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Blue Hydrogen and Ammonia

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1. Introduction

As the world seeks to transition to a low-carbon energy sources to meet the decarbonization goals for 2050, there is an essential need for technologies that can significantly reduce CO_2 emissions without compromising the global energy and industrial production demands.

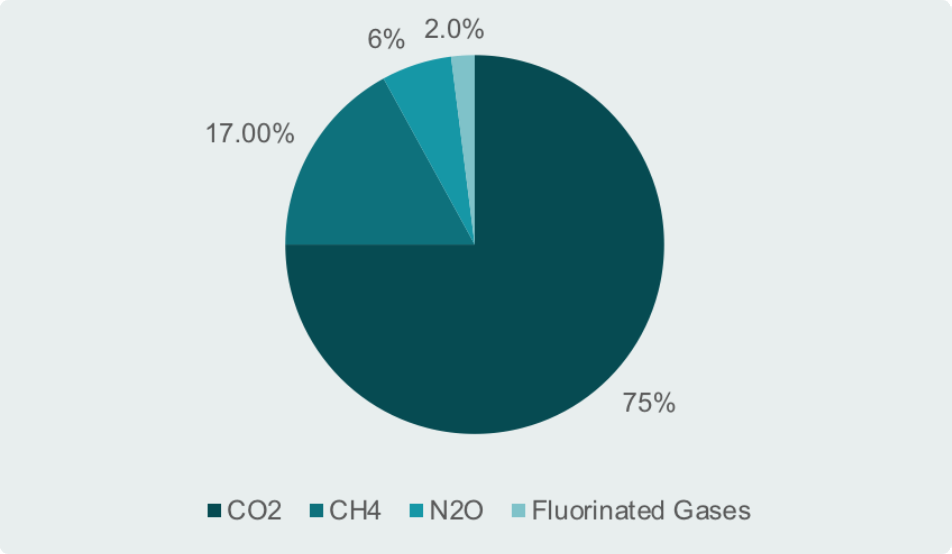

Figure 1: Greenhouse Gas (GHG) Emissions by Source [1]

Among the low-carbon energy alternatives being explored, blue hydrogen and ammonia are considered as practical options. These elements offer promising potential as energy carriers and fuels to significantly reduce carbon emissions across different industries. However, like any emerging technology, blue hydrogen and ammonia come with their unique challenges and obstacles that must be addressed for wider implementation.

Before going further into the details of research, it is important to understand the connection between hydrogen and ammonia, and the reason why ammonia is critical in supporting hydrogen as an energy carrier.

This technical paper will explore the different types of hydrogen and ammonia, which are categorized based on their production source and methods. These variations also have significant impact on production costs.

Hydrogen and ammonia are recognized as an element that can generate substantial energy. However, a key question remains: Can they compete with conventional energy sources, such as hydrocarbons? And if they hold such promise, why haven't they fully replaced traditional energy sources yet?

Hydrogen

Hydrogen (H_2) is known to be the most abundant element in the universe and has been recognized as a potential clean-burning fuel. It can be produced from various sources and, when combusted for power generation or used as a fuel, produces water vapor (H_2O) as the main byproduct. Nevertheless, the environmental impact of hydrogen production varies significantly depending on its source.
Hydrogen is typically categorized by color codes based on its production method [2] (Figure 2):

1. **Gray Hydrogen:** Primarily produced from natural gas (62%) (Figure 3), which is composed of 70-90% methane (CH_4), through a process called steam methane reformation (SMR) without capturing the resulting CO_2 emissions.

2. **Blue Hydrogen:** Produced similarly to gray hydrogen, but with the addition of Carbon Capture, Utilization and Storage (CCUS) technology to capture and store the CO_2 emissions. This type of hydrogen serves as a low-carbon energy carrier.

3. **Green Hydrogen:** Alternative clean energy source which is produced through electrolysis of water using renewable sources, such as wind and solar, resulting in zero direct CO_2 emissions.

4. **Other colors**, such as pink, yellow, and brown, represent different production methods and feedstock sources for making hydrogen. Each hydrogen type has its own environmental impacts.

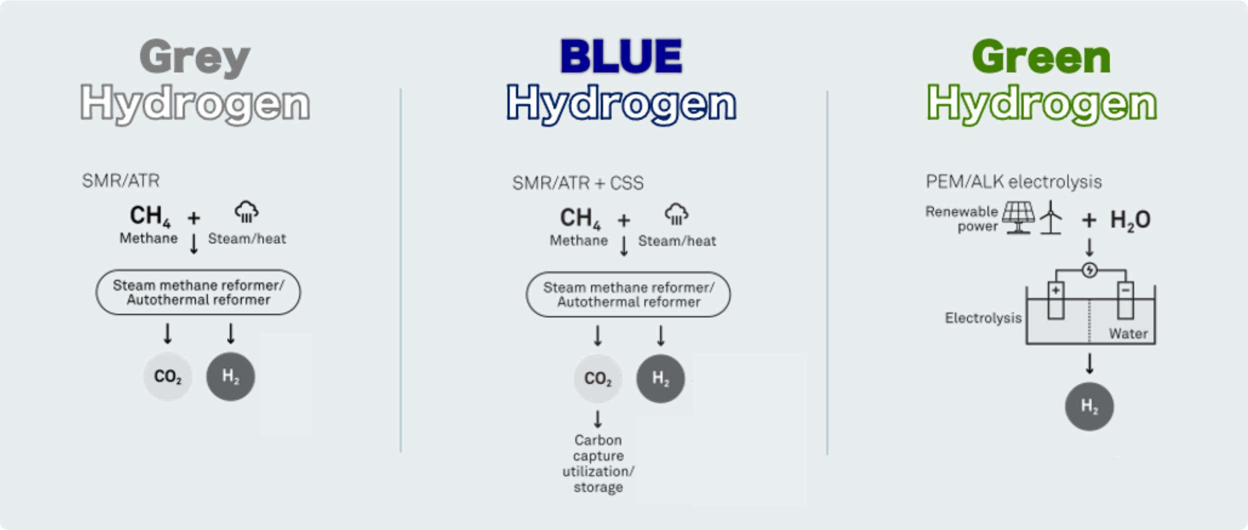

Figure 2: The Colors of Hydrogen

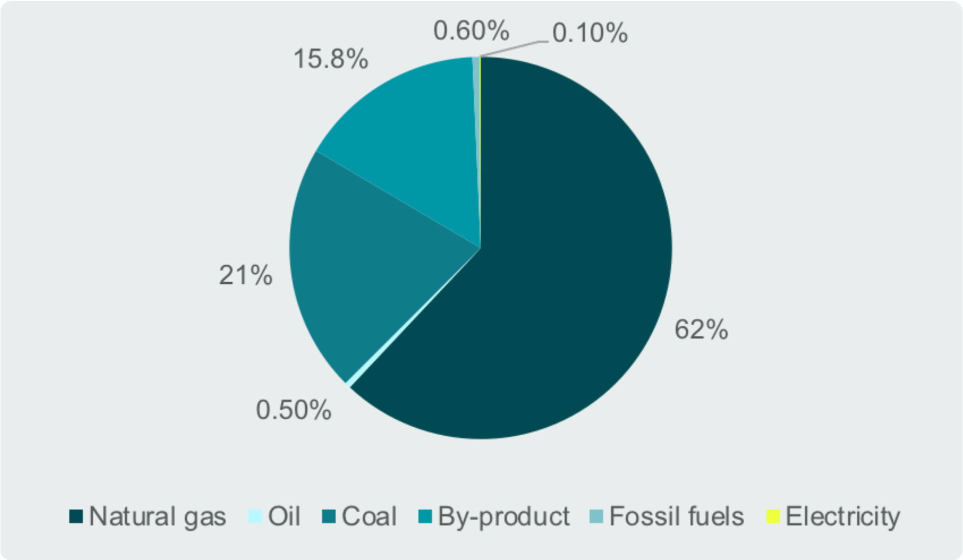

Figure 3: Percentage Breakdown of Hydrogen Production by Source

Despite its potential, as a clean energy carrier, hydrogen has its own challenges in terms of storage and transportation due to its low energy density and the need for high-pressure or cryogenic storage. This is where ammonia comes into the picture as a potential solution.

Ammonia

Ammonia (NH_3), a compound of one part nitrogen and three parts hydrogen ($N_2 + 3H_2 \rightarrow 2NH_3$), has been traditionally associated with fertilizer production. However, it is increasingly being recognized as an excellent hydrogen carrier and a promising carbon-free fuel since it doesn't emit carbon dioxide (CO_2) when it is thermally combusted, although the emitted NOx needs to be managed [3]. Similar to hydrogen, ammonia can be categorized by colors based on its production method and source (Figure 4):

1. **Gray Ammonia:** Produced from methane-derived hydrogen (gray hydrogen), typically using the Haber-Bosch process. About 70% of today's ammonia production relies on hydrogen derived from natural gas [3].

2. **Blue Ammonia:** Produced from blue hydrogen, with the addition of Carbon Capture, Utilization and Storage (CCUS) technology to capture and store the CO_2 emissions.

3. **Green Ammonia:** Produced from green hydrogen and nitrogen separated from the air, using renewable energy and resulting in a zero-carbon emission.

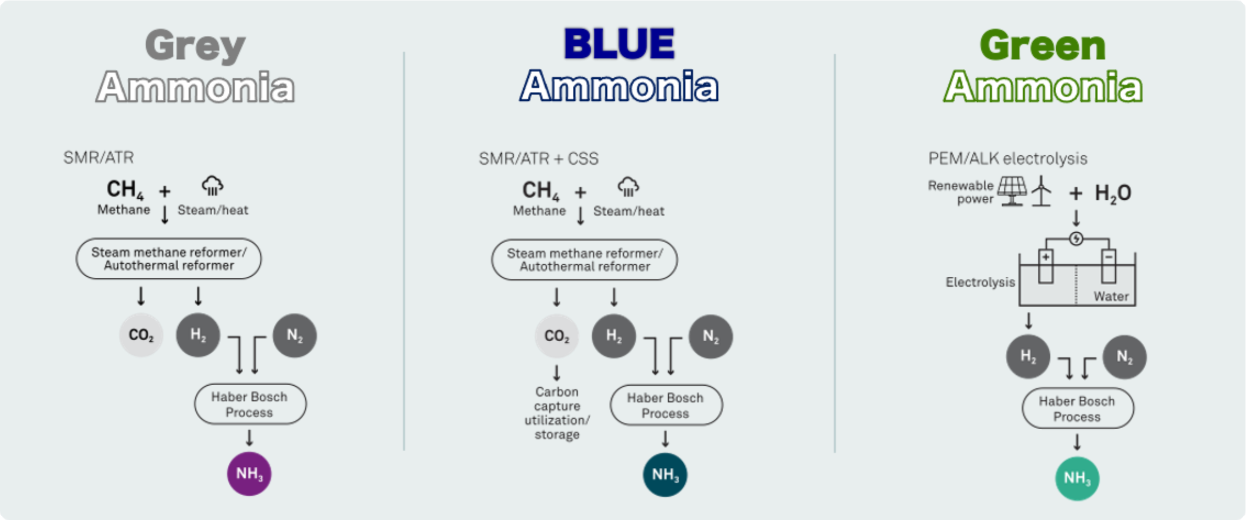

Figure 4: The Colors of Ammonia [13]

Blue hydrogen and blue ammonia production integrate existing fossil fuel technologies, primarily Steam Methane Reforming (SMR), with Carbon Capture, Utilization and Storage (CCUS) methods. SMR uses natural gas to produce hydrogen, while CCUS significantly reduces the carbon footprint of this process.

CCUS involves capturing CO_2 emissions from large point sources such as power plants or industrial facilities, transporting this CO_2, and then either utilizing it in industrial processes or storing it permanently underground [4]. In hydrogen production, CCUS transforms "gray" hydrogen into "blue" hydrogen by capturing and storing the CO_2 that would otherwise be emitted. This blue hydrogen can then be used to produce blue ammonia which create a low-carbon pathway for both hydrogen and ammonia production.

To assess the feasibility of blue hydrogen and ammonia as low-carbon energy solutions, a comprehensive review of the latest literature related to the blue hydrogen and ammonia production and their critical enablers, Carbon Capture, Utilization, and Storage (CCUS), is conducted. The following literature review analyzes recent reports and studies on CCUS, blue hydrogen, and blue ammonia. It outlines their potential, challenges, and future directions in the context of global decarbonization efforts.

2. <u>Literature Review:</u>

In recent years, there has been growing interest in blue hydrogen and ammonia as potential low-carbon energy solutions. This interest led to a wave of research and white papers from various organizations and institutions. This literature review analyzes key findings and insights from recent reports on blue hydrogen and ammonia production and their essential enabler process, Carbon Capture, Utilization, and Storage (CCUS).

2.1 Carbon Capture, Utilization, and Storage (CCUS)

Carbon Capture, Utilization, and Storage (CCUS), one of the blue hydrogen and ammonia enablers, is recognized as a critical technology in the global effort to reduce carbon emission and meet climate targets. Various reports provide comprehensive insights into different aspects of CCUS.

The Intergovernmental Panel on Climate Change (IPCC) Special Report on Carbon Dioxide Capture and Storage [5] emphasizes the critical role of CCUS in mitigating climate change. According to the report, CCUS has the potential to reduce CO_2 emissions from industrial facilities and power plants by 80-90%. The white paper by the Association of International Energy Negotiators (AIEN) [4] supports this by highlighting the current CCUS application such as enhanced oil recovery (EOR), which uses captured CO_2 to increase oil extraction. However, the white paper also outlines a debate about using CO_2 in the EOR process. Critics argue that EOR technology contribute to increased carbon emissions when the additional produced oil is consumed and GHG is released into the atmosphere. However, supporter to the EOR technology focuses on the climate benefits of geological sequestration of CO_2. They say that when CO_2 is permanently stored underground, such as in saline aquifers or in depleted gas reservoirs, it helps reduce the overall carbon footprint of fossil fuels energy production.

IPCC report [5] also discusses the economic barriers of CCUS technologies, which eventually adds to the cost of blue hydrogen and ammonia production. It emphasizes that the high cost associated with the methods used to capture and transport CO_2 can hinder widespread adoption of CCUS. It suggests policy measures like carbon pricing and subsidies to make CCUS financially viable. AIEN white paper [4] expands on this by providing examples of funding models, such as the US 45Q tax credit, which offers financial incentives for EOR projects, CO_2 geological sequestration and CO_2 direct air capture.

In regard to CCUS global implementation strategy, IPCC report [5] emphasizes the need for international cooperation and supportive policy frameworks to facilitate CCUS deployment worldwide. AIEN white paper [4] details some national CCUS implementation and regulatory approaches to showcase the importance of government support for widespread implementation of CCUS. Some of the mentioned innovative implementation are the Denmark's Project Greensand pilot, which received a fund of €26 million from the Danish Energy Agency, and the Norway's Northern Lights project, which received fund of US$1.8 billion from the Norwegian government to cover around 80% of the project cost.

The literature of carbon capture and storage technology suggest that while CCUS holds potential for mitigating climate change, its success depends on international cooperation, government support, and financial incentives.

2.2 Blue Hydrogen Production and Potentials

The transition to a low-carbon future has increased interest in blue hydrogen production because it provides an opportunity to reduce greenhouse gas emissions while utilizing existing infrastructure and integrating carbon capture, utilization and storage (CCUS) in the production process. This review discusses various insights about blue hydrogen production and potentials.

In regard to production methods, the Global CCS Institute report on Blue Hydrogen [6] stated that blue hydrogen is primarily produced through steam methane reforming (SMR) and autothermal reforming

(ATR) of natural gas, with CCS capturing the resulting CO_2 emissions. It also mentioned that coal gasification with CCS is another less common method to produce blue hydrogen. The KAPSARC report [2] also discusses multiple blue hydrogen production methods including the SMR and highlights its role in reducing the GHG emission by capturing CO_2 before it enters the atmosphere. The report also outlines some productive SMR facilities, such as Shell's Quest project in Canada and Air product's facility in Texas. As per the report, those facilities successfully implemented CCS by achieving CO_2 capture efficiencies of 50%-60%.

The implementation of blue hydrogen faces several challenges as stated in the Global CCS Institute and KAPSARC reports [6][2]. According to the Global CCS Institute [6], only about 1% of hydrogen production from fossil fuels involves CCUS process. Blue hydrogen production cost presents one of the major challenges. The cost is influenced by multiple factors, mainly the price of natural gas and the implementation of CCS technologies. The reports indicated that blue hydrogen production costs are currently lower than green hydrogen, which makes it a more economically viable option. Despite being considered one of the lower-cost clean hydrogen production methods, its overall cost still exceeds the cost of grey hydrogen production. The report also notes that the cost of transporting and storing CO_2 impacts the production cost. In addition to the cost, KAPSARC [2] highlights the technical challenges associated with blue hydrogen production method. It stated that carbon capture rates vary depending on the production method. For example, the capture rate of using steam methane reforming (SMR) with CCUS achieves approximately 90%, while autothermal reformation (ATR), a more complex method, can reach 94%. Hence, achieving a higher capture rates requires balancing economics and technical trade-off.

Looking ahead, addressing the challenges of blue hydrogen production becomes increasingly critical. The Global CCS Institute [6] suggests that technological innovations can help reducing the cost of clean hydrogen production. These technologies include chemical looping processes, new adsorption processes, and new physical and chemical solvents for absorption processes as well as new membranes for CO_2 separation. The KAPSARC report [2] stresses the importance of further research and innovation to make blue hydrogen more competitive. Additionally, the report emphasizes a significant gap in the certification framework, as most existing scheme focus on green hydrogen with limited standardization for blue hydrogen certification.

2.3 Blue Ammonia as Hydrogen Carrier

Recent studies have increasingly recognized blue ammonia as a leading candidate among blue hydrogen carriers as it addresses the challenge of hydrogen storage and transportation.

The BNEF and Climate Technology Coalition white paper titled "Scaling Up Hydrogen: The Case for Low-Carbon Ammonia" [7] explores the potential of ammonia as a hydrogen carrier. The report argues that ammonia's existing infrastructure and easier storage and transportation properties make it an attractive option for scaling up hydrogen use globally. This aligns with the growing interest in blue ammonia as a means to facilitate the high cost of blue hydrogen storage and transportation. A comprehensive study by Tanzeem and Al-Thubaiti [8] examines the prospects of blue ammonia through the integration of different technologies within conventional ammonia plants, specifically the Kellogg Braun & Root (KBR) Purifier process, Topsoe, and the Linde Ammonia process. Their analysis reveals that Carbon Capture and Sequestration (CCS) and Gas Switching Reforming (GSR) technology are promising pathways toward blue ammonia production due to cost-effectiveness and ease of implementation. For example, the GSR technology demonstrates remarkable CO_2 capture efficiency of

94.4%, with some emissions emitted from undesired mixing in the cluster outlet stream. Also, the CCUS process, a critical enabler for blue hydrogen and ammonia, offers advantages due to its compatibility with existing infrastructure and ability to produce highly pure CO_2 (99%), which makes it suitable for storage or utilization in industries such as beverages and chemicals. The authors also note that these technologies face challenges in terms of CO_2 purity requirements and operational complexities. For example, the CCUS process struggles with capturing CO_2 from boiler and furnace flue gases due to their low CO_2 concentration, low partial pressure, and high temperature. The GSR technology faces operational complexities in managing pressurized interconnected fluidized beds and preventing undesired mixing of outlet streams. In addition, the BNEF report [7] highlights that the production cost of blue ammonia remains as one of the main challenges. The report shows that blue ammonia production cost from new plants is still relatively high compared to grey ammonia production, but it is much lower than the cost of green ammonia production. However, the report forecasts that green ammonia will reach price parity with grey ammonia in some markets from 2024-25.

Having reviewed blue ammonia's potential as a hydrogen carrier and CO_2 emission reduction, Saudi Arabia has positioned itself as a key player in the advancement of blue hydrogen and ammonia projects [9]. To showcase the industrial potential of the concepts and challenges addressed in the literature, the following section examines Saudi Aramco and SABIC Agri-Nutrients' initiative in blue hydrogen and ammonia production and transportation.

3. The Case of Saudi Aramco and Sabic – Blue Hydrogen and Ammonia Project:

The Blue Hydrogen and Ammonia project is a collaboration between two of Saudi Arabia's industrial giants: Saudi Aramco and SABIC Agri-Nutrients Company.

3.1 Saudi Aramco Company

Saudi Aramco, officially known as the Saudi Arabian Oil Company, was established in 1933 as a partnership between the Saudi government and the Standard Oil Company of California (now Chevron). In 1980, the Saudi government acquired full ownership of the company. Over the decades, Saudi Aramco has grown from a local oil producer to one of the world's largest integrated energy and chemicals companies [10].
Aramco operates primarily in the oil and gas sector, and its operations include:

- Exploration and production of crude oil and natural gas.
- Refining and distribution of petroleum products.
- Production of chemicals and petrochemicals such as crude oil, gas, NGL, condensate, chemicals, refined products, base oils and lubricants, electricity, blue ammonia and nonmetallic.

The company has also been expanding into new areas such as renewable energy and hydrogen production as part of its sustainability efforts [10].

As the world's largest oil company, Saudi Aramco's competes with other major players in the oil industry like ExxonMobil, PetroChina, Shell, TotalEnergies and Chevron. However, Aramco distinguish itself from competitors due to its vast oil reserves and the Saudi government's role as its primary shareholder.

3.2 SABIC Agri-Nutrients Company

SABIC Agri-Nutrients Company, formerly known as Saudi Arabian Fertilizer Company (SAFCO), was established in 1965. It is the first petrochemical company in Saudi Arabia and one of the world's largest fertilizer producers. It became a subsidiary of Saudi Basic Industries Corporation (SABIC) in 1976 and was later renamed SABIC Agri-Nutrients Company.

SABIC Agri-Nutrients operates in the chemical and agriculture sectors and specializes in the production of fertilizers, including ammonia, urea, and phosphate-based products. The company has a strong focus on sustainability and has been working on developing more environmentally friendly fertilizer products.

In the global fertilizer market, SABIC Agri-Nutrients competes with other major producers such as Yara International, ASA, CF Industries, OCI, and Ma’aden [11]. Its competitive advantages include access to low-cost feedstock through its relationship with Saudi Aramco and a strategic location for serving markets in Asia, Africa, and Europe.

3.3 The Journey of Blue Ammonia from Saudi Arabia to Japan

As illustrated in figure 5, the process begins with natural gas as the primary feedstock, which was extracted from Saudi Aramco’s plants and transported to SABIC’s facilities in Jubail, Saudi Arabia. At the Hydrogen Plants in Jubail, the natural gas, mainly methane, undergoes steam methane reforming (SMR) a process that converts it into hydrogen (H_2) and carbon dioxide (CO2). The produced CO_2 is captured at the CO_2 Capture Plant in Jubail and utilized in three ways: a portion is sent to the Methanol Plant in Jubail for industrial use, while the remainder is transported to the Saudi Aramco’s Enhanced Oil Recovery Pilot Plant in Uthmaniyah for geological storage.

Simultaneously, the produced blue hydrogen (H_2) is then directed to the Ammonia Plant, also located in Jubail, where it is combined with nitrogen (N_2) through the Haber-Bosch process to create blue ammonia. The blue ammonia is then liquified at -33°C and transported from Saudi Arabia to Japan. Upon arrival, the ammonia is distributed to three different power generation facilities in Japan: the 2 MW Gas Turbine plant in Yokohama, the 50 kW Micro Gas Turbine plant in Koriyama, and a co-firing boiler in Aioi. At these destinations, the blue ammonia is used directly for power generation, which produce nitrogen and water vapor as byproducts [9].

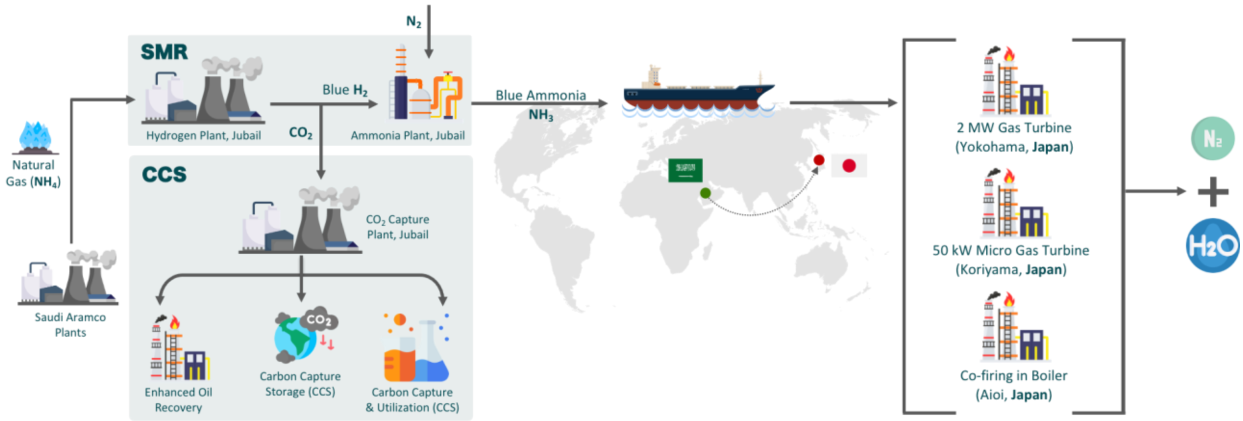

Figure 5: Blue hydrogen and Ammonia Project and Value Chain [9]

While Japan uses the ammonia directly, some facilities in other countries may choose to decompose the ammonia back into hydrogen and nitrogen. In such cases, the hydrogen can be used for power generation, resulting in only water vapor emissions. According to KAPSARC report [9] on blue ammonia shipment, using NH_3 directly for power generation is the most cost-effective option because the extra step to convert ammonia back into hydrogen adds an extra cost to the power generation. Ammonia also has its own disadvantages. While it doesn't emit CO_2 during combustion, it emits nitrogen oxides (NOx) and increases the concentration of nitrous oxide (N_2O), a major contributor to greenhouse gas emissions. Its toxic and corrosive properties make it unsuitable for direct fuel use and require ammonia producers to implement strict safety regulations and make capital investments to mitigate these risks.

3.4 The Project's Key Milestones

Saudi Aramco's journey in hydrogen and ammonia development has seen significant milestones over the past five years. In 2019, Saudi Aramco entered the hydrogen market by inaugurating the first hydrogen fueling station in Saudi Arabia at Air Products' new Technology Center in the Dhahran Techno Valley Science Park. A year later, in 2020, Saudi Aramco collaborated with SABIC to dispatch the world's first shipment of 40 tons of blue ammonia to Japan in a demonstration project. In 2022, Saudi Aramco and SABIC AN reached another milestones by receiving the first accreditation for blue hydrogen and ammonia followed by their first commercial shipment to South Korea. In 2024, Saudi Aramco expanded its market presence in the blue hydrogen sector by acquiring 50% stake in Air Products Qudra's Blue Hydrogen Industrial Gases Company. This strategic partnership aims to advance lower-carbon hydrogen production. Looking ahead, Saudi Aramco has set an ambitious target to ship 11 million tons of blue ammonia annually by 2030, which is equivalent to approximately 363 terawatt-hours of energy.

The project's performance metrics reveals both achievements and areas for improvements. On the success side, Saudi Aramco delivered the first certified blue ammonia and proved its effectiveness by capturing 50 tonnes of CO_2 in its demonstration project with Japan. The company has also established a strong presence in three key markets: Japan, South Korea, and Saudi Arabia. While working toward achieving its 2030 target, Saudi Aramco faces two main challenges. First, the cost of blue ammonia production is still higher than conventional production methods. Second, the company needs to overcome technical and economic challenges in developing the necessary infrastructure for transporting and storing large amounts of ammonia [9].

4. Blue Hydrogen and Ammonia Technical Analysis

4.1 Temperature Considerations in Energy Transport and Storage

The temperature requirements for storing and transporting different energy sources highlight important technical considerations for the blue ammonia project. Figure 6 illustrates the liquefaction and freezing points for five different energy sources. Conventional fuels like gasoline and diesel are liquid fuels by nature, thus requires no additional processing for shipping. However, they produce significant carbon emissions when burned, 2.3 and 2.7 kg CO_2 per liter, respectively [12]. On the other hand, while natural gas and hydrogen can be transported through pipelines in their natural state, the lack of worldwide pipeline infrastructure necessitates alternative shipping methods. Therefore, these energy sources must be liquefied for maritime or land transportation such as trucks and trains. For example, natural gas must be kept below -160°C for liquefaction, while hydrogen requires an even lower temperature of -253°C. Maintaining these low temperatures for natural gas and hydrogen require high energy cost and complex infrastructure. In addition, hydrogen demands precise temperature control system because the margin between liquefaction and freezing point is so minimal (6°C).

Given these challenges, ammonia emerges as a practical and economically viable hydrogen carrier because it requires more manageable temperature compared to liquified natural gas and hydrogen (-33.4°C for liquefaction and -77°C for freezing). These characteristics explain Saudi Aramco's strategic choice of ammonia as a medium for its clean energy exports.

Figure 6: Products liquefaction vs Freezing Points

4.2 Energy Density Comparison Across Energy Sources

Figure 7 illustrates the energy density (kWh/Liters) of different energy sources, highlighting significant variations among conventional and alternative fuels. From an economic perspective, hydrocarbon fuels, such as gasoline and diesel, have higher energy density compared to clean energy alternatives. For example, gasoline produces approximately 9 kilowatt-hours per liter (kWh/L), while diesel and natural gas produce approximately 10 and 6 kWh/L, respectively. In comparison, blue ammonia and hydrogen have lower energy density than conventional energy products (approximately 3 and 2.5 kWh/L), but their zero-emission characteristics makes them attractive option as clean energy sources.

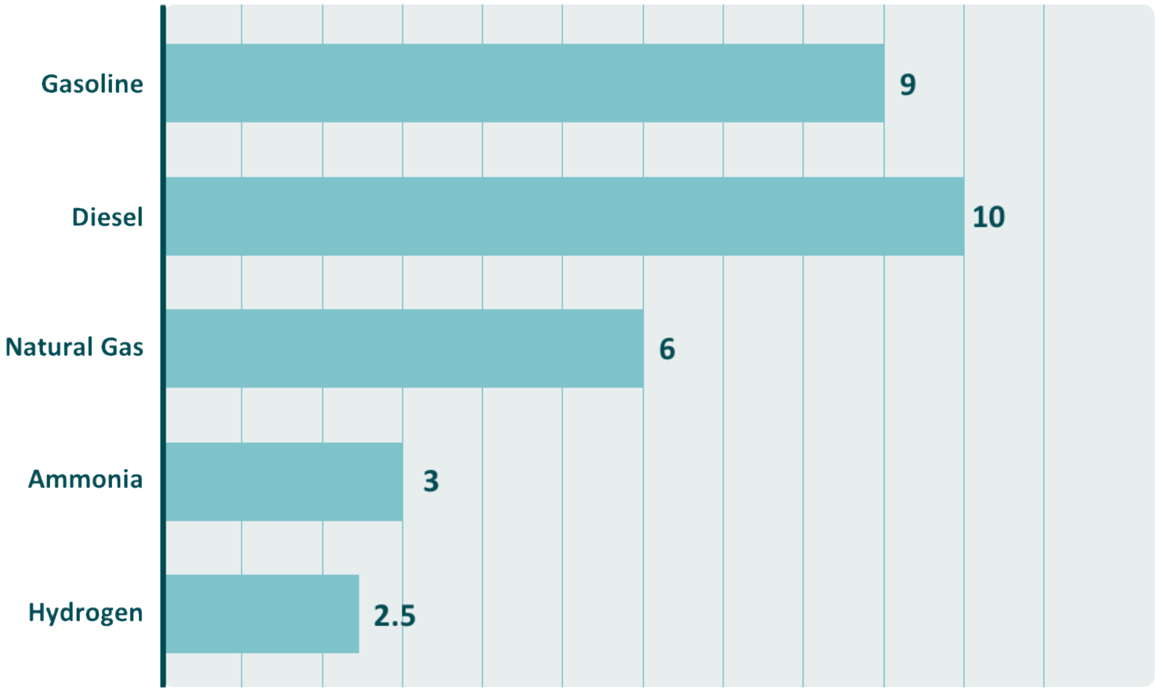

Figure 7: Comparison of Energy Density (kWh/Liters) Among Different Energy Sources

4.3 Challenges of Blue Hydrogen and Ammonia Adoption

While blue hydrogen and ammonia shows potential to become core energy sources, they still have several challenges in their production and implementation. The primary challenge is the high production cost. For example, the production of blue hydrogen and ammonia requires significant infrastructure investment for carbon capture, utilization and storage (CCUS) facilities, in addition to the cost required for hydrogen storage and trasportation. Therefore, increasing the investment will enhance the technology and utalization. According to BNEF, $11 trillion are required for hydrogen production to only meet a quarter of forecasted energy demand by 2050 [7].

The market readiness is also another obstacle facing the blue hydrogen and ammonia implementation due to limited infrastructure and customer readiness to adopt this cleaner energy source. Additionally, lack of policy and regulation support for both supply and demand sides is another barrier to further adoption.

5. Conclusion

The literature on blue hydrogen and ammonia highlights how these energy sources have the potential to surpass other alternative clean energy. It emphasizes that blue ammonia is considered a leading candidate as blue hydrogen carrier to enable hydrogen utilization and worldwide adaptation, as it addresses the challenge of hydrogen storage and transportation. Despite its high production and operational cost highlighted in the literature, blue ammonia remains the most economical option compared to other types of ammonia, excluding gray ammonia. Even so, the transition to blue hydrogen and ammonia requires international collaboration and leading organizations and government support to create the demand. Meanwhile further research and development is essential to find cost-effective production methods.

Given all the challenges highlighted about blue hydrogen and ammonia in both the literature and Saudi Aramco blue hydrogen and ammonia projects, would this energy source be an attractive investment for energy companies? Saudi Arabia has significant potential among other countries to produce the lowest-cost blue and green hydrogen. However, green hydrogen presents more challenges for Saudi Arabia due to the required initial costs to build renewable facilities and the additional processes required for water production through desalination, which could potentially impact the environment. While other competitors have put their projects on hold, Saudi Aramco has continued investing in blue hydrogen and ammonia. With the announcement of new global regulations and policies, Saudi Aramco's early commitment may give it a first-mover advantage in this emerging energy sector, as it will enable it to secure exclusive contracts and establish strategic partnership with key buyers.

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