydrogen" AND "decarbonization" AND "oil and gas", web of science revealed just only 22 journals since 2020. Thus, while numerous studies have explored the realm of green hydrogen, it is assumed that there remains a scarcity of research investigating its role especially in decarbonizing the supply chain of the oil and gas sector.

Finally, these results emphasize the need for more research to fully comprehend and take advantage of the potential of green hydrogen in decarbonizing the supply chain of the oil and gas industry, as well as the function of Green Certificate.

III. Green Hydrogen's Contribution to Decarbonizing the Supply Chain for the Oil and Gas Industry

A. Overview of the oil and gas supply chain and its environmental challenges

The concern of global climate change is no longer only one of theory and research for the distant future; it is now an urgent concern for corporations, international financial institutions, and multinational companies, as well as a focal point for state foreign and domestic policy (Cherepovitsyna, et al., 2023). Groundwater contamination, climate change, and the need for sustainable methods all pose substantial environmental problems to the oil and gas supply chain (Mojarad, et al., 2018). While natural gas is a cleaner fuel, its production and processing have an influence on the environment (Mokhatab & Poe, 2012). Offshore operations in the United Kingdom experience environmental pollution concerns, necessitating the development of sustainable solutions and the reduction of air emissions (Salter & Ford, 2000). Extreme weather events pose a considerable risk to oil infrastructure, exacerbated by climate change (Katopodis & Sfetsos, 2019). The aforementioned concerns, emphasize the importance of ecologically responsible and sustainable strategies throughout the oil and gas supply chain.

Strategies for decarbonization include changing power sources, implementing improved technologies, and adopting energy efficiency (Bennaceur, 2019). The greatest challenge confronting humanity is the transition from a fuel-based energy system to a sustainable and decarbonized system. There is no industry that faces more sustainability challenges than the oil and gas sector, which is acknowledged to be one of the most polluting industries in the world (Cherepovitsyna, et al., 2023). Oil and gas companies can decarbonize the industry through a wide range of strategies, including changing power sources, implementing improved technologies, and adopting energy efficiency in their operations, flaring through improved additional gas processing and infrastructure, reducing routine flaring through improved equipment reliability, portfolio rebalancing, the use of renewables, electrifying operations, increasing the use of carbon capture and storage, and finally producing and using green hydrogen. (Oruwari & Itsekor, 2023).

Finally, the European Green Deal, with its ambitious climate targets, presents both challenges and opportunities for the industry. Thus, expansive investments must be made to build a solid basis for adopting the aforementioned strategies, like green hydrogen (Hainisch, et al., 2020). Broad decarbonization efforts continue to face challenges, such as the unreliability of renewable electricity and gas. (Mojarad, et al., 2018).

B. Introduction to Green Hydrogen and its characteristics

Although colorless, hydrogen is characterized in the energy business by thirteen various color codes that represent the manner or source of its creation. Green, blue, grey, brown, yellow, turquoise, purple, pink, red, and white are among the color codes. Because there is no defined convention, different production methods produce various colors, and the meanings may change globally and over time (Zainal, et al., 2024).

The following figure illustrates all Hydrogen production technologies, either from Fossil fuel, or in our research case from Renewable resources.

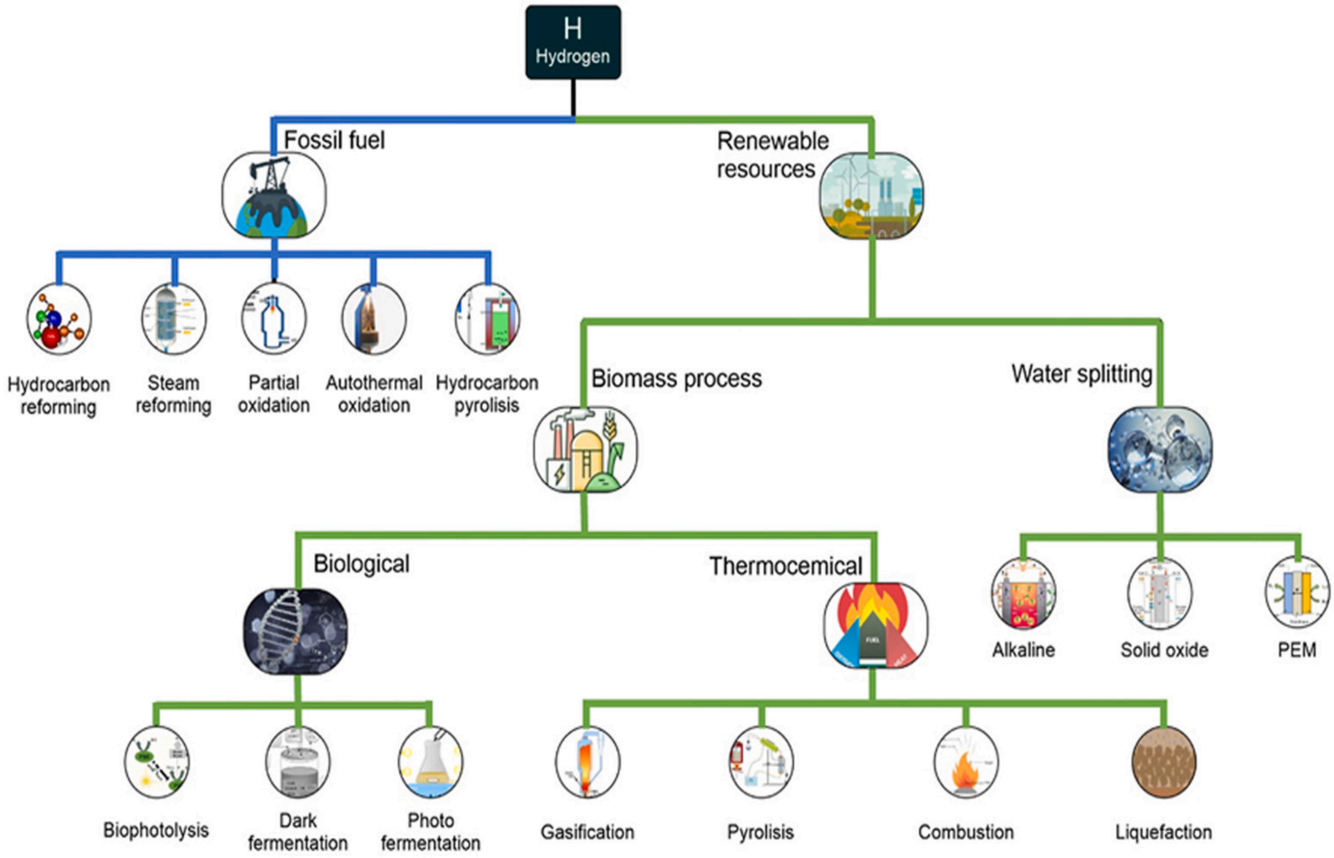


Figure 5: Hydrogen production technologies (Fossil fuel-based and Renewables sources-based) (Zainal, et al., 2024)

Brown, grey, and black hydrogen are substantial sources of greenhouse gas (GHG) emissions among the color-coded hydrogen categories. The production of grey hydrogen, which is commonly made from fossil fuels like coal and natural gas, releases carbon dioxide into the atmosphere. The use of black or brown hydrogen, produced from coal, denotes the kind of fossil fuels used—bituminous or lignite, accordingly. Green hydrogen is made by using green power to electrolyze water, rendering it free of carbon emissions and giving it its name (Zainal, et al., 2024). Green hydrogen, produced from RES, is poised to be essential in the decarbonization of the oil and gas industry's supply chain (Martin, et al., 2020)

An example of a typical green hydrogen supply chain is shown in the figure that follows. As we can see, there are 4 main stages: Electricity production, Hydrogen production, Transportation, and end users.

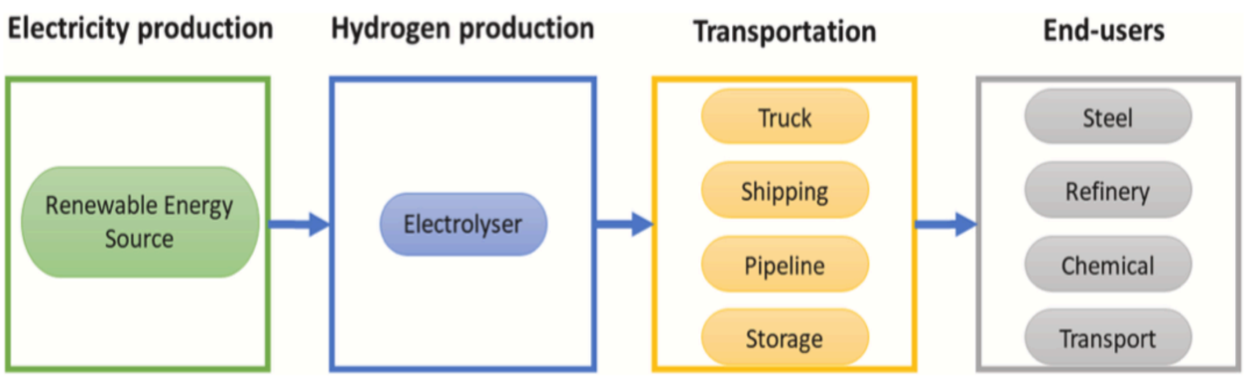


Figure 6: Green hydrogen supply chain (Azadnia, et al., 2023)

As a key player in the energy transition, green hydrogen has the potential to significantly decrease carbon emissions from the supply chain that supplies oil and gas (Stockl, et al., 2021). The trade-off between energy efficiency and temporal flexibility in its supply chains highlights its benefits for the electricity sector, especially in lowering curtailment and surplus generation from renewable sources (Stockl, et al., 2021). By offering a versatile solution, green hydrogen emerges as a valuable asset in optimizing the overall efficiency of the energy system, contributing to the sustainability goals of the oil and gas industry (Elshafei & Mansour, 2023).

However, the integration of green hydrogen into remote oil and gas facilities is not without its challenges. Technical and financial obstacles present hurdles that need careful consideration. Addressing these challenges becomes crucial for unlocking the full potential of green hydrogen in the sector. Velarde's (2021) insights emphasize the feasibility of overcoming these obstacles through the strategic utilization of renewable energy technology (Velarde, 2021).

The technical challenges involve ensuring the seamless integration of green hydrogen technology into existing infrastructure, optimizing processes for efficient production, and addressing potential compatibility issues. Financial obstacles may include the initial investment costs associated with transitioning to green hydrogen-based systems, as well as ongoing operational expenses. Velarde's (2021) proposal to employ renewable energy technology suggests a holistic approach to tackle these challenges, emphasizing the need to leverage cutting-edge innovations to create synergies between renewable energy and green hydrogen production (Velarde, 2021).

In conclusion, green hydrogen's prominence in the decarbonization journey of the oil and gas industry is evident. It not only addresses the challenges within the supply chain but also contributes to the broader energy transition goals. The trade-off it presents between energy efficiency and temporal flexibility showcases its adaptability, especially in the electricity sector. While obstacles exist, the proposal to utilize renewable energy technology offers a promising approach to surmounting these challenges, ensuring that green hydrogen realizes its full potential as a transformative force in the pursuit of a sustainable and decarbonized future for the oil and gas sector.

C. Benefits and challenges of integrating Green Hydrogen in the supply chain

Green hydrogen offers potential applications in transportation, energy storage, and power supply in remote facilities (Velarde, 2021). The hydrogen value chain, seen in the image below, consists of the following: hydrogen consumption in hard-to-abate sectors; hydrogen supply via port-based imports of hydrogen (derivates) and domestic hydrogen production; and hydrogen transport and storage. Transportation, steel, chemicals, and other industries were identified as difficult-to-abate sectors. Ammonia, methanol, olefins, and aromatics are classified as chemical sub-sectors, 'other industries' include refineries, cement, and high temperature heat. Cars, buses, trucks, trains, watercraft, and airborne applications are sub-sectors of the transportation sector (WaterstofNet, 2023).

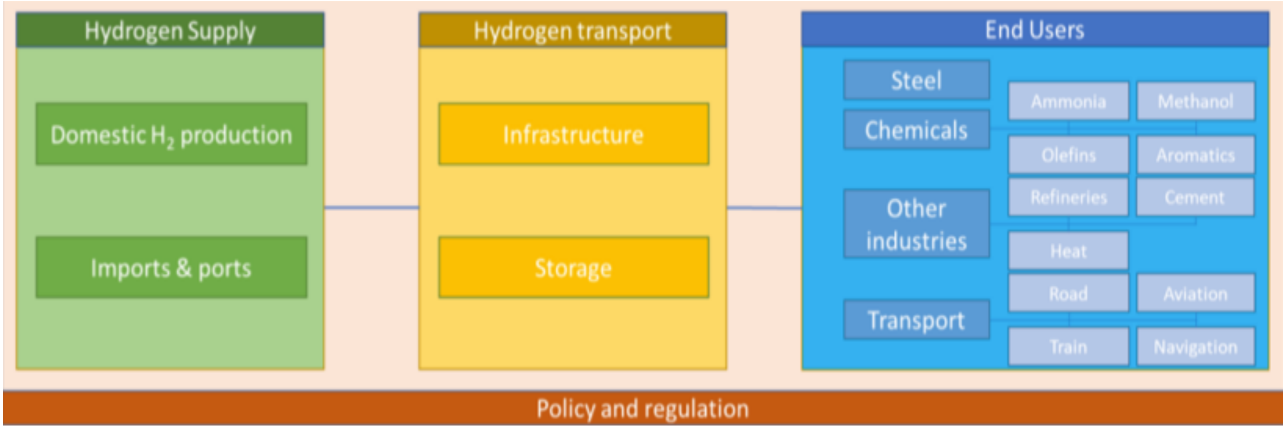


Figure 7: Hydrogen Value Chain (WaterstofNet, 2023)

All economic sectors and the energy system as a whole, including transportation and stationary activities like power generation, large-scale industrial processes, chemical feedstocks, and heating, can benefit from hydrogen's low-emission energy. According to Azadnia et al (2023), these various hydrogen uses can be divided into two categories:

1. Hydrogen as an industrial feedstock: Policymakers are prioritizing climate change, leading to increased usage of hydrogen in various industrial processes. (Azadnia, et al., 2023).
2. Hydrogen as a carrier of energy supporting the energy transition: The versatility of hydrogen to be utilized in a variety of applications, as well as zero-emission production and consumption, underscores hydrogen's vital position in the economy's carbon reduction ambitions (Azadnia, et al., 2023).

The use of hybrid renewable energy sources, such as solar and wind, in green hydrogen generation further enhances its sustainability and reliability (Sarker, et al., 2023). Additionally, blending green hydrogen with natural gas can improve renewable energy utilization without the need for significant infrastructure upgrades (Ekhtiari, et al., 2022)

Thus, green hydrogen has the potential to drastically reduce carbon emissions in the oil and gas industry's supply chain (Velarde, 2021). However, its integration presents both benefits and challenges. On the one hand, it can enhance the flexibility and efficiency of power supply systems in remote facilities (Velarde, 2021) and contribute to the decarbonization of the transportation sector (Stockl, et al., 2021). But its large-scale production cost and infrastructure requirements pose significant barriers (Eljack & Kazi, 2021).

The potential of hydrogen addresses the difficulty of industrial decarbonization, particularly for hard-to-decarbonize industries such as iron and steel, cement, and chemicals. As a plentiful and electricity-dense fuel, hydrogen shows potential for satisfying industrial energy needs and offering long-term energy storage. However, there are considerable logistical obstacles and expenses connected with isolating and harnessing hydrogen for industrial decarbonization. Currently, hydrogen consumption in industries is predominantly linked to oil refining and chemical synthesis, both of which are primarily derived from fossil fuels, emphasizing the need for developments in sustainable hydrogen production technologies (Griffiths, et al., 2021).

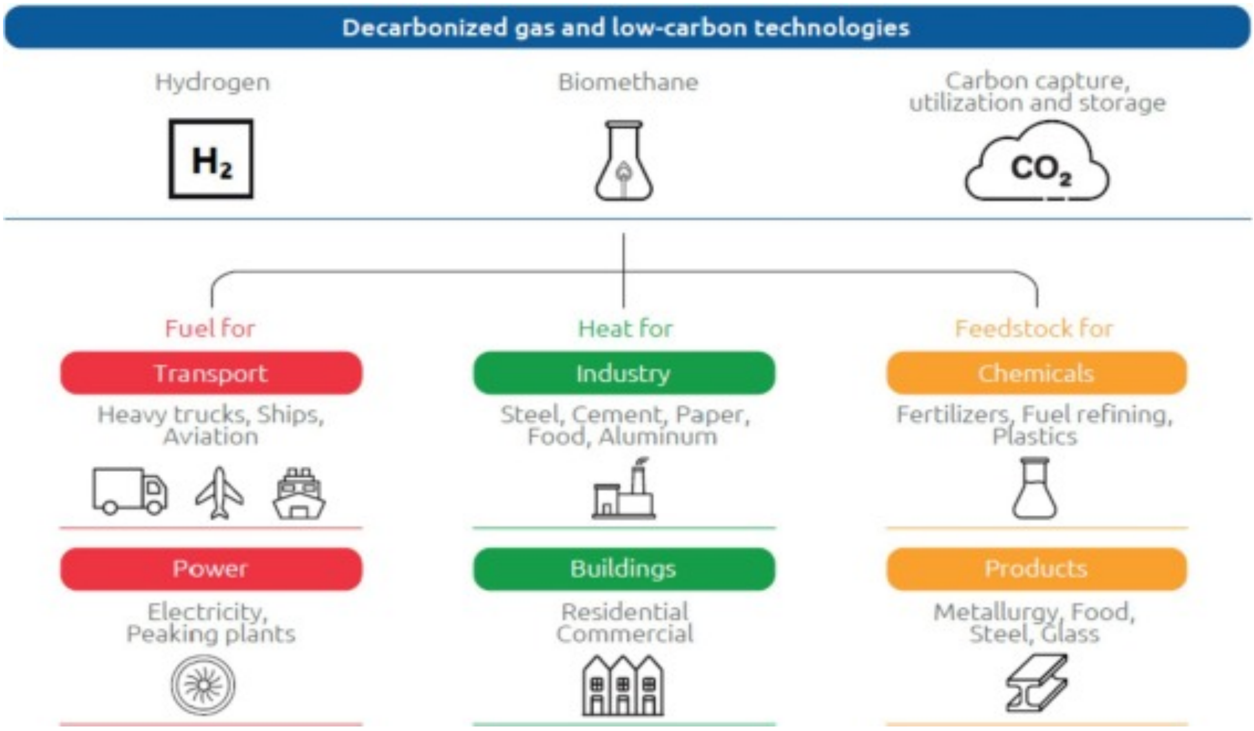


Figure 8: Hydrogen's potential to serve as a versatile decarbonized gas (Griffiths, et al., 2021)

Thus, hydrogen is an appealing source of energy because of its potential for energy security, synergy with existing industries, feasible transition routes, sector coupling for renewable energy integration, and critical role in the decarbonization of industry, particularly in sectors with hard decarbonization processes (Griffiths, et al., 2021).

Currently, eight percent (8%) of the reported global net low-carbon hydrogen generation capacity is held by oil and gas majors, amounting to 102.6 million tonnes per annum (Mtpa), as per Wood Mackenzie's recent analysis (WoodMackenzie, 2023). The global low-carbon hydrogen production is projected to grow from 1 Mtpa in 2023 to 200 Mtpa by 2050, according to Wood Mackenzie's Energy Transition Outlook. With Equinor leading the way in overall announced production capacity, BP, Shell, and Equinor hold the highest shares of the announced capacity for low-carbon hydrogen. (WoodMackenzie, 2023).

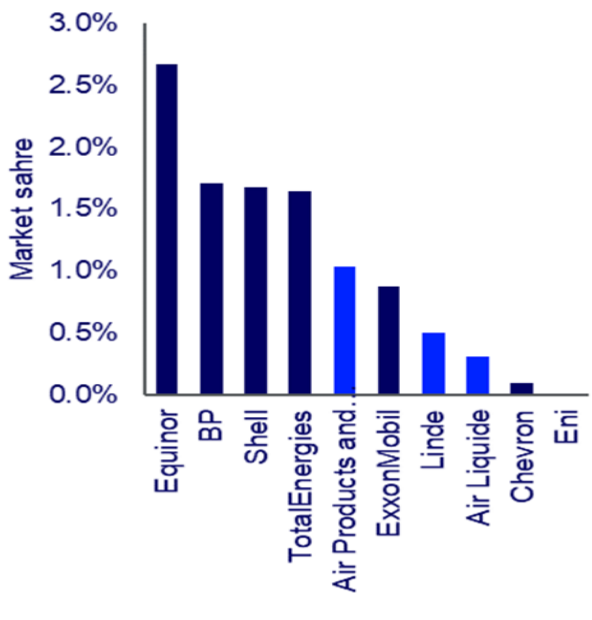


Figure 9:Global net announced capacity (Mtpa), % market share. Source: Wood Mackenzie Lens Hydrogen & Ammonia

Moreover, following a thorough examination, Green hydrogen can also contribute to the decarbonization of the transportation sector and the integration of renewable energy sources. To begin with, green hydrogen is a clean energy carrier that can be used in a variety of forms of transportation, such as fuel cell vehicles and hydrogen-powered trains, lowering carbon emissions associated with traditional fossil fuel-based transportation. Its application extends to sectors where electrification may be difficult or inefficient. Green hydrogen can help with energy storage and long-distance travel in the transportation sector. In comparison to electric vehicles, hydrogen fuel cell vehicles have a longer driving range and quicker refueling times, making them a viable alternative for specific transportation needs. (Stockl, et al., 2021).

Furthermore, the use of green hydrogen as a feedstock and fuel in the chemical industry can help decarbonize the sector. Green hydrogen can be used as a sustainable feedstock in a variety of chemical processes. Hydrogen is frequently generated from fossil fuels in traditional chemical manufacturing, contributing to carbon emissions. The chemical sector may drastically lower its carbon footprint by replacing conventional hydrogen with green hydrogen generated through renewable energy-powered electrolysis. This shift is consistent with the industry's goal of transitioning to more environmentally friendly and sustainable practices. (Rambhujun, et al., 2020).

Green hydrogen, which is produced from renewable energy sources, is a dynamic energy storage solution in the oil and gas supply chain. Offshore renewable energies using PEM electrolysis can generate green hydrogen, which can then be stored via the power-to-gas process (Gondal, 2019). Furthermore, the deployment of large-scale hydrogen supply chains, particularly those utilizing liquid hydrogen, provides significant benefits to the electricity sector, most notably in minimizing renewable curtailment (Stockl , et al., 2021).

In conclusion, in order to address these challenges, a multi-sector industrial-urban symbiosis approach could be proposed. It could allow the development of a multi-sector hydrogen supply chain and improve the interaction between industries and urban planning (Eljack & Kazi, 2021). Despite these challenges, green hydrogen has plenty of potential to help the industrial sector accomplish the goals of the energy transition (Martin, et al., 2020).

IV. Green Certificates (Guarantees of Origin) and their Relevance to the Oil and Gas Industry

A. Explanation of Green Certificates and their purpose

In 2001, the European Union (EU) established the Guarantees of Origin (GOs) system as a complement to Renewable Energy Certificates (RECs) through the adoption of the Renewable Electricity Directive (Linden, et al., 2004). The EU's Renewable Energy Directive of 2001 established certification schemes to certify the origin of power from either renewable or non-renewable sources, resulting in different implementations across European countries including distinctive structures and performance indicators. The key year 2007 witnessed the European Council establish binding targets for the EU, aiming to reach a 20% renewable energy consumption by 2020, opening the path for comprehensive regulations leading to the European Commission's 2009/28/EC Renewables Directive. This directive was important in harmonizing Renewable Energy Sources (RES) policy by providing Guarantees of Origin (GOs) trading, setting national targets for renewable energy shares, and implementing sustainability criteria for biofuels in transportation. The regulation, regarded as one of a turning point in the EU's commitment to renewable energy, underwent significant amendment in 2018 (RED II) to line with the EU's 2030 aim of achieving a least 32% proportion of renewable energy (Hulshof, et al., 2019). Notably, on October 9, 2023, the EU Council adopted the modified RED III, with revisions enhancing existing regulatory measures involving Renewable Power Purchase Agreements (PPAs) and guarantees of origin. This new directive intends to increase the proportion of renewable energy to 42.5% by 2030. The incorporation of GOs trading inside these rules reflects the EU's continued attempts to standardize and promote the usage of renewable energy throughout its member states (Commission, 2023).

Green Certificates, also known as Guarantees of Origin, are documents that verify the production of electricity from renewable sources (Gkarakis & Dagoumas, 2016).They play a crucial role in promoting the use of renewable energy, reducing emissions, and stimulating sustainable development (Pavaloaia, et al., 2015). However, despite their significant impact, the current system of Green Certificates has certain limitations, creating a motivation for exploration and improvement.

One of the primary challenges within the existing system, as identified by Delardas and Giannos (2022), is a lack of transparency. This lack of transparency introduces uncertainties into the process, potentially undermining the credibility and effectiveness of the Green Certificate system (Delardas & Giannos, 2022). Additionally, issues with additionality pose another hurdle, raising questions about the actual environmental impact of the certified renewable energy generation. To address these challenges, the introduction of blockchain technology has been proposed as a viable solution, as discussed by (Delardas & Giannos, 2022). Blockchain, with its inherent characteristics of transparency, immutability, and decentralized record-keeping, has the potential to revolutionize the Green Certificate system. By leveraging blockchain, the certification process can be made more transparent, traceable, and secure, mitigating the issues associated with the current system. This proposed integration of blockchain technology aligns with the broader trend of utilizing innovative digital solutions to enhance the efficiency and reliability of processes in various industries (Mi, et al., 2019).

Green Certificates have effects for the oil and gas industry that go beyond the immediate sphere of renewable energy. Their ability to stimulate investments in renewable energy sources inside the oil and gas sector holds great promise (AINuaimi, et al., 2020). Green Certificates can be strong tools to stimulate and incentivize the adoption of renewable energy practices as the industry grapples with the requirement to move to sustainability. This is especially important for an industry that has traditionally been linked with carbon-intensive activities, underscoring the transformative role Green Certificates may play in driving the oil and gas sector toward a more ecologically friendly and sustainable path (Griffiths, et al., 2021).

In essence, Green Certificates are an important tool in the larger transition to a more sustainable energy sector. While their contribution to the promotion of renewable energy is unquestionable, the current constraints need creative solutions. The suggested incorporation of blockchain technology provides a possible path for overcoming existing issues while also bolstering the credibility of Green Certificates (Zhao, et al., 2020). Moreover, their relevance extends to industries like oil and gas, where these certificates can serve as powerful catalysts for change, incentivizing investments in renewable energy sources and contributing to the overall sustainability goals of these traditionally carbon-intensive sectors. As the world grapples with the urgent need for a sustainable energy future, Green Certificates stand as a bridge, connecting renewable energy producers, industries, and regulatory bodies in a collective effort to mitigate climate change and foster a more environmentally conscious and sustainable global energy landscape.

B. Regulatory frameworks and market mechanisms for Green Certificates

Understanding how Green Certificates are influenced by regulatory frameworks and market mechanisms is crucial for comprehending the dynamics of renewable energy adoption. Studies have delved into this complex landscape, contributing valuable insights to answer the central question: How do regulatory frameworks and market mechanisms influence the efficacy of Green Certificates in promoting renewable energy?

According to Jansen et al (2016), numerous countries have implemented national tradable green certificate systems, over the years, to promote the integration of additional renewable energy into their electricity supplies (Jansen, et al., 2016). Thus, Green Certificates, such as Guarantees of Origin (GOs) in the European Union and as Renewable Energy Certificates (RECs) globally (e.g. in the USA), have played a pivotal role in advancing renewable energy (Linden, et al., 2004). RECs incentivize and monitor renewable energy generation, while GOs provide consumers with information about electricity sources, encouraging the adoption of renewable energy. Tradable Renewable Certificates (TRC) and Quota System with Tradable Green Certificates (TGC) are examples of successful efforts to promote renewable energy usage, illustrating the effectiveness of these certificates (Currier & Rassouli-Currier, 2018).

Moreover, feed-in tariffs and tradable green certificates are probably the two primary instruments used in electricity markets to encourage the use of renewable energy. Tradable green certificates involve setting a green quota, specifying the percentage of electricity sourced from renewables (Currier & Rassouli-Currier, 2018). Producers issue certificates, traded in a separate market, with penalties for non-compliance. This system is implemented globally, including in the United States, India, South Korea, China, Australia, Belgium, Norway, Romania, and Sweden. Feed-in tariffs, guaranteeing a set price or premium over the market price, are widely used in EU countries like France, Germany, the Czech Republic, Greece, and Italy (Mi, et al., 2019). Combining green certificates with a quota obligation, such as a renewable portfolio standard, is crucial for fostering renewable energy, creating a tradable market for certificates that prove compliance.

A range of studies have explored the regulatory frameworks and market mechanisms for Green Certificates. Wang (2019) and Mi (2019) both highlight the potential for these mechanisms to promote renewable energy development, with specifically focusing on the Chinese context (Wang, et al., 2019). Ciarreta (2017) and Hustvedt (2017) compare Tradable Green Certificates to Feed-in

Tariffs, with Ciarreta (2017) suggesting that the former could be more responsive to market conditions (Ciarreta, et al., 2017) (Hustveit, et al., 2017). However, However, concerns about market power and the influence of risk factors on the Green Certificate market are raised (Amundsen & Nese, 2016), (Lind & Rosenberg, 2014). Schusser (2016) adds to this by examining the interplay between Green Certificates, carbon emissions, and electricity prices, finding that increases in carbon prices can positively affect Green Certificate prices (Schusser & Jaraite, 2018).

Furthermore, the use of green certificates has recently expanded beyond the power sector, indicating a significant expansion into other fields. The use of these certificates to promote the generation and use of green gasses is a noteworthy step in this diversification. The expansion of the green certificate framework into areas other than electricity demonstrates its adaptability and growing impact in encouraging sustainability across the energy landscape (Abad & Dodds, 2020).

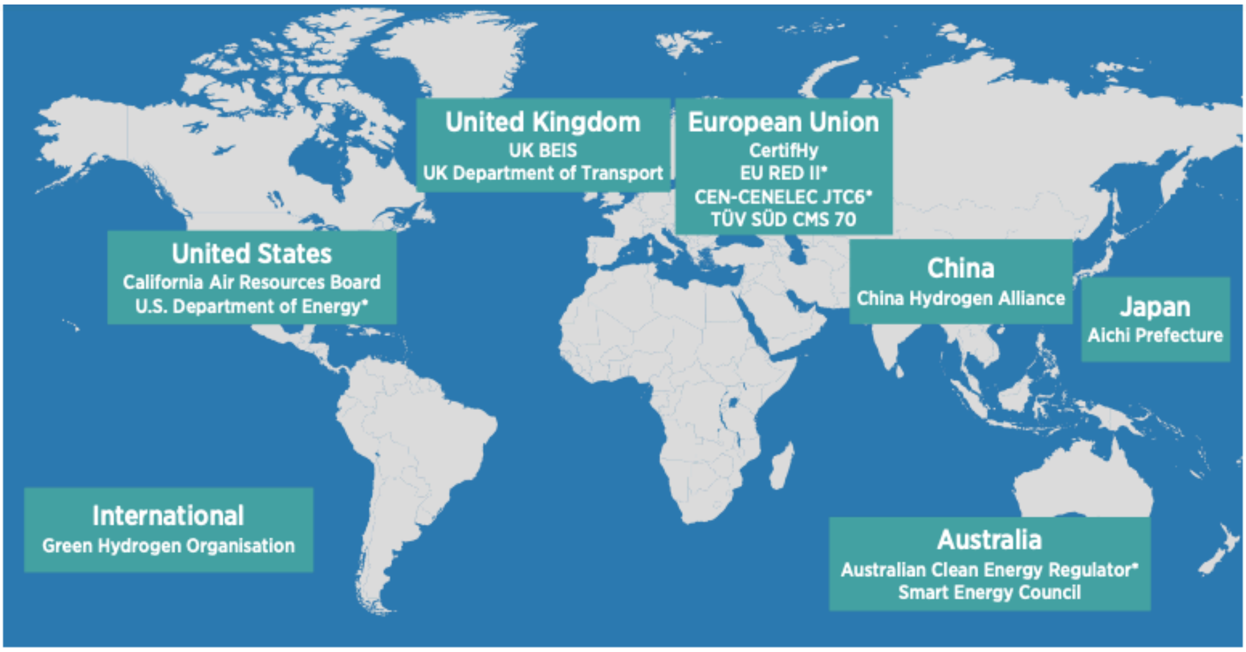
In conclusion, extensive research underscores the global importance of green certificates in driving the shift toward eco-friendly and sustainable energy systems. The introduction of renewable energy certificates has proven to be a compelling incentive for investments in renewable projects over the years. The assumption arises that well-structured market mechanisms not only promote renewable energy adoption but also serve as risk management tools. The roles of RES owners and consumers, legislative frameworks, and the need for context-specific approaches emerge as key components influencing the efficacy of Green Certificates in fostering a sustainable energy transition (Narula, 2013). The interplay between these elements is crucial for shaping the trajectory of renewable energy adoption, aligning with international initiatives to tackle climate change and build a more sustainable future.

C. Potential for Green Certificates to incentivize the use of Green Hydrogen in the supply chain

The potential for Green Certificates to incentivize the use of Green Hydrogen in the supply chain is a multifaceted and intricate issue, necessitating a comprehensive exploration of various factors. In recent research, scholars have delved into this complex terrain, shedding light on the challenges, trade-offs, and opportunities associated with integrating Green Hydrogen into the broader energy landscape. Decarbonization of industry with hydrogen would necessitate regulatory tools that encourage both hydrogen production and demand while also supporting the development of the essential supply chain infrastructure. While policy toolkits for renewable energy generation and consumption can be built on existing initiatives, hydrogen-specific policy instruments are required (Griffiths, et al., 2021).

Stöckl (2021) highlights the trade-off between energy efficiency and temporal flexibility in hydrogen supply chains. Their work underscores that large-scale chains not only offer efficiency benefits but also contribute to the optimization of the power sector (Stockl , et al., 2021). This highlights the intricate balance required in designing hydrogen supply chains that not only harness the environmental benefits but also align with the broader energy infrastructure (Griffiths, et al., 2021).

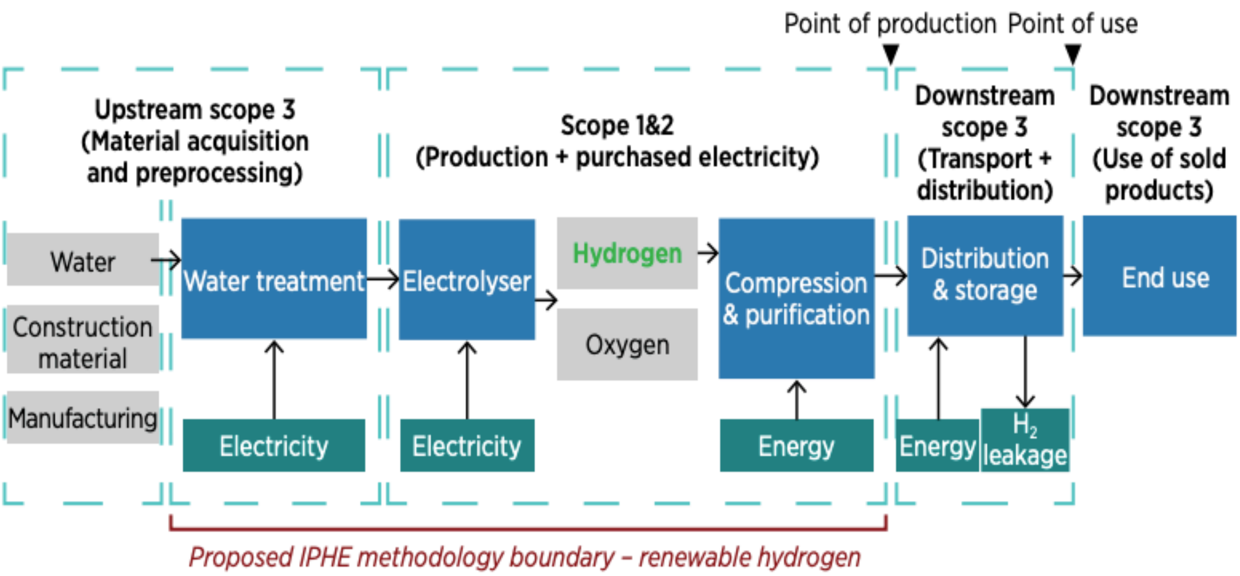
Furthermore, Abad (2020) and Noussan (2020) emphasize the importance of defining and standardizing green hydrogen, with the latter also underscoring the need for a strong international consensus (Abad & Dodds, 2020) (Noussan, et al., 2021). These findings accentuate the need for clear definitions and a globally recognized framework to guide the production and utilization of green hydrogen. Establishing such standards becomes a crucial foundation for the effective implementation of Green Certificates in incentivizing the use of this environmentally friendly energy source.



Notes: * in development. BEIS = Department for Business, Energy and Industrial Strategy; CEN = European Committee for Standardization; CENELEC = European Committee for Electrotechnical Standardization; JTC = Joint Technical Committee; RED II = Renewable Energy Directive II.
Disclaimer: This map is provided for illustration purposes only. Boundaries and names shown on this map do not imply the expression of any opinion on the part of IRENA concerning the status of any region, country, territory, city or area or of its authorities, or concerning the delimitation of frontiers or boundaries.

Figure 10: Map of organizations working on hydrogen certification (IRENA and RMI (2023), 2023)

However, the accepted standard, in order to be successful, should refer to or directly specify a clear system boundary, as far as the green hydrogen supply chain is concerned. This limit should encompass the major emission sources from the hydrogen production supply chain (e.g., power for electrolysis in the renewable pathway; fugitive methane and capture unit upstream in the abated fossil pipeline). Typically, system boundaries are set to encompass either well-to-gate (up to the point of production) or well-to-wheel (up to the point of usage) paths. These limits serve as the foundation for distinguishing hydrogen generation processes. (IRENA and RMI (2023), 2023).



Notes: IPHE = International Partnership for Hydrogen and Fuel Cells in the Economy.

Figure 11: Supply chain and system boundary for green hydrogen (IRENA and RMI (2023), 2023)

In summary, certification procedures, specifically Guarantees of Origin (GO) schemes, are critical in assuring traceability and accountability in the production of low-carbon hydrogen (Abad & Dodds, 2020). These methods, some of which are already in use in renewable energy systems, attempt to account for lifecycle greenhouse gas emissions, support geographically separated production and consumption, and allow policymakers and end users to make informed decisions. Transparency, uniformity, conformity with emissions criteria for other commodities, and comparability with alternative energy sources should be prioritized in the design of GOs (Griffiths, et al., 2021). The following Table summarizes existing and prospective hydrogen GO systems, highlighting significant properties.

Body (Country)	Type	Main Policy Objective	Baseline GHG threshold	Qualification level	Qualifying processes	System boundary
AFHYPAC a (France)	GO scheme (working group proposal)	Renewable energy source	None	Must be 100% renewable	Any renewable pathway, including electrolysis powered by waste (with renewable electricity or biomethane GO).	Point of production
BEIS b (UK)	Standard Consultation (abandoned)	Reduction of CO2 emissions	Never determined	To be determined. A single threshold differentiated according to end use (e.g., transport)	Any (technology neutral)	Point of production
California Low Carbon Fuel Standard	Regulation (active)	Reduction of air quality and CO2 emissions. Third of vehicle hydrogen produced from renewable energy.	WTW emissions from new gasoline vehicles	30% lower GHG and 50% lower NOX emissions (on WTW per mile basis) for fuel cell electric vehicles	Renewable electrolysis, catalytic cracking of SMR of biomethane or thermochemical conversion of biomass, including MSW.	Point of use
CEN/CENELEC CLS JCT 6 WG1/WG2 (International)	International Standard (in preparation)	Terminology, GO, interfaces, operational management, safety, training and education	Adopted from CertifHy	Adopted from CertifHy	Adopted from CertifHy	Adopted from CertifHy
CERTIFHY (EU wide)	GO scheme (testing)	Renewable energy source/GHG emissions	Hydrogen produced via SMR of natural gas	At least 60% lower than SMR c (this is ≤ 36.4 gCO2e/MJ H2 for the past 12 months)	Any renewable pathway meeting the threshold with 99.5% purity	Point of production
TÜV SÜD (Germany)	National Standard (active)	Reduction of CO2 emissions	Hydrogen from SMR of natural gas	35–75% emissions reduction below baseline (83.8–89.7 gCO2e/MJ), depending on production process, and time phase	Renewable electrolysis; biomethane SMR; pyro-reforming of glycerin	

Figure 12:Initiatives to characterize green hydrogen all across the world (Griffiths, et al., 2021)

To fulfill all of its potential as an EU-wide GO, the earlier CertifHy scheme has been standardized as well as harmonizing with the European Renewable Energy Directive III (EU RED III).

Finally, these GOs help to develop functional hydrogen markets, as seen in the following Figure, where both physical and virtual tracing approaches contribute to GO efficacy.

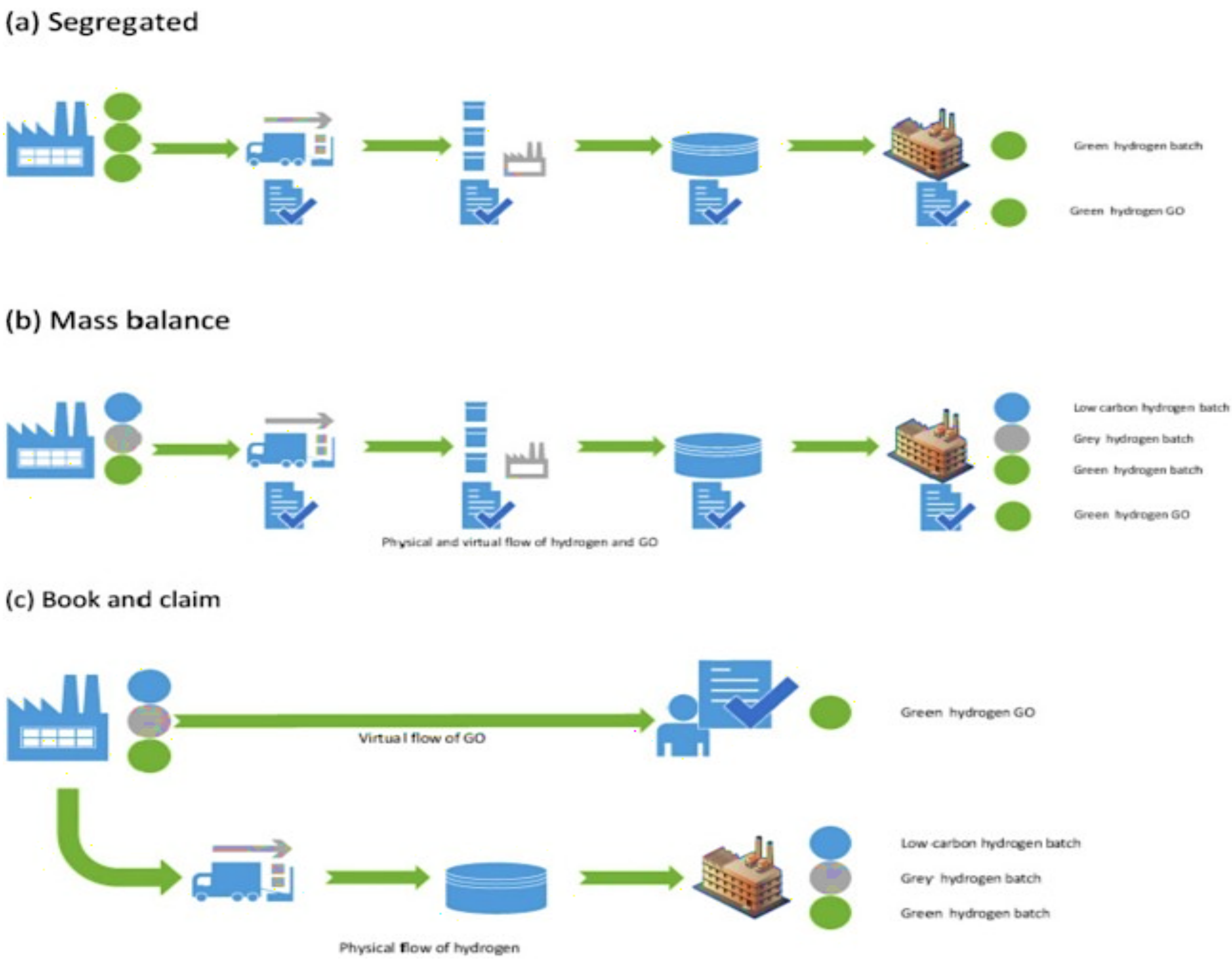


Figure 13:Strategies to chain of custody for green hydrogen origin certification (Griffiths, et al., 2021)

In conclusion, the potential for Green Certificates to incentivize the use of Green Hydrogen in the supply chain is a multifaceted challenge that requires a holistic understanding of energy efficiency, international consensus on definitions and standards, regional legal and policy frameworks, and sector-specific applications. For example, studies by Eljack (2021) and Ballo (2022) discuss the challenges and opportunities of a hydrogen-based economy, with the latter specifically focusing on the legal and policy framework in specific region (Eljack & Kazi, 2021) (Ballo, et al., 2022). This reinforces the idea that the integration of Green Hydrogen into supply chains requires a nuanced understanding of the legal and policy landscapes in various regions. When focusing on sectors rather than regions, consider the instances provided by Maganza (2023) and Atilhan (2021) who explore the potential applications of green hydrogen in the agriculture and livestock sector and the shipping industry, respectively, with both highlighting the need for appropriate policies and financial incentives. Therefore, all the aforementioned studies collectively underscore the intricate dynamics at play and emphasize the importance of well-defined policies and incentives to drive the adoption of green hydrogen across diverse sectors and regions (Eljack & Kazi, 2021).

V. Analysis and Case Study

A. Data analysis and findings from case study

The Equinor case study, with a focus on the NortH2 project, gives a thorough evaluation of the construction of a large-scale green hydrogen generation facility in the Netherlands. The NortH$_2$-project, Europe's largest green hydrogen initiative, is a key case study for understanding the real-world application and challenges of integrating green hydrogen and green certificates into the supply chain (Equinor, 2020). The goal of the NortH2 project is to create green hydrogen using renewable electricity from offshore wind off the coast of the Netherlands. It is a partnership between Equinor, RWE, Shell, Groningen Seaports Gasunie, and the province of Groningen..

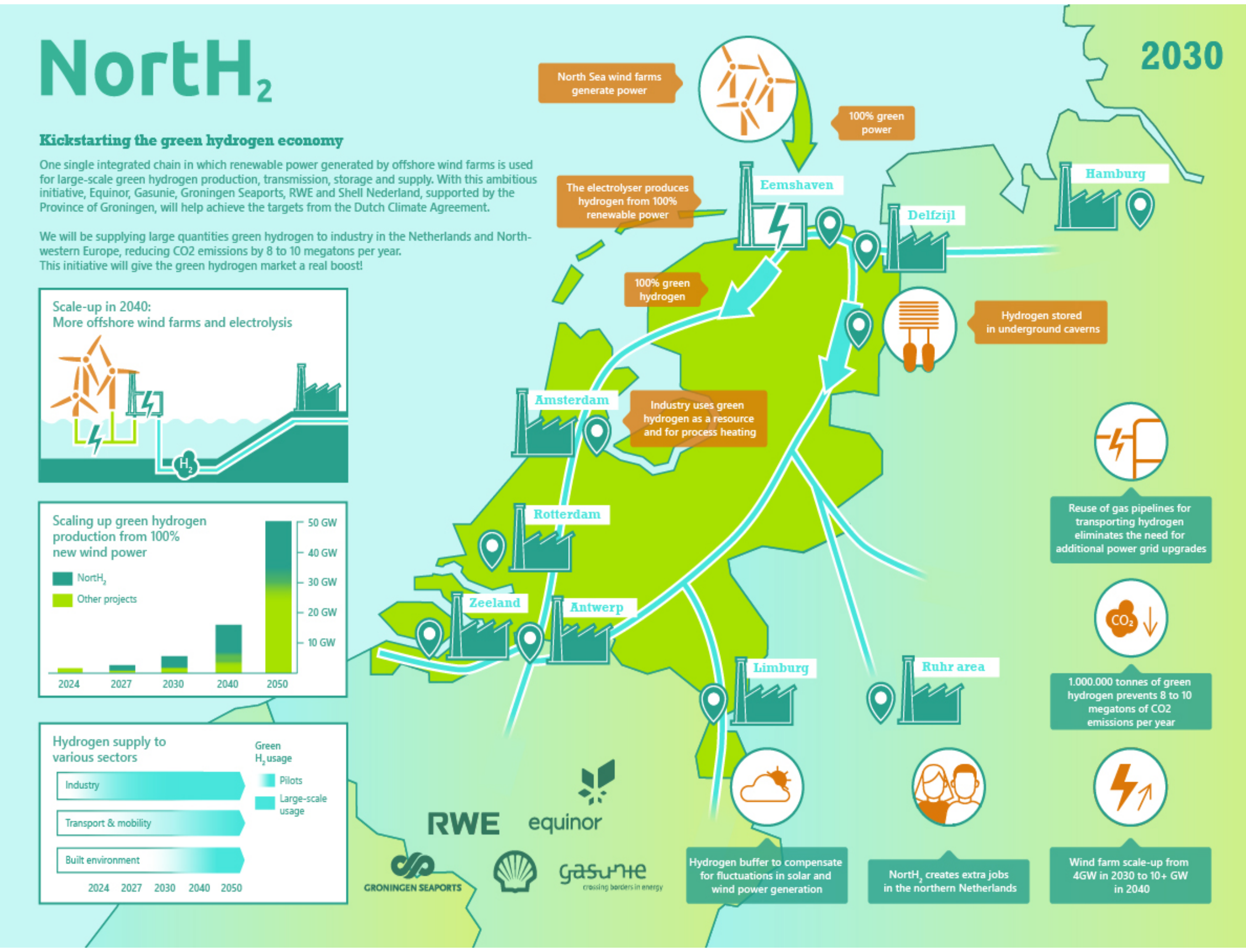


Figure 14: Map of NortH$_2$ Poject (north2, 2023)

This project aligns with the EU's climate targets and is a significant part of the energy transition (Wolf & Zander, 2021). The primary goal of this project is to harness the potential of renewable energy sources, notably offshore wind, to generate hydrogen—an environmentally beneficial and adaptable fuel that has the potential to reduce carbon emissions across a wide range of businesses. The NortH$_2$ initiative is positioned as a key actor in the larger effort to promote a more sustainable energy system.

The NortH$_2$ project, at its core, illustrates a dedication to using offshore wind energy to manufacture hydrogen, thereby offering a clean and renewable alternative to conventional energy sources. This is consistent with broader worldwide initiatives to shift toward sustainable energy alternatives, address climate change concerns, and reduce reliance on fossil fuels. The initiative intends to drastically reduce carbon emissions by harnessing offshore wind, a dependable and abundant renewable resource (Lohr, et al., 2023).

The NortH_2 project, initiated by a consortium comprising Gasunie, Groningen Seaports, and Shell Nederland, is a groundbreaking venture aiming to spearhead Europe's largest green hydrogen production facility. The project, launched in Groningen, envisions a comprehensive energy transition—from renewable power generation to the distribution of green hydrogen—through collaborative efforts among various partners to achieve substantial scale and realize ambitious sustainability goals. Some Key highlights of the project are the following (Gasunie, 2020):

- The project's foundation lies in the construction of significant wind farms in the North Sea, capable of gradually reaching a capacity of around 10 gigawatts (1 GW by 2027, 4 GW by 2030, and 10+ GW by 2040). These wind farms are integral to the production of green hydrogen and are expected to be operational by 2027.
- The heart of the project involves a mega offshore wind farm feeding a large electrolyzer in Eemshaven, converting wind energy into green hydrogen. The consortium is also exploring the possibility of placing electrolyzers offshore to optimize hydrogen production.
- NortH_2 aims to generate approximately 3 to 4 gigawatts of wind energy for hydrogen production by 2030, with aspirations to increase this capacity to about 10 gigawatts by 2040. The anticipated green hydrogen production by 2040 is estimated at 800,000 tonnes annually, contributing significantly to the decarbonization of industries.
- The green hydrogen production from the NortH_2 project is expected to lead to a substantial reduction of approximately seven megatonnes of CO2 emissions annually by 2040. This aligns with the objectives of the Dutch Climate Agreement and the broader European 'Green Deal.'
- The province of Groningen is poised to become a European center for green hydrogen production, setting an example as the first European Hydrogen Valley. Beyond environmental benefits, the NortH_2 project has the potential to create thousands of jobs in the northern Netherlands.

In the following Figure we can see a similar example of an offshore green hydrogen production where Offshore wind farms provide electricity, which is subsequently utilized to power the electrolyzer, which convert water to hydrogen. The hydrogen is transferred onshore to the downstream customer via pipeline. Excess electricity can also be brought ashore via cable if it is generated (Davies & Hastings, 2023).

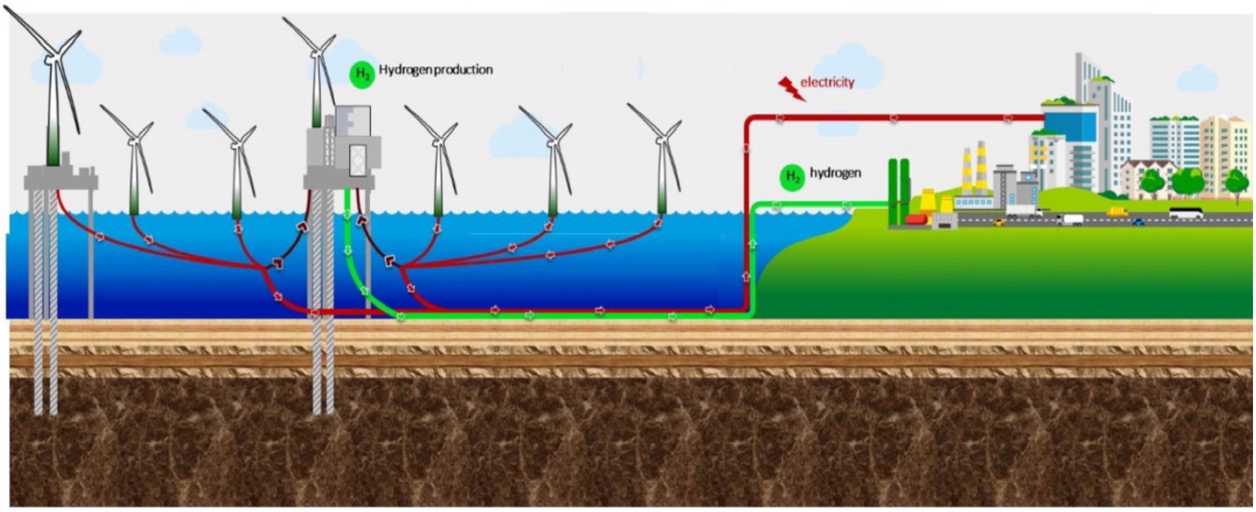


Figure 15: Example of an offshore green hydrogen production

Moreover, according to the European Hydrogen Observatory (2023), the average levelized cost of hydrogen production through electrolysis connected directly to a renewable energy source in Europe is 6.87 €/kg H2. The cost components include marginal costs (67% of total), with electricity costs being the largest contributor (90% of marginal costs), and CAPEX representing the second most significant portion (33% of overall cost). This emphasizes the critical impact of electricity costs in determining the total cost landscape, highlighting the importance of procuring power sustainably. In 2022, the LCoH falls below the price of hydrogen generated by grid electrolysis (9.85 €/kg H2), despite a bigger contribution from CAPEX expenses due to the electrolysis device's lower capacity factor. High grid energy prices, affected by a jump in natural gas prices, and lower grid costs through a direct connection to the renewable electricity source contribute to this outcome. Market dynamics, is a crucial factor, as fluctuations in energy markets, including the prices of natural gas and grid electricity, will continue to influence the overall cost competitiveness of hydrogen production (European Hydrogen observatory, 2023). Moreover, the increasing significance of solar and wind energy, as well as the decrease in renewable energy costs, may make hydrogen production from renewable power, through a power-to-gas process, less expensive (Glenk & Reichelstein, 2019).

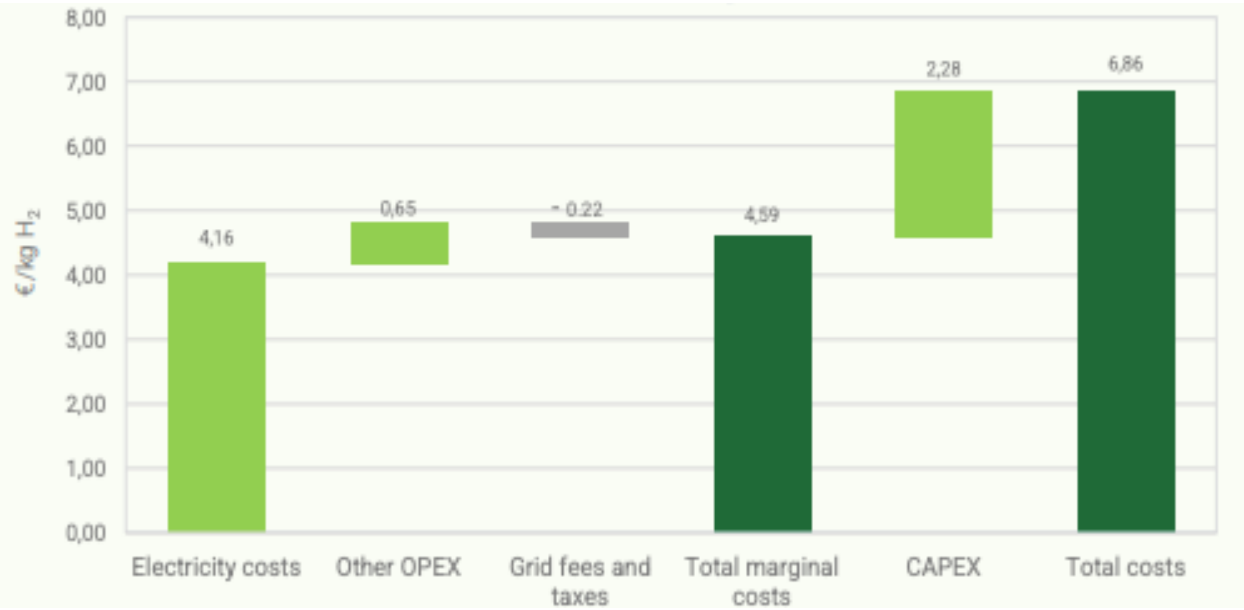


Figure 16:Average LCoH produced via electrolysis directly connected to a RES in Europe (European Hydrogen observatory, 2023)

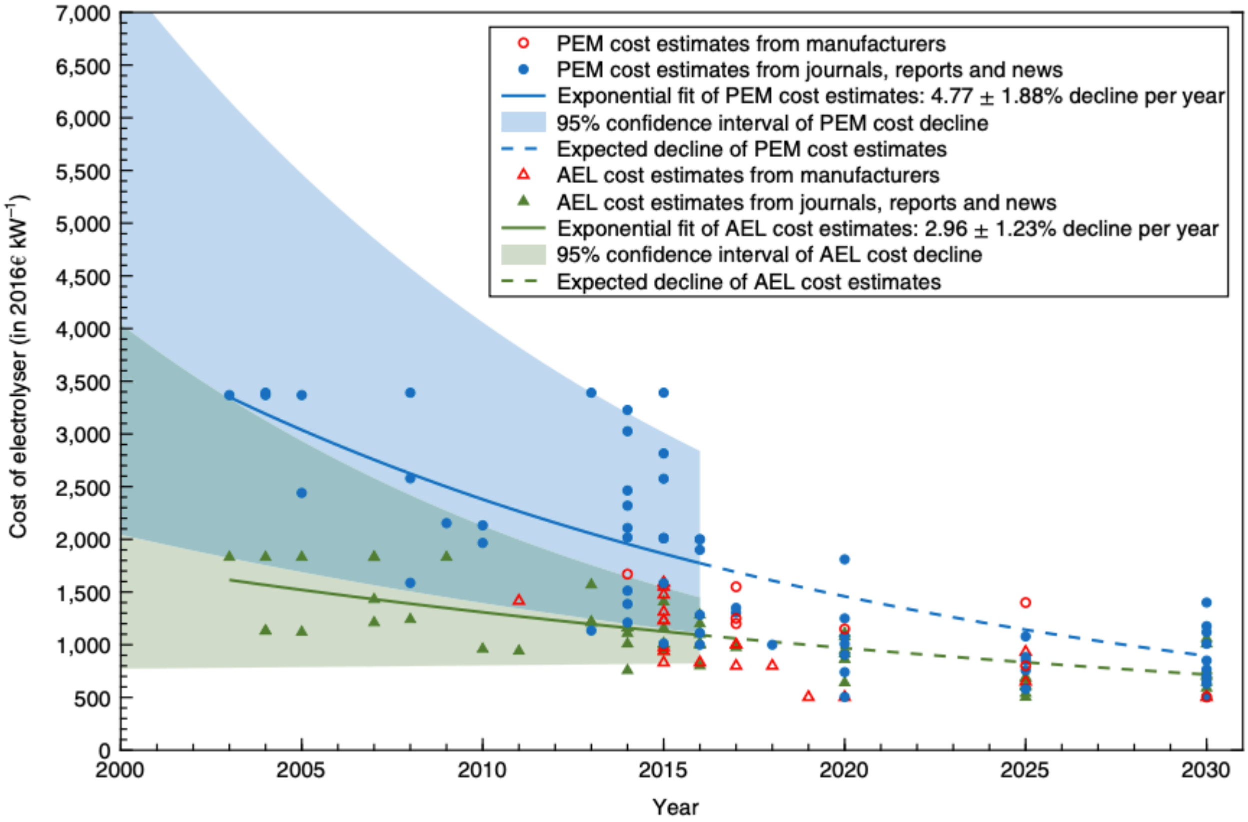


Figure 17: The cost of electrolyser technology for use in PtG. Cost information on PEM electrolysis and alkaline electrolysis (AEL) comes from a variety of sources (Glenk & Reichelstein, 2019)

Based on the data trends of the previous figure, the forecast for renewable hydrogen appears to be optimistic. There is substantial evidence of continual decreases in the system price of electrolyzer, emphasizing the potential for cost-effective hydrogen production by electrolysis. Furthermore, according to Glenk et al (2019), the system price of wind turbines, a critical component in renewable energy systems, has steadily declined, adding to the overall financial viability of green hydrogen production (Glenk & Reichelstein, 2019).

The highest hydrogen production costs through direct electrolysis connection to a renewable energy source are observed in Luxembourg (9.60 €/kg H2), followed by Slovakia (9.32 €/kg H2), Croatia (8.59 €/kg H2), and Slovenia (8.39 €/kg H2). Conversely, Portugal, Greece, and Bulgaria exhibit relatively low renewable hydrogen production costs, with figures of 5.20 €/kg H2, 5.18 €/kg H2, and 4.18 €/kg H2, respectively. In all countries, electricity costs constitute the largest cost component (European Hydrogen observatory, 2023).

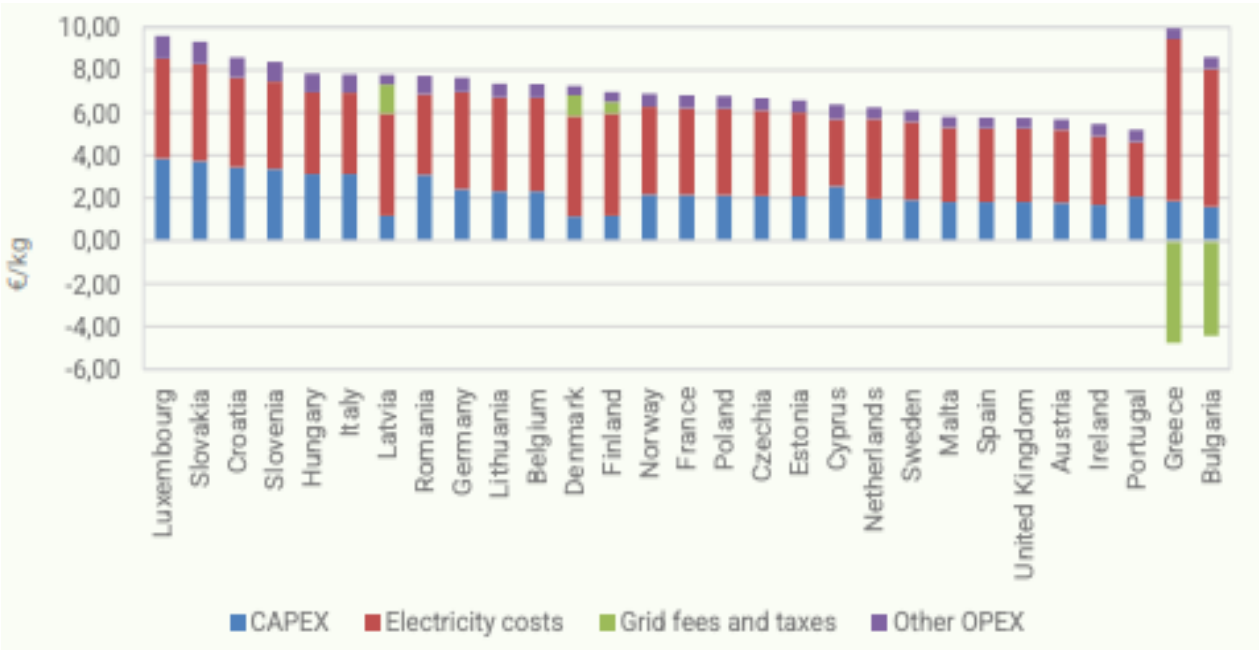


Figure 18: Average LCoH produced via electrolysis directly connected to a RES by country in 2022 (European Hydrogen observatory, 2023)

The development of green hydrogen is encountering challenges, primarily related to technical and commercial barriers. A significant obstacle is the high Levelized Cost of Hydrogen (LCOH) and based on the previous Figure, it is estimated that LCoH in the Netherlands for a project like $NortH_2$ would be in the 6-7€/kg H2 range.

The distinct advantage of NortH2's electrolyser lies in its production of hydrogen using 100% renewable power sourced from North Sea wind farms. This is particularly advantageous since electricity costs, which form the most substantial component of Hydrogen facility operation expenses, are thereby minimized (north2, 2023). On the other hand, CAPEX for an Offshore facility is significant and much higher than other RES (International Renewable Energy Agency, 2023), as we can see in the following figure.

	Total installed costs (2022 USD/kW)			Capacity factor (%)			Levelised cost of electricity (2022 USD/kWh)		
	2010	2022	Percent change	2010	2022	Percent change	2010	2022	Percent change
Bioenergy	2 904	2 162	-26%	72	72	1%	0.082	0.061	-25%
Geothermal	2 904	3 478	20%	87	85	-2%	0.053	0.056	6%
Hydropower	1 407	2 881	105%	44	46	4%	0.042	0.061	47%
Solar PV	5 124	876	-83%	14	17	23%	0.445	0.049	-89%
CSP	10 082	4 274	-58%	30	36	19%	0.380	0.118	-69%
Onshore wind	2 179	1 274	-42%	27	37	35%	0.107	0.033	-69%
Offshore wind	5 217	3 461	-34%	38	42	10%	0.197	0.081	-59%

Figure 19: Total installed cost, capacity factor and LCoE trends, 2010 and 2022 (International Renewable Energy Agency, 2023)

Although the costs of such a massive investment project are high, they may also generate significant revenues. First and foremost, the investment plan would play a major role in helping the country move away from an economy dependent on fossil fuels and toward one where a substantial amount of the energy consumed is derived from renewable sources. This transformation must take place quickly in order to achieve international agreements with the goal of limiting excessive global warming. Second, the initiative would increase jobs. The province of Groningen will serve as the base for major components of the project. The province, which has high unemployment and low household incomes, is among the poorest in the Netherlands, with the exception of its capital city. Therefore, NortH2 might give this area a much-needed economic boost. (Los & Dijk, 2020).

Los and Dijk (2020) estimate that operations related to asset ownership and maintenance will create about 1,000 employments in Groningen, 1,300 jobs in the North, and 1,900 jobs nationwide. These long-term employment consequences for Groningen and the Northern provinces would be good if the majority of labor demand was for medium-skilled workers and if the project was accompanied by significant expenditures in knowledge and skill development. To improve the likelihood of gaining a competitive advantage (over other regions, both in the Netherlands and outside of it), this should take place early in the project. (Los & Dijk, 2020).

B. Identification of success factors and barriers – SWOT analysis

The assessment of f Green Certificates and Green Hydrogen's potential in decarbonizing the oil and gas supply chain is a critical aspect of the Equinor case study. Green Hydrogen, produced from renewable sources, emerges as a key player in the decarbonization strategy for the oil and gas industry. Green Hydrogen Certification is actually the objective of the CertifHy effort, which is led by HINICIO and includes the Association of Issuing Bodies (AIB), GREXEL, Ludwig Bölkow System Technik (LBST), CEA, and TÜV SÜD, and is funded by the Clean Hydrogen Partnership. The initiative, which began in 2014, is currently in its third phase of implementation. The CertifHy Scheme and the Green and Low-Carbon Hydrogen labels were established during the first two phases. Following that, various methods for GO issuance, transfer, and cancellation were developed and tested in a pilot. This created the foundation for the world's first non-governmental Guarantee of Origin scheme for hydrogen. (CertifHy, 2023).

Moreover, the Equinor case study goes beyond mere evaluation and actively identifies the success factors and barriers associated with the integration of Green Hydrogen and Green Certificates in the oil and gas supply chain. Simultaneously, the study highlights potential barriers, such as infrastructural challenges, financial constraints, and regulatory hurdles that may impede the seamless adoption of green energy solutions. This identification of factors influencing success and obstacles aids in formulating targeted strategies for the successful implementation of sustainable practices within the industry.

For example, Hydrogen transport is currently limited and on a modest scale in the Netherlands. The demand for hydrogen is around 50 TWh, which is largely fulfilled by grey hydrogen produced from natural gas. Grey hydrogen is frequently produced near industrial clusters and end-users, with little CO_2 collection. Local pipes are utilized to transmit hydrogen or hydrogen-rich residual gas between industrial estate installations. Air Products and Air Liquide are the primary suppliers of pure hydrogen via private pipeline networks, with annual output estimated at less than 2.7 TWh. Gasunie operates a 12 km hydrogen network in the industrial region of Zeeland province, repurposing a disused natural gas pipeline for hydrogen transmission in 2018. In addition, tiny amounts of hydrogen are carried via truck (WaterstofNet, 2023).

Finally, in addition to national and regional policies for establishing electrolyser plants, numerous initiatives have already been announced in the Netherlands with the goal of producing considerable amounts of green hydrogen by 2030. These projects are at various levels; some have already completed the feasibility study, some are in the investment phase, and yet others are in the installation phase. The table below outlines the major hydrogen initiatives in the Netherlands (WaterstofNet, 2023).

Project	Total Plant Capacity 2030	End-users	Backbone Connection
Hynoca Alkmaar (from certifiebiomass residues)	240t-1.300t H2/year (by 2023)	Local application	No
Djewels-2 – Delfzijl	40 MW (by 2025) and upscaling to 100 MW	Different applications	Yes
Djewels-1 – Delfzijl	20 MW	Different applications	Yes
VoltH2 -Terneuzen	25 MW (by 2025) and upscaling to 80 MW	Different applications	Yes
Energiepark Eemshaven-West	10 MW-100 MW (phase)	Mobility & Industry	Yes
ELYgator – Terneuzen	200 MW (by 2027)	Mobility & Industry	Yes (to AL network)
H2 Conversion Park – Maasvlakte	200 MW of Shell (2024) and 250 MW of H2-Fifty (BP and HyCC; 2025) – upscaling plans to 2000 MW	Different applications	Yes
H2ero – Vlissingen	150 MW (by 2026)	Zeeland Refinery in Vlissingen	No
MULTIPLHY –Rotterdam	2.6 MW (operation in Q2 2022)	refinery's rocesses	No
Haddock – Sluiskil	100 MW (by 2026) and upscaling to 1000 MW	neutral fertilizer products, food value chain, shipping fuel	Yes
SeaH2Land – North Sea Port	1000 MW	Local industrial cluster	Yes
CurtHylproject –Maasvlakte II	200 MW (by 2026)	Mobility & Industry	Yes
VoltH2 -Vlissingen	25 MW (by 2025) and upscaling to 100 MW	Mobility & Industry	Yes
Uniper – Maasvlakte	100 MW (by 2025) and upscaling to 500 MW	Mobility & Industry	Yes
Eemshydrogen – Westereems	50 MW (by 2025) with upscaling to 500 MW	Hard-to-abate industrial sectors	Yes
Hy4Am – Hemweg	10 MW (by 2026)	Mobility and industry	-
GreenH2UB – Eindhoven	5-10 MW (by 2025)	Industry, mobility and built environment	No
GZI NEXT – Emmen	10 MW (by 2025)	Local application	No
Hydrogen Wind Turbine – Wieringermeer	2.3 MW (by 2023)	-	Yes
H2ermes – Amsterdam	100 MW (with possible upscaling to 500 MW)	Tata Steel	No

HyNetherlands – Eemshaven	100 MW (by 2025) and upscaling to 1 GW	Chemical industry	-
GldH2 – Zutphen	2 MW (by 2023)	Different applications	Yes
NorthH2 – Groningen	**3000 MW**	Different applications	Yes
PoDH2 (Zephyros) – Den Helder	2 MW	Mobility (port application)	No
H2era – Amsterdam	500 MW	Industry and mobility applications	Yes
P2F – Hemweg	10 MW (by 2050) and upscaling to 100 MW	Synthetic methanol and kerosine	Yes

Figure 20:Hydrogen Projects in Netherlands (WaterstofNet, 2023)

Finally, someone could get misled while the aforesaid projects are being built, wandering which of the following could be considered the future demand for green hydrogen? Thus, during the construction of the aforementioned projects, individuals might face confusion or uncertainty regarding what can be regarded as the future demand for green hydrogen. The anticipated demand for green hydrogen is a multifaceted and contentious matter, shaped by diverse factors. In total, 8.2 million metric tons of hydrogen are expected to be needed in Europe by 2022, with refineries accounting for the majority of this need (57%), followed by ammonia industry (24%). Hydrogen production capacity in Europe for the year 2022 has been approximately 11.3Mt, higher than the demand (European Hydrogen observatory, 2023). Given the substantial capacity of the NortH2 project in comparison to others, it is imperative to carefully assess and consider the demand forecast, for the next 10-20 years, for green hydrogen to ensure the project's viability. So, future demand for green hydrogen could be a significant barrier for the investment decision of the Project (Guarieiro, et al., 2022).

According to the prior discussion, a SWOT analysis method is being employed to better evaluate the NortH2 project. These SWOT elements for the NortH2-project are based on an in-depth examination of the project's internal and external factors, taking into account the initiative's specific context and goals.

Figure 21: SWOT analysis of NorthH$_2$ project

Strengths:

1. **Higher Funding Availability:** NorthH2, is a European project and hence Europe's commitment to green hydrogen projects, as seen in initiatives like the Green Deal, provides substantial funding (Commission, 2023). Furthermore, project contributors include European corporations with solid financials (north2, 2023).
2. **Technology Transfer Potential:** High cash reserves made available by the project's investors, such as Shell and Equinor, may make technology transfer easier. Thus, regional players could be able to localize green hydrogen technologies and lessen their reliance on global businesses.
3. **Infrastructure:** The presence of established infrastructure, exemplified by the Port of Groningen, positions the region for efficient export of hydrogen and its derivatives (Equinor, 2020). Gasunie operates a 12 km hydrogen network in the industrial region of Zeeland province (Gasunie, 2020). This status signifies a strategic advantage for efficient export and distribution of hydrogen and its derivatives
4. **High-Density Hydrogen Storage:** The potential for high-density hydrogen storage enhances the versatility and practicality of green hydrogen applications (Khan & Al-Ghamdi, 2023). According to the project specifics, storage is an option for future development (north2, 2023).
5. **Proven Energy Trading Ability:** The advanced gas hubs and trading platforms, such as the European Energy Exchange (EEX), showcase the region's proven ability to trade energy commodities effectively..

6. **Abundance of Wind Energy:** The availability of 10 GW of offshore wind parks contributes to a consistent and renewable energy source for green hydrogen production (Equinor, 2020), positioning it as a strength in terms of sustainable resource availability

Weaknesses:

1. **Low National Demand:** Limited domestic demand for green hydrogen poses a challenge, requiring efforts to stimulate local consumption (European Hydrogen observatory, 2023). This is identified as a weakness because of the potential influence on the project's immediate market.
2. **Immature and Energy-Intensive Electrolyzer Technology:** Challenges related to the maturity and energy intensity of electrolyzer technology represent weaknesses that need addressing for widespread adoption. Hence, there is a need for technological advancements.
3. **High Production Cost:** The primary barrier to wider adoption of low-carbon hydrogen is the present high cost of manufacture, particularly for electrolyzer technology. The Offshore Wind Park has a high CAPEX (European Hydrogen observatory, 2023). This is regarded as a disadvantage because of its possible impact on the project's financial viability.

Opportunities:

1. **Localization of Electrolyzer Technology:** The potential for localizing electrolyzer technology presents an opportunity to enhance self-sufficiency in green hydrogen production.
2. **Export Market Opportunities:** Leveraging existing infrastructure, such as Central Europe's hydrogen pipelines and the Port of Groningen, opens avenues for export market growth. Anticipated EU hydrogen imports reaching 100 million tons by 2050 offer substantial opportunities.
3. **Foreign Investment:** Collaboration with international entities brings in foreign investment, to support the project’s growth.
4. **Mobility Sector:** The mobility sector presents an emerging opportunity for green hydrogen applications, especially in transportation (Harichandan & Kar, 2023).
5. **New Job Opportunities:** The growth of the green hydrogen sector creates potential for new job opportunities, contributing to economic development (Los & Dijk, 2020).

Threats:

1. **Global Competitors:** Countries like the USA and China are advancing rapidly in developing green hydrogen capacity and capturing export markets, posing a threat to the EU' position.
2. **Cheaper Chinese Electrolyzers:** The availability of cheaper Chinese electrolyzers may undermine the competitiveness of locally produced technologies. The cost of Electrolyzers contributes significantly to the CAPEX of the project
3. **Safety and Public Acceptance:** The scaling of hydrogen value chains requires careful management of safety risks and public acceptance. Regulatory frameworks need to address these concerns to ensure project viability.
4. **Competition from Low-Cost Technologies:** Alternatives to green hydrogen, especially those with lower production costs.

5. **High borrowing cost:** Due to volatile Macroeconomic Environment **(**High Inflation and high rates)
6. **Regulatory and Policy Challenges:** Evolving regulatory and policy landscapes may introduce uncertainties and challenges that need to be navigated for successful green hydrogen investments (Griffiths, et al., 2021).

VI. Policy Implications and Recommendations

A. Policy and regulatory considerations and recommendations for promoting Green Hydrogen and Green Certificates in the oil and gas industry

The highlighted threat in the SWOT analysis emphasizes the possible challenges posed by changing regulatory and policy landscapes. Changes in legislation or the deployment of new policies have the potential to impact the feasibility and success of green hydrogen projects, introducing uncertainties that must be handled for successful implementation. As a result, changes to the regulatory framework and policies governing the energy sector, particularly those relevant to green hydrogen, may occur, impacting the project's planning, execution, and overall viability (Yang, et al., 2023). Insights from the literature review and findings from the case study analysis, as well, could contribute to the understanding of how regulatory changes have historically impacted the feasibility and success of green hydrogen projects. In response to these challenges, proactive actions should be implemented to overcome uncertainty and ensure project success:

First of all, Stakeholders, particularly government entities, should prioritize the enhancement of policy frameworks to support the development and integration of green hydrogen in the oil and gas industry. This involves establishing clear and adaptive regulations that encourage innovation, provide incentives for investment, and ensure environmental sustainability. Governments should work collaboratively to harmonize policies on an international level, fostering a unified approach that facilitates seamless cross-border trade of green hydrogen and guarantees the effectiveness of Guarantee of Origin (GO) schemes (Abad & Dodds, 2020).

Thus, the potential of green hydrogen in revolutionizing the oil and gas industry has become a focal point in recent studies, as scholars emphasize the indispensable role of robust policies and regulatory frameworks in fostering its widespread adoption. Yang (2023) and Ballo (2022) advocate for clear and supportive policies, with Yang specifically underlining the necessity for a comprehensive development roadmap and integrated administrative supervision systems (Ballo, et al., 2022) (Yang, et al., 2023). These measures, according to the studies, are crucial for providing a structured foundation for the growth of green hydrogen within the industry. As the demand for cleaner energy solutions intensifies, these studies collectively emphasize the pivotal role of policy interventions in steering the trajectory of green hydrogen development.

In parallel, the European Union (EU) has positioned itself as a global leader in the transition from fossil fuels to renewable energy, setting ambitious climate goals. The EU established a bold target in 2018: to create "an economy with net-zero greenhouse gas emissions" by 2050. This long-term commitment demonstrates the EU's resolve to fight climate change and promote sustainable practices. Moreover, The EU has set an intermediate objective of decreasing greenhouse gas (GHG) emissions by 55% by 2030 to advance its climate agenda. This ambitious objective stresses the importance of quick action across several sectors, including those other than electricity generation. Given the extent of decarbonization required to reach the EU's ambitious targets, hydrogen has emerged as a keystone in the EU's climate plan. Hydrogen is seen as a versatile and transformational energy carrier with the ability to play a crucial role in a variety of sectors, hence reducing emissions (Commission, 2023). Neighboring European countries with oil majors, like UK and Norway, covered by this initiative have set similarly strong decarbonization targets, emphasizing hydrogen as an essential response (Hunt, et al., 2022).

An indicative example of EU's ambitious targets is Article 22a of RED III, which outlines ambitious targets for Member States to increase the share of renewable sources in the energy used for final energy and non-energy purposes in the industrial sector. According to RED III (article 22a), the targets include annual average increases and specific contributions of renewable fuels of non-biological origin, especially hydrogen, in the energy mix. Policies and measures for achieving these targets must be included in national energy and climate plans, with a focus on promoting cost-effective renewable-based electrification of industrial processes. The calculation of these contributions follows specific rules and standards outlined in the legislation, emphasizing the exclusion of certain types of hydrogen and the use of relevant European and ISO standards for energy content determination. Additionally, Member States are encouraged to promote voluntary labelling schemes for industrial products produced with renewable energy and fuels of non-biological origin, indicating the percentage of renewables used in different stages of production (Commission, 2023).

In addition, the Additionality Delegated Act, which was enacted by the European Commission on February 10, 2023, is a matter that needs consideration. This Act defines the parameters that determine whether hydrogen, hydrogen-based fuels, or other synthetic fuels qualify as renewable fuels of non-biological origin (RFNBOs). It also includes the Methodology Delegated Act, which specifies the methodology that must be used to calculate the life-cycle greenhouse gas emissions of RFNBOs. Thus, in 2028 the Commission shall assess the methodology defining when electricity used for RFNBO can be considered renewable. The review shall consider the impact of additionality, temporal and geographical correlation. In summary, the RFNBO (Renewable Fuels of Non-Biological Origin) methodology outlines two pathways for companies aiming to produce renewable hydrogen (Commission, 2023):

- Direct Connection Pathway:
    - The hydrogen generator connects straight to a renewable plant
    - The renewable asset cannot be operational before 36 months of the hydrogen plant.
- Network Interconnection Pathway:
    - Renewable power percentage reaches 90% in the bidding zone where the hydrogen plant operates in the previous calendar year.
    - Hydrogen production occurs in a bidding zone with a grid emissions intensity below 18gCO2e/MJ.
    - The hydrogen plant requires a renewable Power Purchase Agreement (PPA) that takes into account both temporal and spatial correlation.
    - Renewable power is pulled from the grid during an imbalance phase, either by redispatching or avoiding it.
    - A renewable PPA is signed for power supply, and the principles of additionality, temporal, and geographical correlation apply.

In contrast to the EU, Norway, & GB, the US government has historically exhibited less assertiveness in establishing long-term greenhouse gas (GHG) emissions reduction goals. However, the revolutionary Inflation Reduction Act of 2022 (IRA) was a long-awaited legislative package for the sector since it encourages investment in alternative energy sources and especially green hydrogen production. It provides substantial incentives for the deployment of technologies, like green hydrogen and CCS, making them cost-competitive with carbon-intensive alternatives (Cheng, et al., 2023).

To summarize, addressing the necessity for well-defined policies and regulations, dealing with the challenges, and taking advantage on the opportunities related to integrating green hydrogen into current energy systems requires coordinated collaboration among policymakers, industry stakeholders, and the international community. This collaborative endeavor is critical for laying the groundwork for a resilient framework that promotes the long-term development and implementation of green hydrogen in the oil and gas industry.

B. Strategies to overcome barriers and accelerate the adoption of Green Hydrogen in the supply chain.

Primarily, a key approach to surmount obstacles and hasten the integration of green hydrogen into the supply chain involves prioritizing technological innovation through collaborative research initiatives. Partnerships among industry stakeholders, governments, and research institutions should be forged to expedite the advancement of cutting-edge technologies for the production, storage, and utilization of green hydrogen. By fostering breakthroughs in efficiency and cost-effectiveness, this strategy aims to overcome current technological hurdles, enhancing the competitiveness of green hydrogen within the oil and gas industry, as highlighted by Abad & Dodds (2020). This joint collaboration has the potential to accelerate technological progress, effectively addressing challenges related to green hydrogen production, storage, and utilization in the oil and gas sector. Furthermore, collective efforts may result in the establishment of standardized practices and technologies, fostering efficiency, reliability, and cost-effectiveness in both the production and application of green hydrogen, in line with insights from Archarya (2022). (Abad & Dodds, 2020), (Archarya, 2022).

Furthermore, Governments and industry players should implement targeted financial incentives and support mechanisms to encourage investments in green hydrogen projects. This includes subsidies, tax credits, and grants for research and development, infrastructure development, and the deployment of green hydrogen technologies. By alleviating financial burdens, stakeholders can create a more favorable investment environment, attracting private and public capital to scale up green hydrogen initiatives. The World Bank Group is leading programs to build green hydrogen as a fuel and energy storage solution in Brazil, Panama, Costa Rica, Colombia, and Chile. Globally, countries such as Australia, India, China, Japan, Bangladesh, and Germany are focusing on green hydrogen as part of their energy transformation strategies. Sub-Saharan Africa has the greatest potential for green hydrogen production, with Australia intending to be a key producer by 2030. Australia's National Hydrogen Strategy prioritizes overcoming market obstacles, ensuring regulatory uniformity, and forming global trade alliances. (Zainal, et al., 2024).

In addition, to promote the sustainable growth of green hydrogen, it is imperative for both industry stakeholders and governments to channel investments towards infrastructure development, as emphasized by Menes (2021). Prioritizing such investments in infrastructure emerges as a strategic imperative to expedite the integration of green hydrogen into the supply chain. (Menes, 2021). Stakeholders should collaborate to build a comprehensive and interconnected hydrogen infrastructure, including production facilities, transportation networks, and storage solutions. Integration of green hydrogen into existing energy systems requires well-designed infrastructure that ensures reliability and accessibility, mitigating challenges related to transportation and storage. Since hydrogen gained popularity as a potential clean energy source, global technology investment has increased. Countries such as South Africa, South Korea, China, Canada, and India have made considerable investments in the research and deployment of hydrogen technology. Countries such as the European Union, the United States, and Australia have also investigated and invested in the technology (Zainal, et al., 2024).

The European hydrogen infrastructure projects are excellent example of collaboration, as part of the REPowerEU Plan, which aim to rapidly reduce dependence on Russian fossil fuels and accelerate the green transition. The plan acknowledges the need for swift actions to deploy hydrogen infrastructure, covering production, storage, import, and transportation of 20 million tonnes of hydrogen by 2030. Collaborative efforts by organizations such as ENTSOG, GIE, CEDEC, Eurogas, GEODE, and GD4S, along with the European Hydrogen Backbone initiative, have resulted in an interactive Hydrogen Infrastructure map. The following map consolidates data on hydrogen projects from Transmission System Operators (TSOs), Distribution System Operators (DSOs), Storage System Operators (SSOs), LNG System Operators (LSOs), and third-party promoters, presenting a comprehensive overview accessible to stakeholders and policymakers (European Hydrogen observatory, 2023).

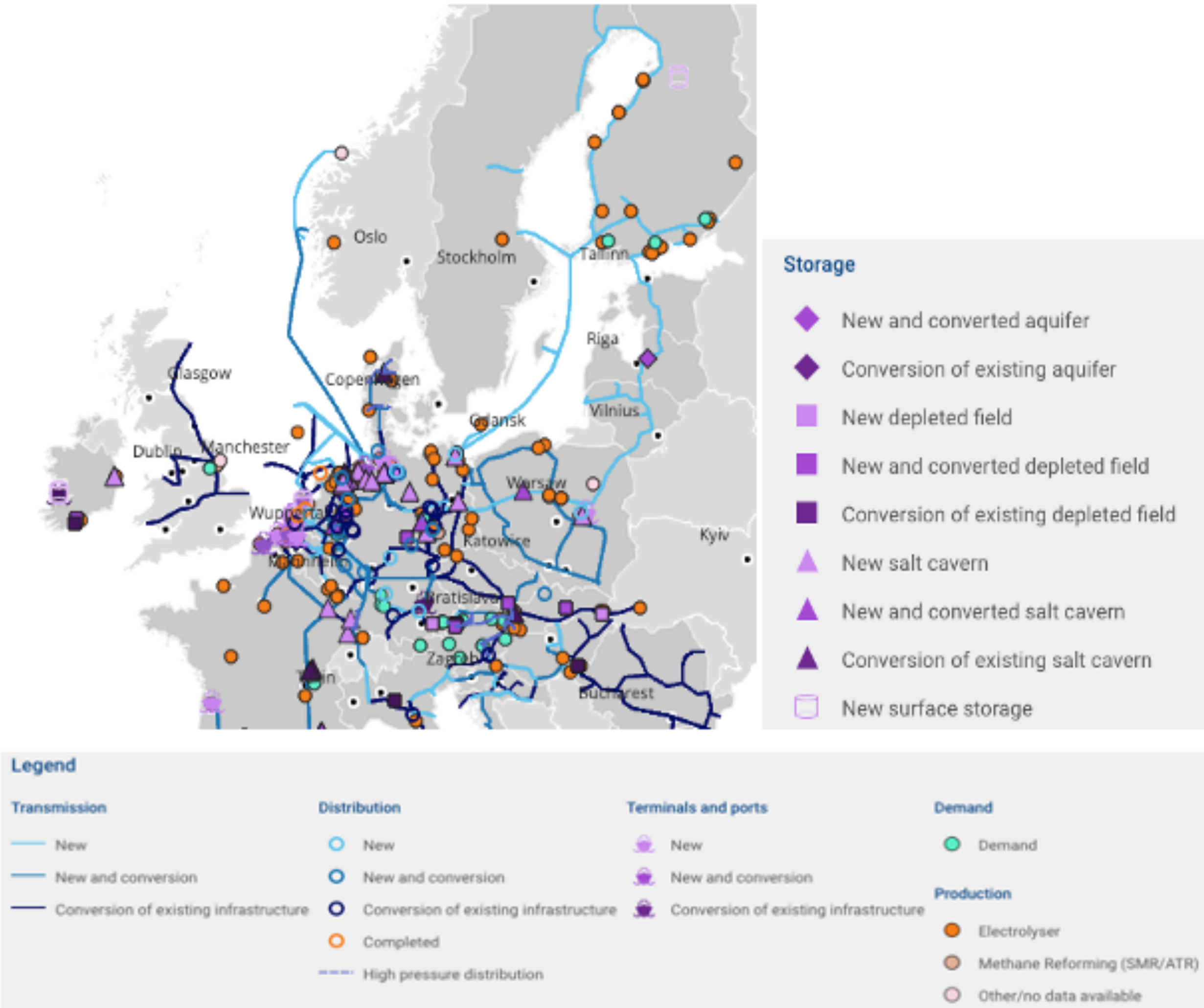


Figure 22: Europe's interactive map with hydrogen infrastructure projects (https://www.h2inframap.eu)

The alignment of policies and regulations across different regions is crucial for creating a conducive environment for green hydrogen adoption. Stakeholders should actively engage in policy harmonization efforts, working towards standardized regulations that facilitate cross-border trade and investment. Regulatory streamlining will reduce uncertainties for industry players, encouraging them to navigate the green hydrogen landscape with more confidence (Archarya, 2022).

Furthermore, Industry stakeholders, including energy corporations, research institutions, and technology developers, should engage in collaborative training initiatives. Governments and industry stakeholders should prioritize educational initiatives to address the evolving needs of the workforce in the context of green hydrogen technologies. Training programs should be designed to equip professionals with the skills required for the research, development, and implementation of green hydrogen solutions. Collaboration with academic institutions and vocational training centers can ensure a continuous pipeline of skilled professionals, fostering innovation and industry growth (Kovac, et al., 2021).

Increasing public awareness and engaging stakeholders are pivotal in building acceptance and support for green hydrogen. Governments, industry associations, and corporations should invest in educational campaigns to inform the public about the benefits of green hydrogen and its role in the energy transition. Engaging with local communities, industry associations, and non-governmental organizations will help garner support and address concerns related to the adoption of green hydrogen in the supply chain (Kovac, et al., 2021).

Collaborative initiatives at the international level should be prioritized to share knowledge, best practices, and lessons learned in the adoption of green hydrogen. Establishing forums for dialogue and collaboration enables stakeholders to learn from each other's experiences, fostering a global community dedicated to overcoming common barriers. This knowledge-sharing approach accelerates the development and deployment of green hydrogen solutions by leveraging collective expertise (Iles & Mulvihill, 2012).

Recognizing the evolving nature of the energy transition, stakeholders should adopt flexible transition planning. This involves designing strategies that can adapt to technological advancements, policy changes, and market dynamics. Building flexibility into transition plans allows for agile responses to emerging opportunities and challenges, ensuring that the adoption of green hydrogen remains dynamic and resilient (Griffiths, et al., 2021).

In Europe, where the EU and national governments are aggressively pursuing decarbonization legislation, major oil companies have responded with commitments to reduce emissions and strategic modifications in their business practices (Hunt, et al., 2022). For example, the Danish business Oersted (Oersted, 2023) has completely exited its oil and gas interests. In addition, four European oil majors: BP (BP, 2023), Equinor (Equinor, 2023), Total (TotalEnergies, 2023), and Shell (Shell, 2023), all of whom have committed to achieving net-zero targets by 2050 or sooner, have made large investments in renewable energy companies through strategic acquisitions and shifts in business focus. European oil majors have found green hydrogen to be a natural fit, given the overall favorable regulatory environment for this technology in Europe and the substantial investments made in renewable energy. Major players like Shell, Equinor, BP, and Total have all announced projects producing hydrogen through renewable electrolysis. These projects often rely on government investments, with subsidies covering a significant portion of capital costs for pilot initiatives.

In contrast to European oil and gas majors, Chevron (Chevron, 2023) and Exxon (Exxon, 2023) have taken a different approach on emissions reduction targets and renewable energy expenditures. While both firms have produced climate reports, they diverge from the majority of European giants in that they have neither declared a net-zero goal for 2050 or publicly disclosed a carbon price. Chevron and Exxon address risks connected with new business strategies in their investor reports, emphasizing a preference for continued development in oil and gas activities. Instead of major modifications in business strategy, both firms' climate goals are primarily focused on lowering emissions from oil and gas operations and investing in carbon capture and storage (CCS) technologies.

The oil and gas industry should actively seek collaboration with other sectors, such as renewables, manufacturing, and transportation, to explore synergies and shared solutions. In that approach, European oil companies are leveraging their renewable energy knowledge by investigating both green and blue hydrogen projects (Tholen, et al., 2021).Cross-sectoral collaboration can create integrated value chains, driving efficiency and promoting a holistic approach to green hydrogen adoption. Joint ventures and partnerships between traditionally separate industries can lead to innovative solutions that benefit the entire supply chain (Archarya, 2022).

Finally, industry associations, governments, and research bodies should advocate for the standardization of green hydrogen production, certification, and trading processes. Developing international standards ensures the consistency and credibility of Guarantee of Origin (GO) schemes, providing transparency and confidence in the green hydrogen supply chain. Stakeholders should actively participate in standard-setting organizations to contribute expertise and foster a collaborative approach to standardization (CertifHy, 2023).

By implementing these strategies, stakeholders can collectively address barriers, foster innovation, and create an environment conducive to the accelerated adoption of green hydrogen in the oil and gas supply chain. This multifaceted approach ensures a comprehensive response to the challenges at hand, promoting the sustainable integration of green hydrogen into the broader energy landscape. Policy-making for green hydrogen development may play a crucial role in supporting the industry's defossilization efforts.

VII. Conclusions

In conclusion, this research makes an important addition to the continuing debate over the oil and gas industry's critical transition to a sustainable and decarbonized supply chain. The investigation of Green Certificates, specifically Guarantees of Origin (GOs), as a catalyst for boosting renewable energy, notably Green Hydrogen, emphasizes the importance of tackling environmental concerns in an industry that has historically been associated with significant carbon emissions (Griffiths, et al., 2021). The detailed literature analysis sets the stage for understanding the complexities and environmental issues faced by the oil and gas sector. The dissertation lays the stage for a comprehensive assessment of the potential game-changer: Green Hydrogen, by unraveling the complexity. Green hydrogen schemes play a crucial role in meeting sustainability criteria, with variations in their characterization influenced by factors like the definition of green hydrogen, system boundaries, chain of custody, emission intensity thresholds, and pathway eligibility (Griffiths, et al., 2021; Abad & Dodds, 2020). The investigation into the NorthH_2-project, Europe's largest green hydrogen initiative, provides real-world insights into the challenges and opportunities associated with incorporating Green Hydrogen and Green Certificates into the supply chain.

This research aims to uncover critical findings regarding the potential applications of Green Hydrogen within the oil and gas supply chain. The study underlines Green Hydrogen's transformative potential for lowering carbon emissions and enhancing sustainability (Martin, et al., 2020). Simultaneously, it delves into the constraints, such as operating or infrastructure requirements and financial considerations, that may impact the seamless integration of Green Hydrogen. The pivotal role of Green Certificates in encouraging the use of renewable energy, with a spotlight on transparency, traceability, and accountability, is a central aspect of this research (Linden, et al., 2004). These certificates are identified as crucial instruments in incentivizing the adoption of renewable energy (Abad & Dodds, 2020). Finally, this research outlines the complexities and considerations in establishing green hydrogen standards, emphasizing the need for a well-defined and stable policy framework.

As the research concludes, it synthesizes the key insights derived from the case study and literature analysis, shedding light on the implications for the industry's transition to a sustainable supply chain. Acknowledging the inherent limitations, the study lays the groundwork for future research avenues, recognizing the dynamic nature of the energy transition landscape. This reflects the complexity and significance of the transition to a more sustainable energy future. The identified keywords - Green Hydrogen, Oil and Gas Industry, decarbonization, supply chain, Green Certificates, Guarantees of Origin, sustainability, renewable energy, and carbon emissions - encapsulate the multifaceted dimensions explored in this research. Recognizing the continual shifts of the energy landscape, this dissertation emphasizes potential research directions. The use of green hydrogen in Power-to-Gas (P2G), Gas-to-Power (G2P), and Gas-to-Gas (G2G) energy systems adds a new dimension (Abad & Dodds, 2020; Oruwari & Itsekor, 2023). The practical recommendations put forth in this research aim to accelerate the adoption of Green Hydrogen and Green Certificates in the oil and gas industry, offering tangible steps toward achieving a decarbonized supply chain (Griffiths, et al., 2021). However, a comprehensive analysis of hydrogen pathways, considering costs and greenhouse gas emissions, is essential, in order to inform the implications of different definitions (Abad & Dodds, 2020).

In essence, this research not only contributes to the expanding body of knowledge on sustainable energy solutions but also provides actionable recommendations. By addressing the critical intersection of Green Hydrogen, Green Certificates, and the oil and gas industry, this research advocates for a more sustainable and environmentally conscious future, aligning with global efforts to combat climate change. The identified keywords - Green Hydrogen, Oil and Gas Industry, decarbonization, supply chain, Green Certificates, Guarantees of Origin, sustainability, renewable energy, and carbon emissions - encapsulate the multifaceted dimensions explored in this research, reflecting the complexity and significance of the transition to a more sustainable energy future. The objective of a decarbonized oil and gas supply chain driven by Green Hydrogen and supported by robust Green Certificates can become a reality via collaborative efforts, regulatory support, and technological innovation.

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