Developing a Global Hydrogen Market

October 2022

The following content is a summary of available third-party information. Your input at the upcoming workshop will inform the Final Report relating to this material. While this paper was commissioned by the Energy Futures Initiative (EFI) and King Abdullah Petroleum Studies and Research Center (KAPSARC), it does not represent the views and conclusions of the authors or either organization. EFI and KAPSARC have not endorsed or approved the statements and conclusions contained in these documents, but rather have approved the limited sharing of these materials as part of the study process. Please do not disseminate or otherwise use this information for other than its intended purpose.

Introduction

A global hydrogen market does not exist today. Currently, hydrogen supply and demand is localized, with minimal transportation. Multiple pathways exist for market development with opportunities for the expansion of existing infrastructure and the development of new production methodologies for hydrogen. Similarly, there are many current and potential uses for hydrogen, as shown in Figure 1.

Interest in hydrogen has evolved in the 21st century from a specialty chemical to an energy commodity that can support the transition to a clean energy future. However, both producers and consumers of hydrogen are looking for adequate market signals to deploy the necessary capital that is required to establish functional hydrogen markets locally, regionally, and globally. The conundrum associated with risk sharing - where suppliers seek confidence in the off-take of hydrogen and consumers seek abundant, reliable, and affordable volumes of hydrogen - must be addressed if hydrogen is to become a significant and clean fuel source for the energy transition.

This paper is a summary of current reporting on the opportunities and challenges; and, is meant to set the stage for discussion on question areas facing traditional energy-producing nations as they aim to become a frontrunner in the nascent global hydrogen market.[vi] Subsequently, investment in the full value chain will play a significant role in shaping country strategies.

Figure 1: Hydrogen Pathways (Sources and Uses)

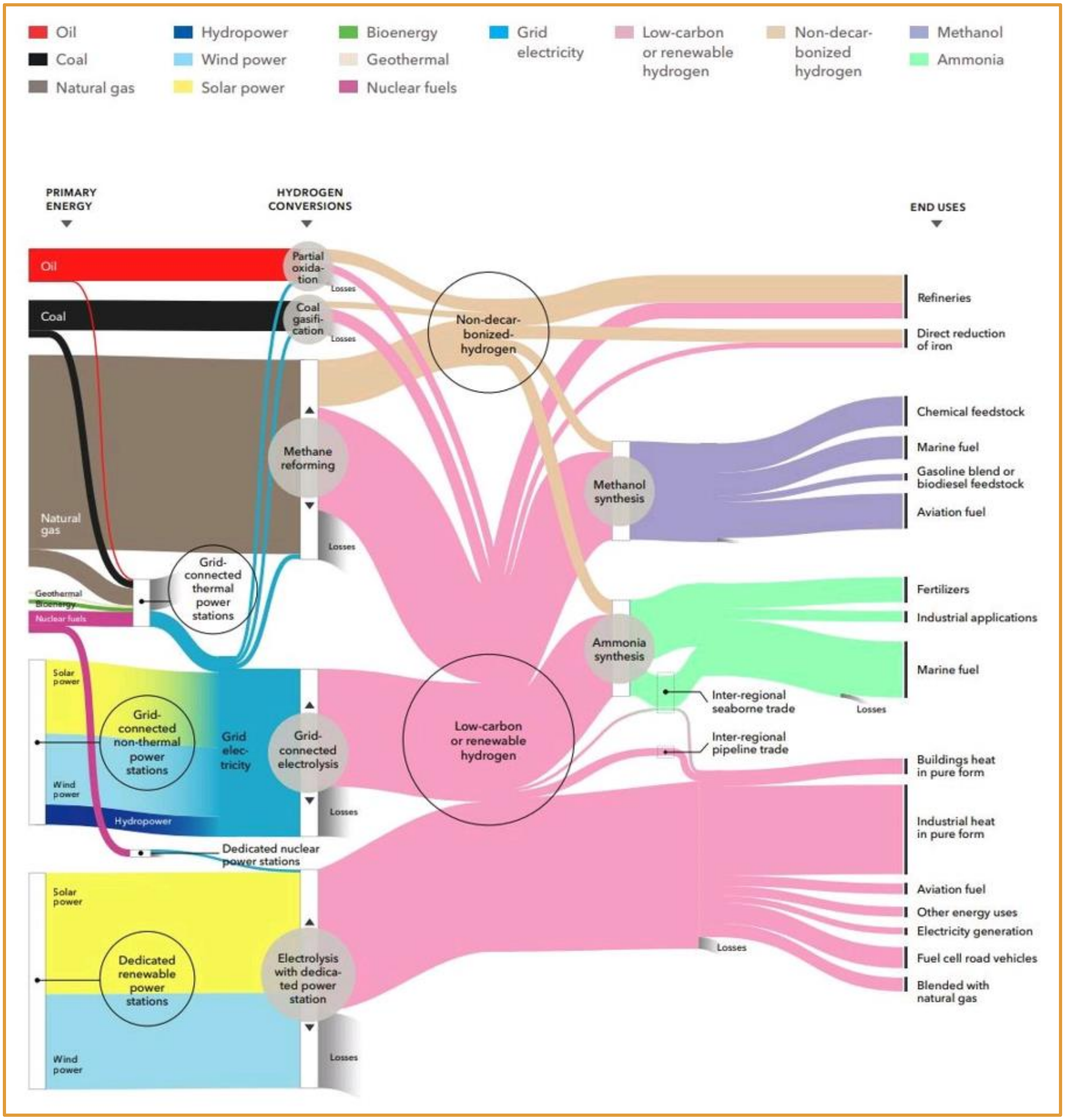


Figure 2.

Key Terms

Clean Hydrogen: As defined by the U.S. Department of Energy is hydrogen produced with a carbon intensity of 2 kg or less of carbon-dioxide equivalent produced at the site of production per kg of hydrogen produced. (https://afdc.energy.gov/fuels/laws/HY?state=US)

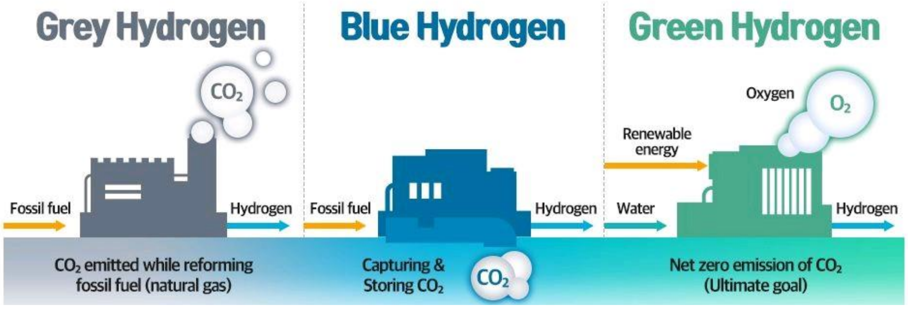


Table of Contents

1. Hydrogen Production and the Cost of Supply

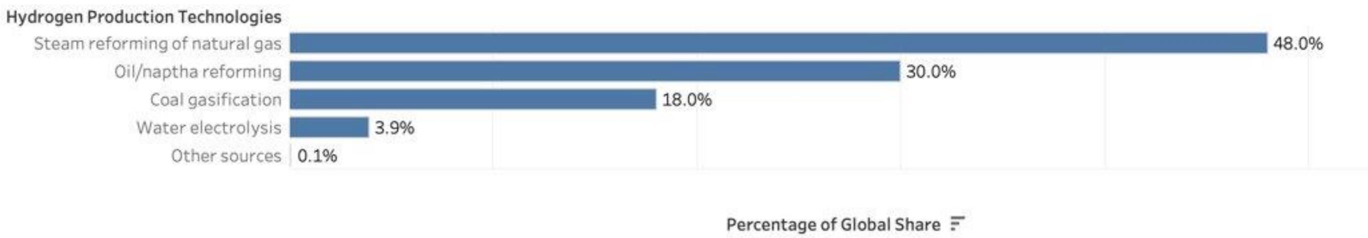
At a basic level, hydrogen is produced from methane or water splitting. Methane production requires significantly less energy to obtain an equivalent amount of hydrogen.[i] Currently, most hydrogen is produced by carbon-heavy emitting technologies.

Hydrogen allows for a variety of production pathways that range in scale, cost, and emissions. At present, most hydrogen production leverages highly emitting technologies.[ii] **Steam methane reforming (SMR)** and **Autothermal methane reforming (ATR)** use fossil fuel with steam or oxygen inputs to produce syngas (CO and H_2), which is then converted into carbon dioxide and hydrogen via the water-gas shift.[iii] SMRs and ATRs are comparable in terms of emissions of ~9 kg CO_2/kg hydrogen at the point of production and 11.2 kg CO_2/kg hydrogen when accounting for upstream emissions.[iv] While ATRs have lower capital recovery costs, the price of hydrogen per kilogram can be more expensive across its lifetime due to the relative efficiencies.[v] For the purpose of producing a high-purity hydrogen product, SMRs are the standard reformation technology to date, with as many as 1,000 commercial facilities across the world. ATRs are commonly used for ammonia and methanol production.[vi]

Coal gasification is another mature technology for producing hydrogen, but the associated emissions are nearly 20kgCO_2/kg hydrogen at point of production.[vii] The costs of coal gasification are typically more expensive than reformation – the former costing $1-$2.50 per kilogram of hydrogen, whereas SMR/ATRs cost around $.70-$2.20 per kilogram.[viii] The process uses pyrolysis, a method of decomposing hydrocarbons with heat, and feeding oxygen into the combustion chamber to gasify char that transforms into tar vapors, carbon monoxide, and hydrogen.[ix] Coal gasification for hydrogen production is largely used for chemical manufacturing in China.[x]

The reformation and coal gasification thermolysis (chemical decomposition via heating) technologies constitute 96 percent of global hydrogen production, as shown in Figure 3.[xi] Approximately 90 Mt of hydrogen was produced globally in 2020, resulting in 900 Mt of unabated CO_2, the equivalent of 28 percent of the entire emissions portfolio of the MENA region.[xii] Cleaner production pathways are needed to achieve national and global emissions targets, such as Saudi Arabia's Nationally Determined Commitment (NDC) Paris Agreement target of 278 Mt of CO_2 reduction by 2030.[xiii]

Figure 3.



Sum of Percentage of Global Share for each Hydrogen Production Technologies. The marks are labeled by sum of Percentage of Global Share. Details are shown for Hydrogen Production Technologies. The view is filtered on Hydrogen Production Technologies, which keeps Coal gasification, Oil/naptha reforming, Other sources, Steam reforming of natural gas and Water electrolysis.

As of 2020, the largest production segment for hydrogen is **oil refining**, which represents 30-35 percent of global production of hydrogen.[xiv] This production is mostly due to the steady increase in ratio of hydrogen per barrel of oil needed to treat sour crudes. Since refinery demand moves in tandem with oil demand it is expected that the oil industry and refineries will return to pre-pandemic production levels. However, this also presents an opportunity for markets to move toward cleaner hydrogen sources. [xv] Despite clean hydrogen's cost premium, relative to more carbon-intensive production pathways, hydrogen demand is highly inelastic, within the petroleum industry, due to its essential role in the refining process. Additionally, hydrogen accounts for a small percentage of the total operating cost of refining plants, further reducing the impact of potential fuel cost increases.[xvi]

A close second for hydrogen production is used in the production of **ammonia,** at 38 percent. The global ammonia market is around 176 Mt per year and is commonly used as a feedstock for agricultural fertilizers. Ammonia is also used in refrigerants and air conditioning units, as well as other niche applications such as AdBlue for NOx control in vehicles, pharmaceutical, textile, and even explosives manufacturing.[xvii,xviii] In the International Energy Agency's (IEA) *Announced Pledges Scenario* by 2050, ammonia accounts for 50 percent of all trade in hydrogen and hydrogen-based fuels, meeting 10 percent of global energy demand.[xix]

As noted in the following section on potential demand, in the transportation sector ammonia could play a role as a flexible, non-emitting energy carrier for long-haul shipping. In fact, if sufficient safety measures are put into place, ammonia could become the new bunker fuel on ships. International shipping is currently three percent of total global greenhouse gas (GHG) emissions, a percentage that becomes important in view of net zero targets and potential pending carbon border adjustments. The existing pipeline infrastructure, shipping routes, and ports that handle large quantities of ammonia are already robust, which would allow for ammonia to play a larger role in the shipping industry.[xx] Unfortunately, ammonia production itself is one of the largest industrial emitters and the largest chemical emitter at 450Mt of CO_2 annually. [xxi] Most of the energy used in making ammonia comes from hydrogen production, which highlights the decarbonization potential of the industry.

Methanol production accounts for approximately 15 percent of global hydrogen. Like ammonia, it can be produced effectively around the world. The production of methanol requires 130 kg of hydrogen per ton and, globally, approximately 100 megatons (Mt) of the product was used in 2020.[xxii] By virtue of the many applications of methanol, methanol production can be expected to increase to 500 Mt by 2050.[xxiii] Some of those applications include ethanoic acid for paint, silicone for lubricants, olefins for plastics, and formaldehyde for plywood. As a fuel, it can be blended with gasoline and diesel as an efficient energy carrier in marine shipping or converted to other fuels or chemical applications. In the coming decades, because of energy and fuel applications, there is significant potential demand for methanol.[xxiv] With a combination of CO_2 capture and clean hydrogen processes, methanol can achieve net zero emissions.

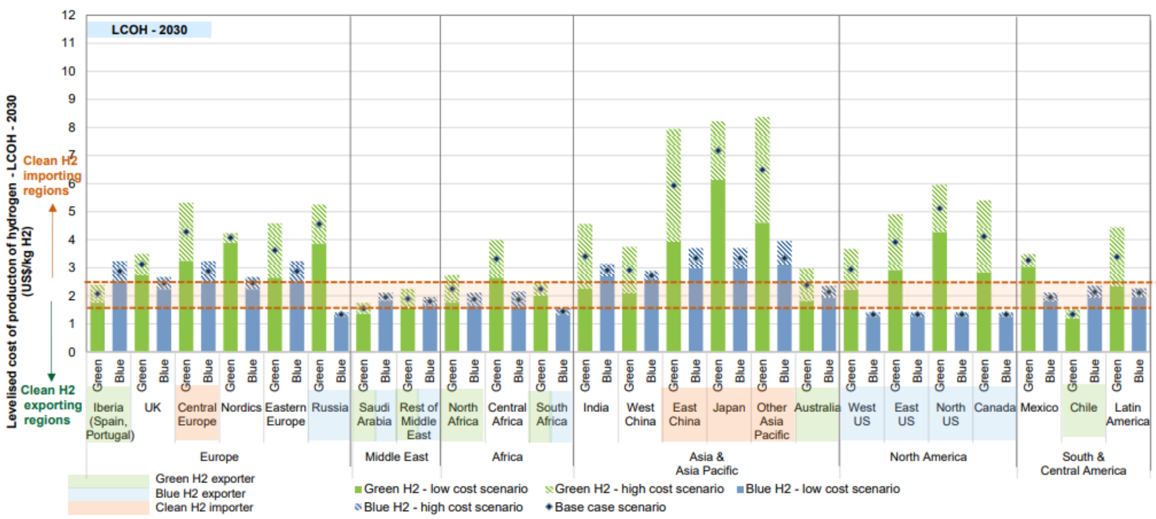
In addition to the top three uses of hydrogen, steel production is a significant consumer as well. Currently, the steel industry accounts for 10 percent of global industrial hydrogen demand.[xxv] **Direct reduction of iron (DRI)** accounts for seven percent of total global crude steel production.[xxvi] In the DRI process, synthetic gas reduces iron ore to sponge iron.[xxvii] Some steel plants (e.g., ArcelorMittal in Germany) are looking to reduce emissions through a transition to 100 percent hydrogen for DRI. ArcelorMittal is building two DRI facilities that could produce around 3.5 million tons of steel by 2030, with a CO_2 savings potential of 5 Mt by fuel-switching to hydrogen.[xxviii]

Beyond combustion uses, hydrogen has great potential as a valuable commodity for producing electricity as well. Fuel cells can use the chemical energy of hydrogen to produce electricity with only water as a byproduct. Fuel cells are highly efficient and have the added benefit of not creating NO_x emissions, which is a concern when combusting hydrogen.[xxix] Today, fuel cells are used most notably used in materials handling (e.g., forklifts) and mobility applications, though the market is relatively nascent compared to the uses.

Figure 4 (below) highlights country and regional hydrogen differences in the cost of supply. While the cost factors associated with the production of hydrogen are generally known, excepting emerging technologies, variability exists from localized factors, such as - the costs associated with primary energy used, raw materials, labor, tax regimes, and government incentives. These factors create an opportunity for suppliers who produce hydrogen in the most efficient manner, which will shape the competitive landscape as a global hydrogen market emerges.

Figure 4.

MENA, Chile (and other LatAm), Australia and Iberia could emerge as key clean hydrogen exporting regions while Japan, Korea, Central Europe and potentially parts of East China could become key clean hydrogen importing regions, depending on the scale and importance of clean hydrogen in their respective economies



Source: Goldman Sachs Global Investment Research

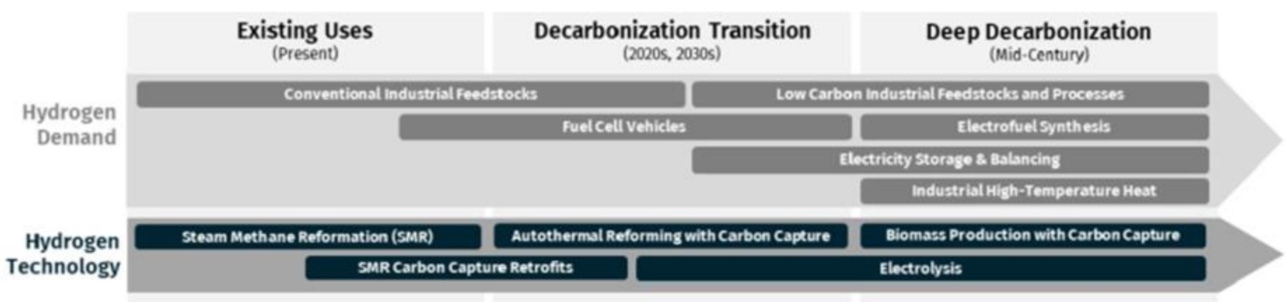
As part of the discussion leading into the sections on demand and pricing, the transportation challenges for shipping/delivery and storage must be touched upon. Challenges to hydrogen delivery include reducing cost, increasing energy efficiency, maintaining hydrogen purity, and minimizing hydrogen leakage. As the market develops, further research and eventually market experimentation is needed to discover the best trade-offs between the hydrogen production options and the hydrogen delivery options when considered together as a system.[xxx] Storage issues along the value chain are complex and range from regulatory (as mentioned in another workshop whitepaper on Regulatory and Policy concerns) to weight and volume, life cycle issues, and eventually cost.[xxxi] To resolve these issues nations, and companies therein, are likely to deploy a myriad of solutions to resolve the transportation challenges from creating *hub and spoke* types of networks, such as are under development in the United States, to more top-down led approaches such as Germany's recent efforts with Canada and Saudi Arabia.[xxxii,xxxiii, xxxiv, xxxv]

- **What regions are attractive for hydrogen growth and why?**
- **How is the global hydrogen market expected to grow as the technologies for hydrogen production evolve?**
- **Does the development of a hydrogen market domestically in the United States provide a competitive advantage for U.S. producers internationally?**

2. Development of Global Hydrogen Market Demand

As shown on Figure 5 below, new market entrants on the consumption side are paving the way to increased usage of a clean fuel that can help decarbonize today's most carbon intensive sectors.

Figure 5: *The Rhodium Group figure shows how the hydrogen market could evolve over time as the decarbonization of hydrogen becomes a priority in fossil fuel-producing and consuming countries around the world.*



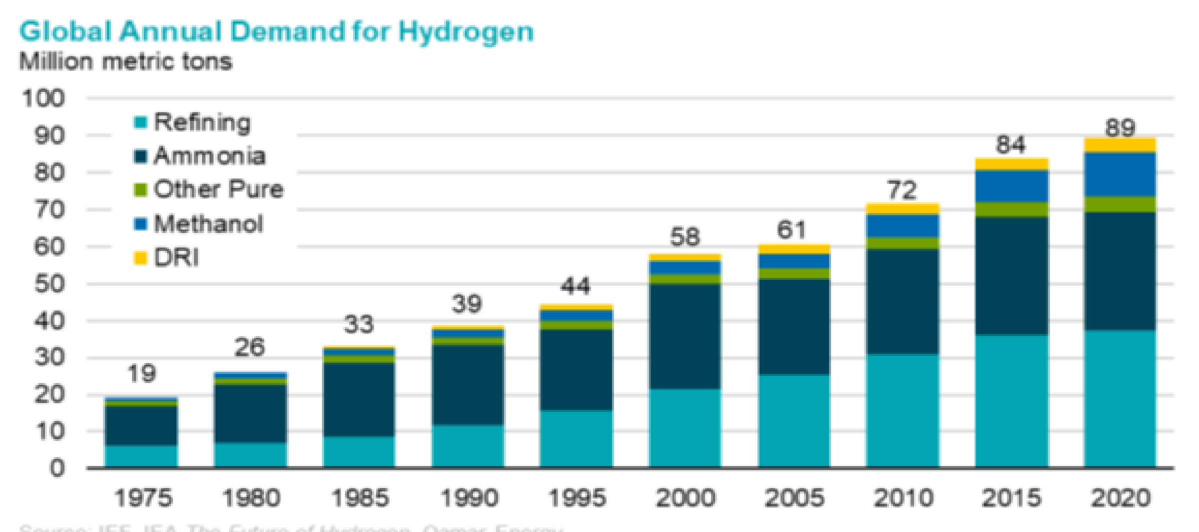
Nationally determined contributions (NDCs)[1] are a major market driver for clean hydrogen as difficult-to-abate sectors require creative solutions to decarbonization. Existing industries that rely on grey hydrogen are looking to transition to clean hydrogen in addition to new markets developing, specifically in the realm of on-road mobility and stationary fuel cells. With new applications for hydrogen, global demand could rise to over 200 Mt by 2050 (Figure X.[xxxvi] This new demand must be met by a steep increase in zero and low-carbon hydrogen production if NDCs are to be achieved. Likely production pathways to produce zero and low-carbon hydrogen include SMR and ATR with Carbon Capture Utilization and Storage (CCUS) as well as renewable electricity-powered electrolysis.

[1] Nationally Determined Contributions (NDCs) submitted by countries under the Paris Agreement of the United Nations Framework Convention on Climate Change (UNFCCC) represent pledges on climate action that seek to limit global warming to well below 2°C, preferably to 1.5 °C, over pre-industrial levels.

Retrofitting existing SMRs and ATRs with carbon capture may be the cheapest option to meet demand for low-carbon hydrogen. The on-site emissions produced by ATRs and SMRs with a capture rate of 85 percent, have an emissions intensity of 0.62 and 1.98 kgCO_2/kg hydrogen, respectively.[xxxvii] The levelized cost of hydrogen production increases to $1.50-$2.90 per kg for SMRs/ATRs with CCUS, with ATRs expected to be on the lower end of that cost range (no ATRs with CCUS exist today for reference).[xxxviii] However, solutions must be developed for decreasing lifecycle emissions, such as upstream methane emissions and the energy required to compress and transport captured CO_2. When accounting for lifecycle emissions, ATR and SMR with an 85 percent capture rate have a carbon intensity of 3.61 and 6.66 kgCO_2/kg hydrogen, respectively.[xxxix]

Although retrofitting existing infrastructure to produce low-carbon hydrogen is a cheap solution, electrolysis using electrolyzers is the fastest growing clean energy hydrogen production technology. Simply, an electrolyzer splits water into hydrogen and oxygen through a chemical reaction that only releases water vapor as a byproduct.[xl] The electrolyzer is powered by electricity, and thus the lifecycle emissions of the electrolytic hydrogen production are based on the electricity mix. Electrolysis using dedicated or curtailed renewables creates zero-carbon hydrogen. However, electrolyzers are very energy intensive to run. If an electrolyzer was running at 100 percent efficiency, it would require 39 to 55 kWh to produce one kilogram of hydrogen.[xli] According to some analysts, the compound annual growth of electrolyzer capacity will grow 78 percent by 2030.[xlii]

Figure 6.



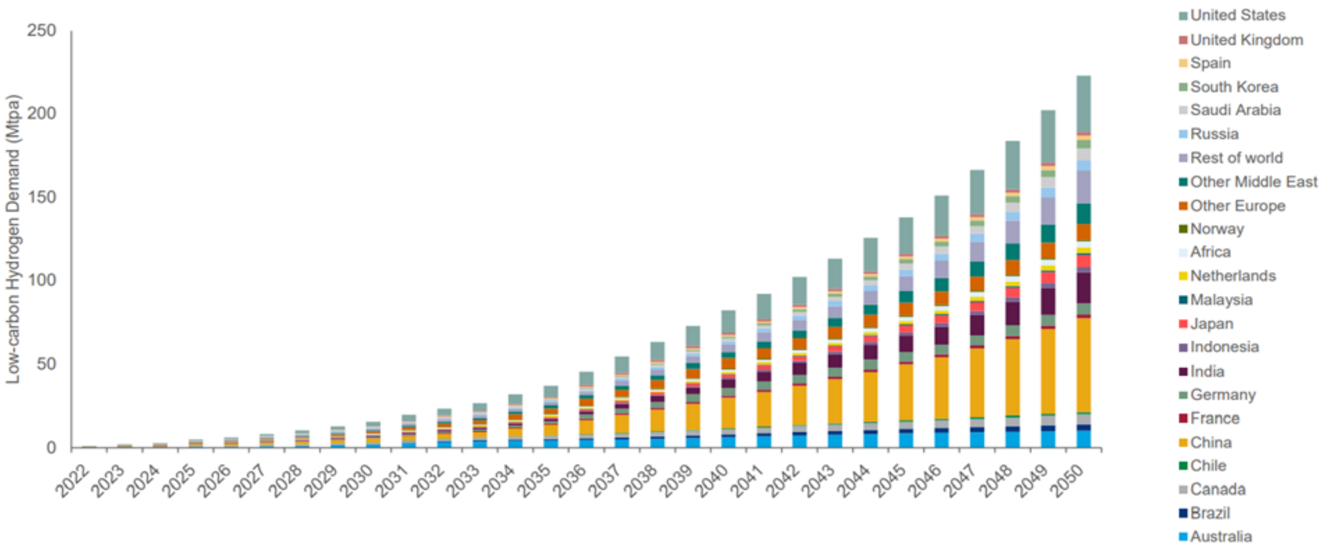
One critical area of future demand is the transportation and industrial mobility sector. As fuel cell innovation grows, heavy-duty vehicles (HDVs) could be more competitive than passenger fuel cell electric vehicles (FCEVs), due to longer range capabilities, lower fuel use, and cost less than comparable battery electric vehicles (BEVs). Off-road uses of FCEVs are viable too and a successful market has emerged for fuel cell-powered forklifts, due to their strong performance standards. Opportunities also exist for replacing diesel engines with fuel cells in drayage trucks at ports, mining and agricultural equipment, equipment handling mobility at airports, tractors, and small watercraft.

Additionally, stationary fuel cell options could contribute to an increase in demand. Stationary fuel cells have the added advantage of modularity and use can scale up with minor renovation. On a small scale, stationary fuel cells can replace expensive backup diesel generators in critical facilities such as hospitals or data centers.[xliii] On a much larger scale, wholesale electricity providers could have fuel cells that store electricity on the grid, lowering energy prices and reducing curtailment of clean energy sources, such as wind and solar.

Given that hydrogen can be used for combustion or as a storage medium for electricity production. Utilities may be able to replace natural gas feedstocks with hydrogen. With a little renovation, hydrogen can be blended into the feedstock, up to 20 percent, before changing the gas turbine is required. Hydrogen for power generation and load balancing can drastically lower emissions of the residential and commercial sectors.

Hydrogen is viable for other difficult-to-decarbonize sectors such as cement manufacturing and aviation. For cement, hydrogen fuel can be blended with gas or used by itself to mitigate emissions in the heating stages of production.[xliv] In aviation, it may someday be possible to fly a plane using a fuel cell engine. In the nearer term, hydrogen will be used in the creation of sustainable aviation fuels (SAFs). Specifically, biofuels can be hydro-processed and/or hydrotreated by hydrogen to improve the energy yield of those biofuels. Additionally, upstream use of hydrogen to produce biofuels can replace the emission-intensive fermentation process.[xlv]

Figure 6: IEA Projections of Global Hydrogen Demand



Hydrogen remains a vital petrochemical feedstock and key ingredient in fertilizer production. Finally, there exists opportunities for demand growth in the consumption of hydrogen from fuel switching in the transportation sector. Hydrogen could represent a clean fuel that could be used in the marine and long-haul (train or trucking) sectors in addition to aviation.

- **Similarly, what end uses (that are not currently being targeted) are attractive for hydrogen growth and why?**
- **How will critical mineral supply chains impact market development? How will a shift to energy production dependent on renewables impact the development of a hydrogen market?**
- **How will the implementation of the Inflation Reduction Act impact hydrogen development in the U.S. and subsequently an eventual global market?**

3. Hydrogen Market Development & Pricing – A Natural Gas Analog

As in natural gas, development of a global hydrogen market will depend on resource availability and pricing compared to alternative fuels. While much of the attention associated with identifying alternative and sustainable sources of energy to facilitate the energy transition is focused on the supply side of the equation (i.e., R&D, or regulatory frameworks designed to incentivize new technologies), of equal importance is the demand – both existing and new - for hydrogen. In this context, a review of the development of natural gas markets is instructive because as much as an abundant, affordable, and sustainable supply is needed commitments to combat climate change, market forces, and competition must also be considered.

Understanding the global framework, as well as some of the historical practices that have influenced the natural gas industry and the development of an associated market, is key. In the Middle East, natural gas markets evolved from flaring gas as a by-product of oil production into local use in the industrial sector as a feedstock for the petrochemical industry or for power generation. Ultimately it attracted foreign direct investment (FDI) from the oil industry and evolved into a key export from the region travelling through either gas pipelines or liquid natural gas (LNG) sales. As both local and global demand for natural gas grew, the interconnectivity of markets occurred and many non-associated gas resources within the region developed. As the hydrogen market evolves into true interconnectivity, we expect similar behavior. However, for large scale hydrogen export projects, the economics will dictate the cost of supply and the market competitiveness vis-a-vis other energy alternatives that will determine if a project goes forward. While natural gas is not a completely fungible commodity, this interconnectivity of markets has shaped the overall pricing of natural gas and hastened its evolution toward global liquidity. Thus, the cost of holding supplies versus the pricing of natural gas must be evaluated to ensure that the full value and potential of this resource is achieved.

In North America, due to market liquidity, the price is set by gas-to-gas competition between suppliers, with the long-term floor and ceiling prices tied to fuel alternatives (e.g., coal and fuel oil). In these markets, pricing is established primarily on short- and medium-term gas supply and demand fundamentals. Transparent gas prices (i.e., prices accepted by both the market as valid and available, on a timely basis) are provided through gas price surveys published as daily and monthly indices, settlement prices (e.g., Henry Hub[2]), and through publicly traded futures on NYMEX[3].

In contrast, initial LNG price formation for buyers in Asia was set by competing energies at the burner tip, primarily derived from the prices of oil products. In periods of surplus natural gas, prices below oil parity were expected to cause a reduction in new gas developments, initiating a supply-driven price rise. Conversely, natural gas prices above oil parity[4], due to scarcity of oil supply, would result in an increase of LNG project development thereby starting a demand-driven price drop. Over time, gas prices would theoretically gravitate toward parity. Similarly, the principles of gas pricing can be applied to the development of a hydrogen market.

The mix of competing fuels is an important factor in establishing the base price and in identifying subsequent changes in competition and market composition that may be considered during subsequent price reviews for long-term contracts. Hydrogen may be an alternative for consumers in selected markets. A base price reflecting gas competition to the extent that it is the best alternative for a buyer should be considered carefully. Such an assessment should be supported by detailed benchmarking of competing gas projects to better understand the pricing leverage of competitors. Such benchmarking analysis needs to consider the cost structure of other projects, and anticipate probable pricing proposals, based on historical track records, and an assessment of current marketing strategies and objectives.

Looking through the lens of natural gas market development, along with a comprehensive analysis and understanding of market factors and alternatives, the development of a hydrogen market can be envisioned, and potential demand pathways identified, such as in Figure V. Additionally, when combined with an inventory of potential hydrogen projects and the

[2] For a definition see: https://www.investopedia.com/terms/h/henry_hub.asp
[3] New York Mercantile Exchange
[4] On a thermal or Mtbu basis

associated costs of supply, this could provide a basis for a market-based model of the associated hydrogen price–volume elasticity.

Figure 7.

- **Should LNG be used as an analogy to predict hydrogen market growth? If not, what forces might drive hydrogen growth?**

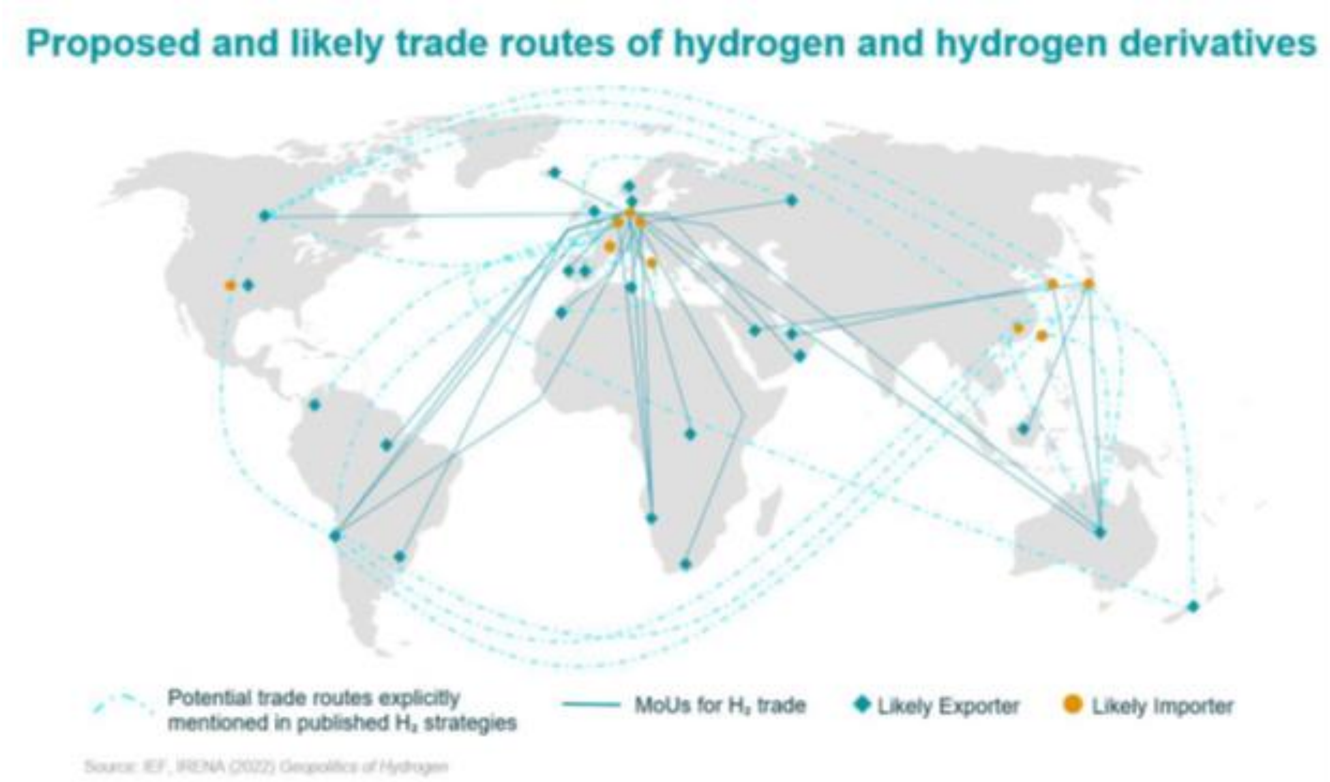
- **Will Supply Drive Demand or will Demand Drive Supply to Facilitate a Global Hydrogen Market?**

4. Hydrogen Trade Possibilities

Outside of the EU, a few G20 countries are committed to developing electrolyzer capacity, production, and demand targets. Most of these countries lack dedicated policy support for hydrogen. In addition to formulating ambitious blue and green hydrogen targets, any dedicated resource-producing export-driven policy approach will have to address many challenges amid this uncertainty. To build local production capacity, many countries, such as those in the MENA region, may require a top-down long-term view of investing. In addition to spearheading the development of hydrogen hubs, resource-rich nations have several intervention options. One option is to set progressive quotas for specific industries to gradually increase the share of hydrogen among the fuels used. Another is to provide producers with regulated returns, which would allow them to realize pre-determined returns on costs. Additionally, producers can provide subsidies to end users of hydrogen and support the construction of supporting infrastructure (e.g., pipelines, port infrastructure) to handle H_2 exports. These subsidies would enable users to pay a premium to use clean hydrogen instead of incumbent carbon-intensive fuel.[xlvi]

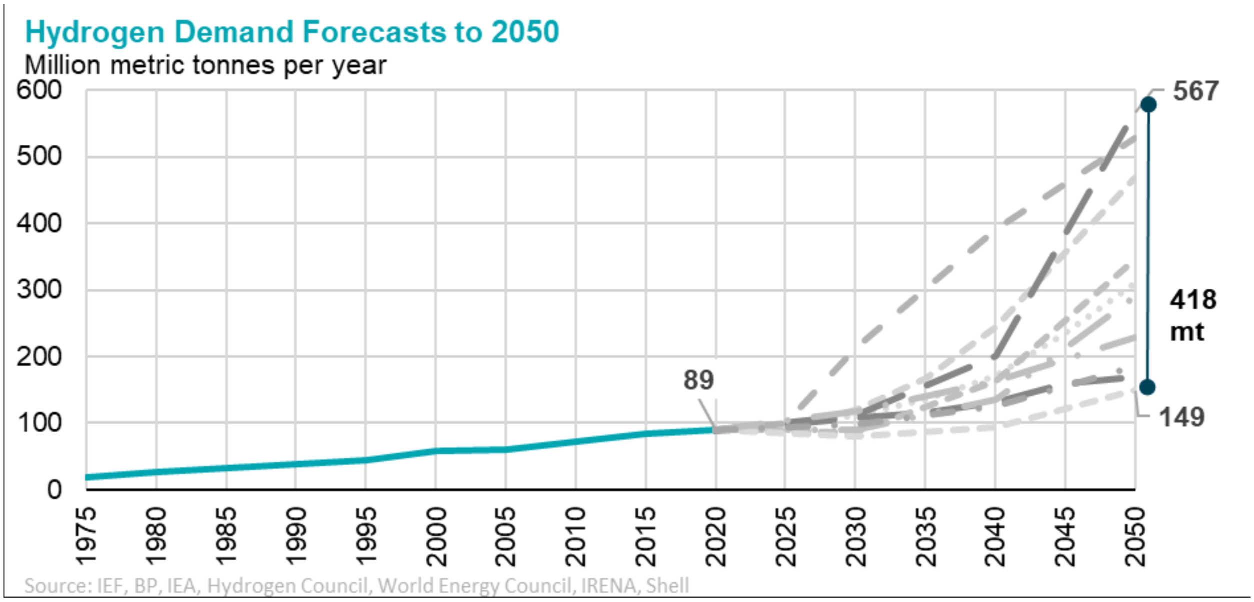
The war in Ukraine has caused supply constraints of natural gas in Europe and brought the continent to a unique juncture whereby European nations must balance energy security, affordability, and climate commitments with designs for a new energy transition. In the European Union (EU), renewable or low-carbon hydrogen will be key in addressing critical challenges linked to the decarbonization, dependability, and competitiveness of EU industries. The EU is a technology leader in several clean hydrogen technologies with half of electrolyzer manufacturers in Europe. However, the EU depends on imports of raw materials for key components as well as the supply of renewable energy.[xlvii] The growth in climate policy efforts worldwide, and especially in the EU, is reasonably likely to lead to an impactful CO_2 price in the medium to long term. Progress toward implementing climate goals in line with the Paris Agreement will, directly and indirectly, impact investment decisions for highly ambitious exporters. Such progress will strengthen the incentives to rapidly scale up clean hydrogen production and demand.[xlviii]

Figure 8.



Interest in hydrogen has accelerated in the past five years as decarbonization targets have moved to the top of government priorities. More than 50 countries have developed, or are in the process of developing, a national hydrogen strategy(Figure N). The EU has quadrupled its low-carbon hydrogen supply target for 2030 from 5.6 million metric tons per annum (Mtpa) to 20.6 Mtpa, as part of its *REPowerEU* strategy to reduce reliance on Russian natural gas. Over 500 large-scale projects have been announced in the last few years and approximately50 percent of those were announced within the past 12 months (as of April 2022). There are many ambitious targets, but it is not clear how they will be achieved. Increased production and strong demand will be needed to reach these goals as hydrogen development progress towards the 2050 forecasted growth (Figure 9).[xlix, l] Through a comprehensive review of market factors and alternatives, the development of a hydrogen market can be assessed, and the potential demand established. This, when combined with an inventory of potential hydrogen projects and the associated cost of supply, will provide the basis for an understanding of market formation that could inform a market-based model of hydrogen growth as part of the global energy sector.

Figure 9.



- **How can government strategies/policies (at a national and international level) support hydrogen market growth? What sorts of government interventions are needed?**

- **What other trade aspects for hydrogen need to be considered?**

- **Will the war in Ukraine impact the development of hydrogen in Europe and how?**

5. Endnotes

[i] https://www.energy.gov/eere/fuelcells/hydrogen-production-natural-gas-reforming

[iii] https://www.hindawi.com/journals/cpis/2013/690627/ p. 3
[iv] https://www.sciencedirect.com/science/article/pii/S0196890422000413 p. 9
[v] https://www.nrel.gov/docs/fy02osti/32405b2.pdf p. 6
[vi] https://www.nrel.gov/docs/fy02osti/32405b2.pdf p. 11
[vii] https://www.goldmansachs.com/insights/pages/gs-research/carbonomics-the-clean-hydrogen-revolution/carbonomics-the-clean-hydrogen-revolution.pdf p. 30
[viii] https://energyfuturesinitiative.org/wp-content/uploads/sites/2/2022/03/The-Future-of-Clean-Hydrogen-in-the-U.S._Report-1.pdf p. 22
[ix] https://www.goldmansachs.com/insights/pages/gs-research/carbonomics-the-clean-hydrogen-revolution/carbonomics-the-clean-hydrogen-revolution.pdf p. 30
[x] https://iea.blob.core.windows.net/assets/5bd46d7b-906a-4429-abda-e9c507a62341/GlobalHydrogenReview2021.pdf p. 51
[xi] https://www.intechopen.com/chapters/72194
[xii] https://iea.blob.core.windows.net/assets/5bd46d7b-906a-4429-abda-e9c507a62341/GlobalHydrogenReview2021.pdf p. 5
[xiii] https://unfccc.int/sites/default/files/resource/202203111154---KSA%20NDC%202021.pdf p. 3
[xiv] https://www.woodmac.com/press-releases/low-carbon-hydrogen-demand-in-refining-could-reach-50-mtpa-by-2050/
[xv] https://iea.blob.core.windows.net/assets/5bd46d7b-906a-4429-abda-e9c507a62341/GlobalHydrogenReview2021.pdfiea report 2021
[xvi] https://www.energy.gov/eere/fuelcells/h2scale p. 5
[xvii] https://royalsociety.org/-/media/policy/projects/green-ammonia/green-ammonia-policy-briefing.pdf p. 6
[xviii] https://iea.blob.core.windows.net/assets/5bd46d7b-906a-4429-abda-e9c507a62341/GlobalHydrogenReview2021.pdf iea report 2021

[xix] https://iea.blob.core.windows.net/assets/5bd46d7b-906a-4429-abda-e9c507a62341/GlobalHydrogenReview2021.pdf pg. 161
[xx] https://royalsociety.org/-/media/policy/projects/green-ammonia/green-ammonia-policy-briefing.pdf p. 8
[xxi] https://iea.blob.core.windows.net/assets/6ee41bb9-8e81-4b64-8701-2acc064ff6e4/AmmoniaTechnologyRoadmap.pdf iea ammonia report 2021
[xxii] https://iea.blob.core.windows.net/assets/5bd46d7b-906a-4429-abda-e9c507a62341/GlobalHydrogenReview2021.pdf iea 2021 h2 report
[xxiii] https://www.methanol.org/the-methanol-industry/
[xxiv] https://www.methanol.org/applications/
[xxv] https://iea.blob.core.windows.net/assets/5bd46d7b-906a-4429-abda-e9c507a62341/GlobalHydrogenReview2021.pdf

[xxvi] https://iea.blob.core.windows.net/assets/5bd46d7b-906a-4429-abda-e9c507a62341/GlobalHydrogenReview2021.pdf iea 2021 h2 report

[xxvii] https://iea.blob.core.windows.net/assets/5bd46d7b-906a-4429-abda-e9c507a62341/GlobalHydrogenReview2021.pdf iea h2 2021 repot

[xxviii] https://corporate.arcelormittal.com/media/news-articles/arcelormittal-plans-major-investment-in-german-sites-to-accelerate-co2-emissions-reduction-strategy-and-leverage-the-hydrogen-grid
[xxix] https://www.energy.gov/eere/fuelcells/fuel-cells
[xxx] https://www.energy.gov/eere/fuelcells/hydrogen-delivery

[xxxi] https://www.energy.gov/eere/fuelcells/hydrogen-storage-challenges
[xxxii] https://www.csis.org/analysis/how-build-hydrogen-hub-houston
[xxxiii] https://www.power-eng.com/hydrogen/mitsubishi-power-highlights-four-hydrogen-projects/#gref
[xxxiv] https://www.bloomberg.com/news/articles/2022-08-23/germany-taps-boundless-fuel-potential-in-canada-hydrogen-deal
[xxxv] Hydrogen cooperation potential between Saudi Arabia and Germany, A joint study by the Saudi-German Energy Dialogue. Bmwk.de, 7 June 2022
[xxxvi] https://www.woodmac.com/our-expertise/focus/transition/2050---the-hydrogen-possibility/
[xxxvii] https://www.sciencedirect.com/science/article/pii/S0196890422000413 p. 9
[xxxviii] https://energyfuturesinitiative.org/wp-content/uploads/sites/2/2022/03/The-Future-of-Clean-Hydrogen-in-the-U.S._Report-1.pdf p. 22
[xxxix] https://www.sciencedirect.com/science/article/pii/S0196890422000413 p. 9

[xlii] https://www.prnewswire.com/news-releases/guidehouse-insights-anticipates-the-global-electrolyzer-capacity-will-grow-at-a-compound-annual-growth-rate-of-78-through-2031-301507971.html
[xliii] https://www.energy.gov/eere/fuelcells/hydrogen-and-fuel-cells-data-center-applications-project-meeting
[xliv] https://energyfuturesinitiative.org/wp-content/uploads/sites/2/2022/03/The-Future-of-Clean-Hydrogen-in-the-U.S._Report-1.pdf p. 23
[xlv] https://www.nrel.gov/docs/fy21osti/77610.pdf, pg. 18
[xlvi] Braun and Shabaneh, KAPSARC, “Commentary - Saudi Arabia’s Clean Hydrogen Ambitions: Opportunities and Challenges, June 2021, p. 10-11
[xlvii] https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions/executive-summary
[xlviii] Braun and Shabaneh, KAPSARC, “Commentary - Saudi Arabia’s Clean Hydrogen Ambitions: Opportunities and Challenges, June 2021, p. 10-11
[xlix] https://ec.europa.eu/commission/presscorner/detail/en/ip_21_6682
[l] https://www.ief.org/_resources/files/pages/hydrogen-market-pathways/ief-hydrogen-market-pathways-report---scaling-up-the-hydrogen-market---optimized.pdf?v=2, p. 8-22