MSc Program
Environmental Technology & International Affairs

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Strategic Geoeconomics of Hydrogen: Shaping Europe´s future energy market

A Master's Thesis submitted for the degree of
“Master of Science”

supervised by
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Vienna, 07.06.2024

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Vienna School of International Studies
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Affidavit

I, **PIUS SÉGUR-ELTZ, BA**, hereby declare

1. that I am the sole author of the present Master’s Thesis, "STRATEGIC GEOECONOMICS OF HYDROGEN: SHAPING EUROPE´S FUTURE ENERGY MARKET", 102 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
2. that I have not prior to this date submitted the topic of this Master’s Thesis or parts of it in any form for assessment as an examination paper, either in Austria or abroad.

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Signature

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Abstract

Hydrogen has re-emerged as a crucial component in Europe's decarbonization initiatives, detailed in the European Hydrogen Strategy and REPowerEU Plan. Hailed as the "coal of the future," renewable hydrogen is vital for technologies aimed at lowering emissions in hard-to-abate sectors. By 2030, decreasing green electricity costs are predicted to make green hydrogen more affordable, especially in favorable regions. Global hydrogen demand is expected to rise, driven by industry and transportation, leading to significant worldwide trading volume, with Europe aiming to import 10 million tons of renewable hydrogen by 2030, raising transportation concerns. Pipelines are suggested for distances up to 8.000 kilometers, while shipping is advised for longer routes. Transport cost-effectiveness depends on construction costs and infrastructure. The global hydrogen industry, unlike the oil market, is predicted to be more dispersed due to diverse hydrogen production potential, resulting in competitive pricing and more providers. Low production and transportation costs are critical, especially for Europe. The EU faces challenges in retaining competitiveness in hydrogen technologies. China leads in grey hydrogen generation and green hydrogen electrolysis capacity, while the US offers significant incentives under the Inflation Reduction Act. The EU must encourage domestic investment to fund its green transformation and prevent company relocation. Potential trade partners such as Chile, Morocco, and Algeria have similar production potential, but North African countries face water scarcity, whereas Chile offers political and economic stability with low production and delivery costs. Europe's critical iron and steel sector risks shifting to regions with cheaper hydrogen and abundant iron ore, such as Australia. Economic policy measures like Carbon Contracts for Difference and Green Lead Markets could support Europe's hydrogen-based green products without disrupting production or burdening taxpayers.

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An equally big thank you goes to my two interview partners Dr. Albrecht Zimburg, Austrian commercial attaché of the Republic of Austria in Casablanca, Morocco, and Mag. Drazen Maloca, Austrian commercial attaché of the Republic of Austria in Santiago de Chile, Chile. In their in-depth interviews, both were able to give me an understanding of the role of hydrogen, especially that of green hydrogen, from the perspective of two countries that may play a decisive role in the energy transition.

I would also like to thank my family, who have always offered me support and support, as well as my friends and fellow students, who have also always accompanied and encouraged me.

Finally, I would like to express my appreciation to all the authors and scientists whose work I have consulted for this master's thesis.

Without the help and support of all the people mentioned here, the completion of this work would not have been possible. Many thanks to all of you.

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"I believe that water will one day be employed as fuel, that hydrogen and oxygen which constitute it, used singly or together, will furnish an inexhaustible source of heat and light, of an intensity of which coal is not capable."

Jules Verne 1874

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1. Introduction

1.1. Personal motivation

My enthusiasm for the topic of renewable energies has only developed in recent years. A professional stay in Chile in 2022 enabled me to get to know the potential of green hydrogen in the field of industry and the entire energy transition. I became aware of the dimension of a wind park, which is required to drive electrolysis, while at the same time I understood how much future trade relations will change. Through my studies in the field of "Environmental Technology and International Affairs", I became aware of the interdisciplinary importance of the environment and diplomacy, and especially of the mutual influence of the two components. From this point of view, it was obvious for me to combine these two areas in my master's thesis, and I very much hope that I have succeeded in doing so with this work.

1.2. Research questions

Which role does the EU assign hydrogen regarding the energy transition?

This question is of fundamental importance as it focuses on the strategic direction of the European Union regarding hydrogen. As a crucial lever in the energy transition, hydrogen is gaining importance, which is why it is important to understand its future role in Europe.

Which transformative strategies will shape the future landscape of the EU's hydrogen market and by which characteristics will it be driven?

This question aims to examine the developments of the hydrogen market in the EU, which should help to predict future challenges. Both investment and political will are increasing to integrate hydrogen into the energy mix of individual nations. Therefore, it is important to understand which strategic decisions and factors will influence the development of this market, which emerges in times of geopolitical tensions.

How will the geoeconomic dimension of hydrogen influence new supply risks and Europe´s iron and steel industry?

This question focuses on the concrete impact of the hydrogen economy on future trade patterns including dependencies. Also, emphasis is laid on the European iron and steel industry, as the introduction of green steel could have far-reaching consequences for this industry, even a migration to remote regions of the world appears to be possible.

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1.3. METHODOLOGY: A HOLISTIC APPROACH

This master thesis deals with the topic of investigating the geoeconomics of a hydrogen economy from an EU perspective in the current global energy transition. The aim is to identify geoeconomic consequences and to derive recommendations for action for European policy.

A holistic approach

For this master's thesis, a holistic approach was chosen. This approach is particularly well suited for this purpose, as it makes it possible to capture and analyze different aspects and dimensions of the topic. The geoeconomics of hydrogen and its role in the energy transition are extremely complex topics that encompass many different aspects and influencing factors that have far-reaching implications for society, the economy, and the environment. In this respect, a holistic approach makes it possible to consider the complexity, as different technical, political, economic, and social aspects are integrated and interconnected. This approach supports both data collection and analysis and allows a comprehensive and integrated analysis of the geoeconomics of hydrogen in the context of the energy transition from the EU's point of view.

<u>Geoeconomics</u>

The term “Geoeconomics” has gained popularity in recent years, especially since the beginning of the trade war between the US and China in 2018 however there is no universal definition yet. Commonly it is seen as a concept involving the pursuit of geopolitical objectives with economic instruments (Schneider-Petsinger 2016).

Geoeconomics as a term was introduced in Edward Luttwak´s essay „*From Geopolitics to Geo-Economics. Logic of conflict, Grammar of Commerce*” in 1990 (Luttwak 1990). The American strategist and military consultant argued that geoeconomic power is replacing military power, following the cold war.

The Finnish Institute of International Affairs defines Geoeconomics as “*the application of power politics by economic means*”, meaning a battle which is no longer fought on the battlefield anymore, but rather steered by global trade and investment. It is furthermore argued that in terms of sovereignty and economic resilience, there were an increasing concern regarding security risks resulting out of economic interdependence (World Economic Forum 2024).

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China, the US and Russia currently hold the top spots when it comes to use economic instruments as weapons ("Weaponized interdependence" (Farrell and Newman 2019)). China has withheld several times rare earth exports to Japan or cut off Chinese car imports from Japan to reduce Japan's influence in the region. Russia also has repeatedly used its power as an energy supplier to destabilize neighboring regions as it turned off its gas pipelines connected to Europe during winter. Similarly, in Ukraine War the US recently use sanctions to harm Russia, rather than sending troops. A strategy which also has been implemented to affect the nuclear policies of Iran (Schneider-Petsinger 2016). Energy, as well as natural resources has always been vulnerable to become weaponized. This is why hydrogen being crucial for the energy transition becomes also subject to this discussion of geoeconomic concerns.

This holistic approach includes the following cornerstones:

I. Literary analysis and historical contextualization

It was developed with an extensive literature review and historical contextualization are important to gain an in-depth understanding of the development of hydrogen technologies. This also makes it possible to understand the importance of hydrogen for the energy transition and helps to understand and classify the current developments and strategies of the EU in the hydrogen sector.

II. Technical analysis of hydrogen production

It is also crucial to carry out a detailed and technical analysis of green hydrogen to understand and evaluate the different possibilities of hydrogen production. This helps to analyze and evaluate the potential impact on geoeconomics.

III. Comparison with the gas market and identification of new dependencies

The comparison with the gas market is important to understand the specifics of the emerging hydrogen and to identify the potential impact on existing dependencies and trade relations. This also made it possible to assess the EU's strategies to diversify energy supply and reduce dependencies.

Relevant literature in this regard: The publication series "Geopolitics of the Energy Transition – Hydrogen (GET H2)" by the Stiftung Wissenschaft und Politik by the German Institute for International and Security Affairs served as a good basis for this.

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Various studies include an assessment of the German and European hydrogen strategies, as well as the essential importance of electrolysis within the European Union.

IV. Case study on hydrogen exporting countries

Conducting case studies on hydrogen-importing countries makes it possible to analyze the political and economic framework in key partner countries and to identify potential risks and opportunities for the EU's long-term hydrogen supply. This supports the development of strategies to secure hydrogen supply to promote partnerships with economically attractive, but especially politically stable countries.

Data used to illustrate a countries' profile: Governance Effectiveness, Regulatory Quality Index, Economic Freedom Index, Corruption Perception Index, Water stress level, Poverty Rate 2024, Unemployment Rate 2024, EU Imports in EUR Billions, EU Exports in EUR Billions, FDI from EU in EU, FDI to EU in EUR Billions & H2 Production costs, H2 Delivery costs.

V. Discussion on the impact on domestic production

The discussion about the impact on domestic production, i.e. European production, is considered essential, as hydrogen has the potential to bring about global changes in this area as well. This supports the development of policies to promote sustainable and competitive domestic production, considering the EU's climate targets. As an example, the European Iron and Steel industry was used.

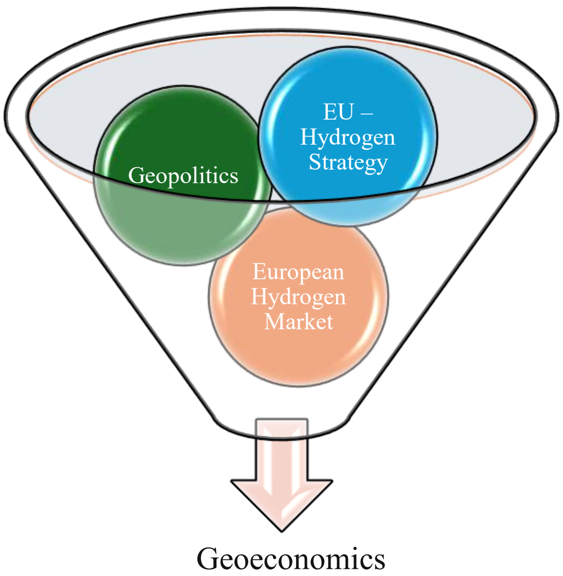

Figure 1: Geoeconomics. A holistic approach. Own illustration

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2. LITERATURE REVIEW

2.1. HYDROGEN IS REGAINING PROMINENCE

This chapter serves as an introductory chapter to introduce to the world of an energy carrier which is considered to play a pivotal role in the ongoing energy transition to reach climate neutrality by 2050. A short historical discussion is followed by a technical and chemical introduction of hydrogen to obtain a solid basic knowledge.

Even though hydrogen is currently praised as the game changer and hailed as an all-rounder, the potential of hydrogen is not new. The detection of its significant potential dates back centuries, as in 1874 the French author Jules Verne called water "*as the coal of the future*" (French: " *l'eau est le charbon de l'avenir*") (Ryabchuk et al. 2016).

However, what is new, is that hydrogen is gaining popularity as an energy carrier useful in various industries – the so called hard to abate sectors, which are nearly impossible to decarbonize through electrification. Hard-to-abate sectors have significant CO2 emissions and their decarbonization is becoming a cornerstone of carbon-neutral economy.

But let's start in the beginning. In the 16th century Philipp von Hohenheim (1493-1541) (known as Paracelsus) was first to artificially synthesize hydrogen, however being unaware that he discovered a new chemical element. In 1671 Robert Boyle succeeded to reproduce hydrogen (Barron 2020). This was followed by the realization of hydrogen gas as a discrete gas in 1766 by the English chemist and physicist Henry Cavendish, who managed to synthesize hydrogen gas through the dissolution of metals in acids (Levere 2024). However, the initial eponym of this new element was the French chemist Antoine Lavoisier, after he managed to reproduce Cavendish´s accomplishments (Barron 2020).

The next great technical advancement was brought by the English scientists William Nicholson and Sir Anthony Carlisle in 1800 – namely the discovery of the electrolysis, the technical instrument needed, involving the application of electrical current, to split the H2O molecule in Water and Oxygen to obtain pure hydrogen (Britannica 2024b). The accomplishment in hydrogen technology occurred in 1842 when William Grove invented the world´s first hydrogen fuel cell (Britannica 2024a). This paved the way for diverse applications and in 1966 the first fuel cell powered car was developed, the Chevrolet Electrovan by General Motor (Corby 2021).

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The 1990s and early 2000s marked the beginning of increasing climate change consciousness which led to a new surge of interest for hydrogen. In 1993 Japan funded a long-term program for international hydrogen trade based on renewable energy in 1993 with a volume of JPY 4.5 billion (Mitsugi, Harumi, and Kenzo 1998). One year later in 1992, the European Commission and the Government of Quebec started the funding of many hydrogen pilot projects, in collaboration with businesses and research institutes (Drolet et al. 1996). In 2009 the Italian company Enel made another landmark achievement. The Fusina Hydrogen Plant was the world's first power plant fueled exclusively by hydrogen. (ENEL 2009).

However, the growing interest in hydrogen was slowed down, primarily since battery electric vehicles gained prominence and hydrogen infrastructure was still associated with high costs. When in 2017 the Hydrogen Council emerged as a global initiative at the World Economic Forum, hydrogen energy was pushed again back to the forefront as an important factor of the clean energy transition (Hydrogen Council, n.d.). The following years witnessed new far reaching applications, as the world's first hydrogen-powered tugboat, developed by Belgian shipping company Compagnie Maritime Belge in 2019 (CMB.TECH 2019).

From 2020 onwards, hydrogen has been assigned with a critical role on the decarbonization path. By the end of 2022, 32 governments have adopted national hydrogen strategies, mainly focusing on so-called clean hydrogen (green and blue hydrogen) paired with ambitious production targets (IEA, n.d.).

To wrap it up, the prospect of hydrogen as a viable energy carrier has rekindled contemporary interest. The preceding periods of disenchantment were primarily rooted in the perceived inadequacies of climate policy implementation, high costs associated with hydrogen infrastructure development, and the parallel advancement of battery electric vehicles. Presently, there is a renewed momentum surrounding hydrogen, notably marked by the European Commission's release of a comprehensive hydrogen strategy in 2020 (European Commission 2020), which will be examined in detail further. This initiative is complemented by analogous efforts from influential nations such as Germany, Japan, and Australia, each formulating distinct national strategies for hydrogen, complete with specific implementation plans geared towards fostering a hydrogen-based economy.

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2.2. HYDROGEN´S PROPERTIES AND COLORS

H2 properties

Regarding future technology hydrogen is a new nope as it is applicable in various industries, from fertilizer and methanol production to iron and steel industries. Hydrogen, holding promise as a major energy solution, is dubbed as the “energy storage system of the future” and as the "climate savior" (Schattauer 2022).

With an occurrence of 92.7 percent hydrogen is by far the most abundant element in the universe, however, due to its strong reactivity it does not exist in its pure atomic form on earth. It immediately forms bonds with other atoms, most of the time with itself to H2. The molecule H2 also cannot be found in its pure form on earth, except in volcanic gases, and is therefore found most often in the compound H2O. But also, other compounds including inorganic hybrids and organic compounds such as methane (CH4) or ethane (C2H6) are common. In the atmosphere however, hydrogen occurs in its atomic form due to very low temperature and pressure and it is so diluted with about 1 hydrogen atom per cm^3 that it can be considered a vacuum. Furthermore, hydrogen is the main component of stars, which derive their energy from the fusion of hydrogen into helium (Eichlseder and Klell 2008).

There is one decisive advantage which hydrogen offers: It can be stored. However, due to its property as the smallest and lightest chemical in the world, this storage only works under very high pressure (350-700 bar) for example in containers or in underground storage. Due to its low weight, a storage tank is well suited for small quantities and is used, for example, in vehicle tanks. Larger quantities can be stored and transported as liquefied hydrogen (LH2) but ambient pressure at low temperatures must be exerted (LH2 has its boiling point at −252.8 degrees Celsius). However, the processes of liquefaction and cooling must also be taken into account in terms of energy (‘Hydrogen Storage’, n.d.). Hydrogen transport is possible via pipelines or shipping. Pipelines are already being utilized to transport hydrogen in industrial production facilities up to 200 kilometers, (Schattauer 2022), but certainly bear risks when it comes to bilateral trade and concerns of supply risks.

Another big benefit hydrogen offers is the wide range of possible applications. First, it is important to distinguish between material and energetic use. In terms of material, the element is used in the chemical industry to produce indispensable raw materials such as

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ammonia (NH3) or methanol (CH4O), and in the refinery sector to process crude oil – areas of application with decades of tradition and being a major economic factor (E. C. Blanco et al. 2023). There is also a high potential in the use of energy. For example, it is possible to reverse the generation by electrolysis and chemically convert hydrogen and oxygen directly into electrical energy using fuel cell systems. The reversal saves combustion processes, in which thermal energy is first converted into mechanical work and only then electricity is generated in the generator (Welder et al. 2019).

Therefore, hydrogen is not an energy source like crude oil, wind, or solar energy, but rather an energy carrier, useful for electricity generation or as a fuel. In addition, hydrogen production is possible in a climate-neutral way and does not produce any pollutants when it is used. With these prerequisites, hydrogen is an essential building pillar for the transformation towards a climate-neutral economy in the future. Due to the different production and application possibilities, it is essential for the transition of the energy system towards the storability of renewable energies, and for the decarbonization of industry. (European Commission 2020). Consequently, the ramp-up of a cross-sectoral and sustainable hydrogen economy is crucial for achieving the climate targets by 2050 and must be done globally (Wappler et al. 2022).

Pros and Cons of H2	
Advantages	**Disadvantages**
Clean production possible: Emissions contain only water and energy, no CO2	Current H2 production almost entirely from carbonaceous resources (coal, gas)
Sector coupling possible; This refers to the energy sectors of electricity, heating, transport, and industry	Green hydrogen is currently uncompetitive and the possible future cost reductions are difficult to anticipate
Compared to most other fuels, H2 stores more energy per unit weight	High transport and storage costs, due to low energy density under atmospheric pressure measured by volume
CO2-neutral production is possible, so-called "green hydrogen"	Extreme energy losses during the conversion of electricity to hydrogen and vice versa
It can be used in a variety of ways: as a fuel, as an energy carrier for energy transport, for energy storage and as a basic chemical material	Complex supply and value chains that are already planned, but most of them are not yet being implemented
Great potential to achieve decarbonization in the so called hard-to-abate industries	New safety standards and social acceptance required

Figure 2: Pros and Cons of H2. Own creation based on Allianz Risk Consulting (Gellermann 2021).

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H2 different "colors"

To split hydrogen from these mentioned compounds energy is needed, which is why hydrogen production encompasses various processes and energy sources. To ease the discussion a color-coded nomenclature is provided (see Figure 3 (IRENA 2020)). There four main hydrogen production methods are: **Grey, Blue, Turquoise & Green hydrogen**, each being differently produced and are differently contributing to Carbon Dioxide (CO2) emissions.

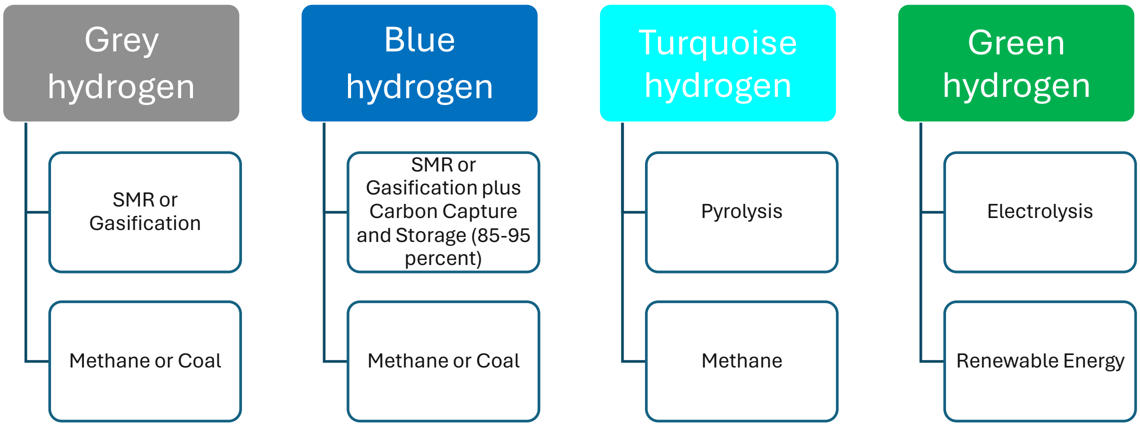

Figure 3: Four types of hydrogen. Own illustration based on IRENA 2020.

<u>Grey hydrogen</u>

Grey hydrogen is produced through the usage of fossil energy sources. The main production process in this regard encompasses the so-called steam methane reforming (SMR) or coal gasification to generate hydrogen from methane. This procedure however results in significant emissions of CO2, consequently making this technologies inappropriate for future carbon free production methods (IRENA 2020).

<u>Blue hydrogen</u>

Another form of hydrogen production ends up in blue hydrogen. This production method is like the production of grey hydrogen, however, includes Carbon Capture and Storage technology (CCS). Despite technological challenges regarding CCS, this technology is the reason why blue hydrogen is seen as a **promising interim solution**, especially for industrial applications like steel production, where a non-stop hydrogen supply is essential. Presently, approximately three-quarters of hydrogen production relies on natural gas, globally. Integrating CCS into existing facilities allows for the sustained use

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of current assets while achieving lower greenhouse gas emissions. Including CCS provides a means to produce hydrogen with reduced greenhouse gas emissions on the one hand and reducing pressure on the installation rate of renewable energy capacity required for green hydrogen production on the other hand (IRENA 2020).

However, blue hydrogen faces hurdles that have hindered its widespread adoption. It relies on finite raw materials, is very vulnerable to price shocks of fossil fuels, and does not align with energy security objectives. Moreover, CCS capture efficiencies, even at their best (85-95 percent), still result in 5-15 percent of CO2 emissions, and even achieving these high capture rates remains difficult. Despite reducing carbon emissions in hydrogen generation, methane use during the process causes upstream leaks, with methane being a more potent greenhouse gas per molecule than CO2. Consequently, while blue hydrogen contributes to CO2 emission reduction, it still falls short of aligning with the criteria for a carbon neutrality. Therefore, blue hydrogen should be regarded as a short-term transitional solution to pave the way for the broader adoption of green hydrogen towards the net-zero target (IRENA 2020).

Turquoise hydrogen

This form of hydrogen is based on a thermal decomposition of CH4. This also originates from fossil fuels, however like the blue hydrogen also offers advantages. Through the application of a pyrolysis, the carbon within CH4 does not transforms into CO2, which is emitted into the atmosphere, rather it transforms into a solid carbon black. The solid nature of carbon black allows for more convenient storage compared to CO2 which is gaseous. Notably, there is an established market for carbon black, offering an extra revenue source (IRENA 2020). Likewise it has to be mentioned, that this is fairly new production method, which still has to be examined regarding environment and climate related categorization (Umweltbundesamt 2021).

Green hydrogen

Within the spectrum of hydrogen production methods, green hydrogen stands out as the most suitable one to play an essential role in the sustainable energy transition. Generated by a water electrolysis which is powered by renewable energy sources, like wind and solar power, this production method stands as a beacon of hope in the emerging energy landscape. Through the usage of a water electrolysis the H2O molecule is split when electrical current. Those electrochemical proceedings are like those of a fuel cell, only

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differing in the fact that the electrolysis is using electricity, while the fuel cell emits it. The efficiency of such an electrolysis can be estimated to approximate 75%, depending on specific processes (Umweltbundesamt 2021).

The main advantage of green hydrogen production is that it aligns with the trajectory toward net-zero emissions, since there are no CO2 emissions which enables various green applications (Figure 4). Anticipated declining costs of renewable energy and ongoing technological advancements further will lead to a reduction of overall production cost for green hydrogen. Consequently, interest in green hydrogen has been increasing due to its alignment with sustainability targets and its potential to play a major role in the future (IRENA 2020).

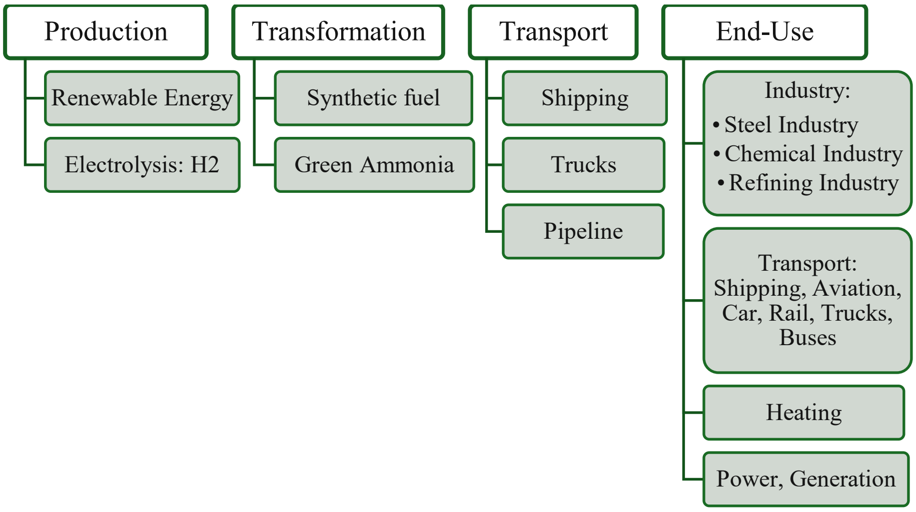

Figure 4: Green H2 production to application. Own illustration based on IRENA, n.d.-b

Costs of different production methods

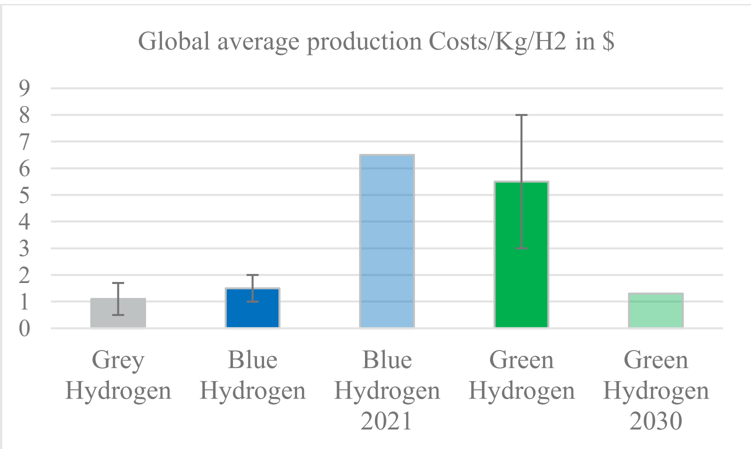

Figure 5: Global average production Costs/Kg/H2 in $. Own illustration based on IEA 2021; ING Think 2021. Note: Turquoise H2 does not have any estimated production costs yet.

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The primary challenge which hinders the widespread adoption of low-carbon hydrogen[1] lies in the current existing cost disparity when compared to hydrogen production methods incorporating fossil fuels without CCS. Currently, the most economical method for producing hydrogen globally results in grey hydrogen. This process yields a levelized cost ranging from USD 0.5 to USD 1.7 per kilogram. Blue hydrogen raises the levelized cost to approximately USD 1 to USD 2 per kilogram (IEA 2021). However, both production methods (grey and blue) very much depend on regional gas prices. Even before the peak of the energy crisis in the past years the production costs for grey and blue hydrogen increased enormously to approximate USD 6.5 per kilogram, due to increased demand and lower supply (reserves) (ING Think 2021). Alternatively, utilizing renewable electricity for hydrogen production incurs higher costs, ranging from USD 3 to USD 8 per kg (IEA 2021).

Focusing on the significant cost disparity between green hydrogen production and other methods, it is anticipated that enhanced technology and large-scale implementation might reduce green hydrogen production. The IEA outlined scenarios for 2030, in which countries destined with high amounts of renewable resources, could benefit from green hydrogen production costs around USD 1.3 per kilogram, making it competitive blue hydrogen. In the long term, for some regions production costs might further decrease to a level where solar and photovoltaic derived hydrogen potentially becomes economically competitive with natural gas hydrogen (even without CCS) (IEA 2021).

[1] Note: The term "low-carbon hydrogen" refers to the production methods resulting in blue and green hydrogen

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3. RESEARCH CHAPTERS

As a crucial component for reaching the climate targets set in the EU Green Deal hydrogen has received a lot of attention in the EU policy framework. This chapter is dedicated to the EU hydrogen policies to provide a detailed understanding of key hydrogen strategies and initiatives. Here the key initiatives, the EU Hydrogen Strategy & REPowerEU are examined.

The European hydrogen strategy[2], together with the REPowerEU plan, presents a detailed outline to promote a widespread adoption of hydrogen, mainly focusing on renewable[3] and low-carbon hydrogen[4]. On the one hand those initiatives aim to effectively decarbonize the energy sector of the EU, while on the other it seeks to reduce its reliance on imported fossil fuels (European Commission 2020; 2022d). This can be seen as quite ambitious endeavor, as in 2022, hydrogen´s share of Europe´s energy consumption was less than two percent and was in the first place used to produce chemical goods like specific fertilizers or plastics. Furthermore, roughly 96 percent of this hydrogen was derived from natural gas, followed by substantial CO2 emissions (European Commission, n.d.-b).

3.1. EU HYDROGEN STRATEGY

The overall goal of the EU Hydrogen Strategy is to strengthen the development of green and renewable hydrogen and regarding its implementation sub-divided into three periods.

The initial phase (2020 to 2024) aims to decarbonize existing hydrogen production, while at the same time adopt hydrogen for new applications. A capacity of **6 GW** installed electrolysis plants should be used produce up to 1 million tons (Mt) of renewable hydrogen (European Commission 2020).

The second phase (2024 to 2030) shall integrate renewable hydrogen as a pivotal element within an interlinked energy framework, progressively diversifying its application into new sectors which include heavy-duty transportation, steel

[2] Correct term: "A hydrogen strategy for a climate-neutral Europe" (European Commission 2020).
[3] Renewable hydrogen = clean hydrogen = green Hydrogen: "*Hydrogen produced through the electrolysis of water (…), and with the electricity stemming from renewable source*" (European Commission 2020: 3f.).
[4] Low-carbon hydrogen: "*encompasses fossil-based hydrogen with carbon capture and electricity-based hydrogen, with significantly reduced full life-cycle greenhouse gas emissions compared to existing hydrogen production*" (European Commission 2020: 4).

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manufacturing, maritime operations, and railway systems. Electrolysis capacity should reach at least **40 GW** by 2030, equivalent with producing **10 Mt** of renewable hydrogen (European Commission 2020).

The third phase (2030 to 2050) is expected to bring forward renewable hydrogen technologies that reach maturity and readiness for large-scale deployment, including all sectors where decarbonization reveals challenges, and where alternative solutions are either impractical or entail higher costs (European Commission 2020).

Furthermore, significant investments in renewable hydrogen are forecasted, reaching 180 to 470 billion euros by 2050, alongside additional funding for low-carbon fossil hydrogen, which should lead to the creation of approximately 1 million jobs (European Commission 2020). Moreover, the EU seeks to promote new avenues of cooperation in clean hydrogen, leveraging sun- and wind-rich nations, as North African (European Commission 2020).

3.2. REPowerEU

The European Commission adopted the REPowerEU plan on the 18th of May 2022, as a direct response to the energy disruptions due to Russia's invasion of Ukraine. Proposed targets include raising the share of renewables to 45 percent and reducing energy consumption by at least 13 percent by 2030. The plan aims to accelerate the energy transition, as it accounts for imports (Figure 6). By **2030**, the EU aims to produce and import **10 Mt** of renewable hydrogen (European Commission 2022d), resulting in a doubled amount of renewable hydrogen by 2030, compared to the EU Hydrogen Strategy.

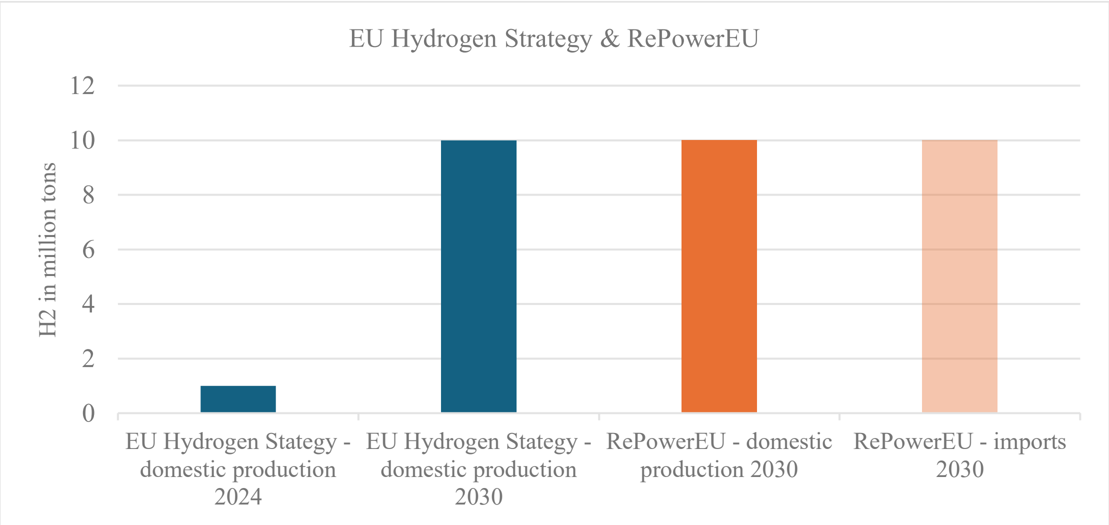

Figure 6: EU Hydrogen Strategy & REPowerEU. Own illustration based on European Commission 2020; 2022d.

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3.3. EUROPEAN HYDROGEN BANK

The Hydrogen Bank, also launched by the EU Commission in 2022, is another important in Europe´s hydrogen landscape. Its primary mission is to bridge the investment gap, attract private investments, and strengthen the growth of a solid hydrogen market that contributes to the EU's climate goals. Auctions will be used to address investment gaps while creating a link between supply and demand (European Commission, n.d.-a)

The bank is built upon four pillars:

- Pillar 1: EU domestic market creation: The bank arranges auctions and offers subsidies to lessen the cost difference between renewable and fossil hydrogen. That is aimed to increase renewable hydrogen generation in the EU while reducing capital costs.
- Pillar 2: International imports to the EU: The bank intends to push for an integrated EU policy for renewable hydrogen imports. It involves looking into financing options within the scope of the European Union's budget, as well as systems for demand aggregation and collaborative renewable hydrogen auctioning (European Commission, n.d.-a).
- Pillar 3: Transparency and Coordination: The bank aims to give transparent pricing information and establish price guidelines. It additionally encourages the coordination of declarations of intent among member states, businesses, and international producers (European Commission, n.d.-a).
- Pillar 4: Streamline existing financing instruments: The bank encourages information transfer and raises awareness of support measures throughout the EU and its member states. Additionally, it strives to increase resource efficiency by coordinating multiple EU and state finance tools (European Commission, n.d.-a).

3.4. EUROPEAN HYDROGEN BACKBONE

The European Hydrogen Backbone (EHB) is a projected system of hydrogen pipelines that encompass the whole continent. Like natural gas pipelines, this infrastructure shall make it easier to transfer hydrogen from producing locations to distribution terminals and end consumers across a variety of industries. The devoted hydrogen pipeline systems are mostly based on converted natural gas pipes (app. 70 percent), as well as new ones (app. 30 percent). Until now, the EHB initiative has evolved and has now 33 European network

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providers included, with infrastructure in 24 EU Member States as well as Norway, Switzerland, the United Kingdom, and Ukraine. The December 2023 EHB report emphasizes a collection of 40 specific projects overseen by the EHB's TSO members. These projects entail the development of approximately 31.500 kilometers (Figure 7) of pipelines, dedicated to transport hydrogen, projected for commissioning before 2030 (EHB 2023). As illustrated, the largest grid growth is expected to happen in 2030, the year where according to REPowerEU it is planned to have a renewable hydrogen flow (domestic production and imports) of 20 million tons. Delayed projects and increased costs (as mentioned later on) pose a real risk for that endeavor (Martin 2023). However, many of those initiatives already met their early development stages and are projected to start operations between 2025 and 2031. In the end, a total of 40 projects are planned for commissioning by the beginning of the upcoming decades (EHB 2023).

The proposed Hydrogen Backbone for 2040, spanning 53.000 kilometers as, necessitates an approximate total investment ranging from **€80 to €143 billion**. This projection is based on utilizing **60 percent of reused natural gas pipelines** and implementing **40 percent new pipeline** sections (EHB 2024). However, there is a high risk that this calculation is massively underestimated. Costs for compressors increased to EUR 4 million/MW equivalent, from EUR 3.4 million/MW in 2019. Also the average per-kilometer cost of onshore H2 pipelines increased by EUR 300.000 for 20 inch-diameter pipelines, EUR 1 million for 36 inch-diameter pipelines, and EUR 1.6 million for 48-inch-diameter pipelines (Martin 2023).

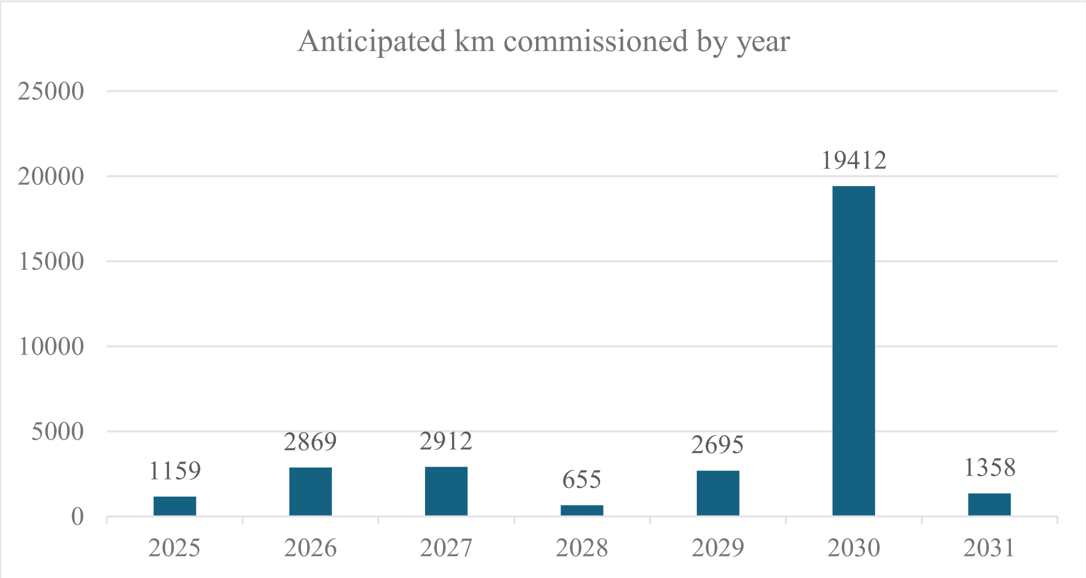

Figure 7: Anticipated km commissioned by year. Own illustration based on EHB 2023

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There are five corridors mentioned explicitly, which are planned to be used for hydrogen transportation, also encompassing import routes. Two of them are examined further as they will play a geopolitical role in the future when it comes to hydrogen imports and potential dependencies. Corridor A and Corridor B.

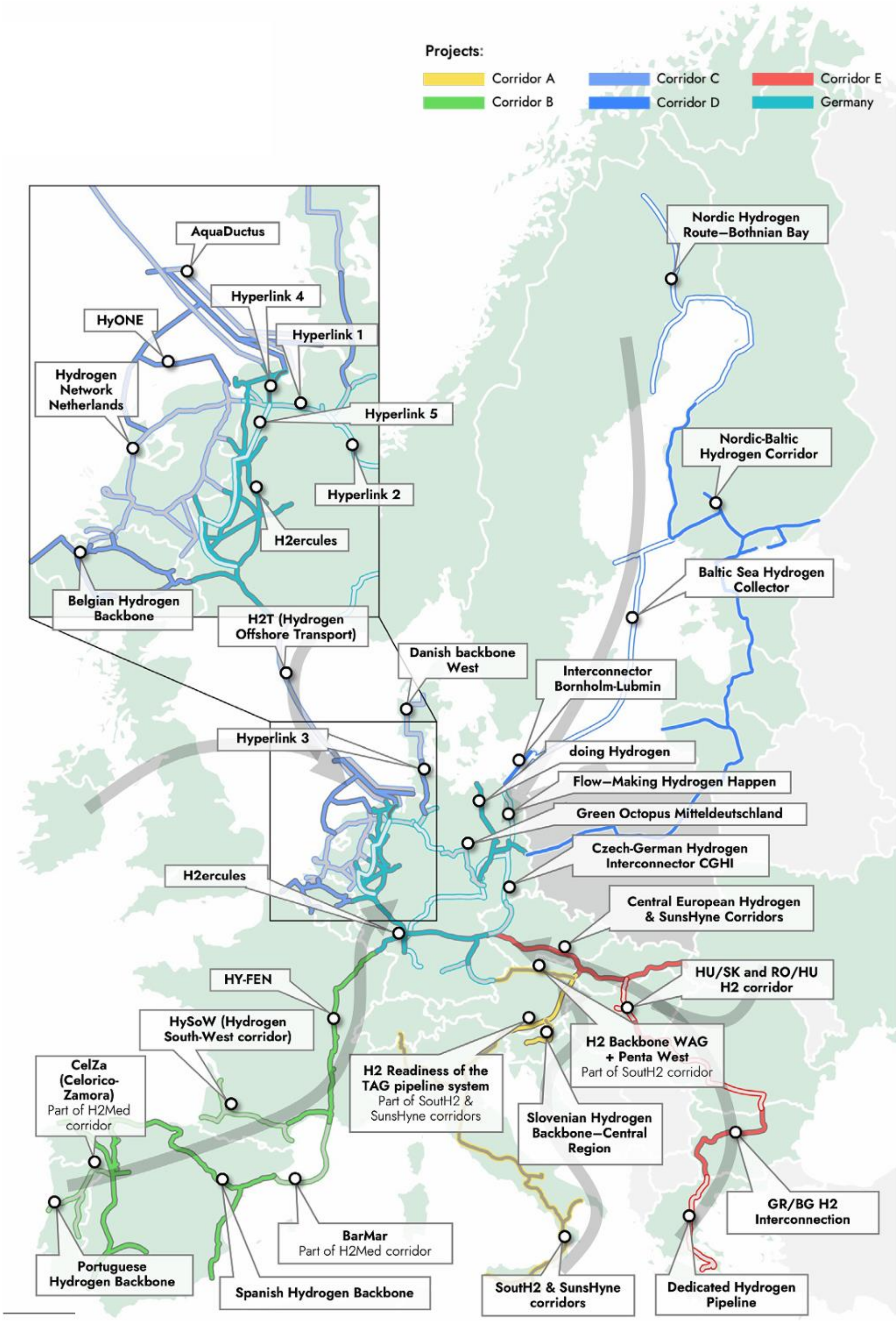

Figure 8: European Hydrogen Backbone. Source: EHB 2023

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Corridor A: North Africa and Southern Europe

This supply route plans to transport H2 via pipeline from North African countries, like Tunisia or Algeria, over Italy further to Central Europe. The Italian hydrogen backbone, including the initiatives SunsHyne and SoutH2 Corridor combine national projects into larger alliances. It is projected that Austria will use repurposed pipelines for further H2 transportation to Germany, which should be facilitated by storage installations and connections like HyPipe Bavaria. (EHB 2023).

Corridor B: Southwest Europe & North Africa:

This is the second corridor connecting North African countries, in this case most probably Morocco, with Europe. H2 transport is planned to ultimately reach German demand centers via project called H2ercules. The hydrogen connection amongst Portugal, Spain, France, and Germany is regulated through the H2Med corridor. The BarMar project is projected with an offshore pipeline from Barcelona to Marseille or further distribution across France the other Western European countries. (EHB 2023).

Corridor C – North Sea:

This corridor plans a H2 transport from the northern regions (Norway and Denmark) to western Germany, taking advantage of offshore wind potential. It is also planned to use the ports Rotterdam and Antwerp. to import hydrogen derivatives. Northern projects such as the Belgium Hydrogen Backbone and the Hydrogen Network Netherlands make fast progress to distribute hydrogen across mainland Europe, with the latter already under construction (EHB 2023).

Corridor D: The Nordic and Baltic regions:

Those regions benefit from high amounts of renewable energy resources. This is why major project are planned to the Baltic hydrogen market with Germany, as well as the Finland, Sweden and Germany with each other (EHB 2023).

Corridor E: East and Southeastern:

This hydrogen supply route encompasses the transport from Greece or Ukraine, through Bulgaria, Romania, Hungary, Slovakia, and Austria to Central Europe. Several projects are aimed to be run by 2030, also being combined with initiatives of neighboring countries. Especially in Slovakia and Austria, a technical flexibility in the transmission system, is vital to enable multi-directional flows (EHB 2023).

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4. Discussion: hydrogen market and it´s geoeconomics

The role hydrogen will have at the regulatory and technical level in the future has already been described in detail. In the following chapters, the cornerstones of the emerging hydrogen economy will be presented and analyzed. This is followed by thorough discussion regarding the geopolitical and geo-economic aspects of a hydrogen economy, as it will have far-reaching implications if its full implementation should be realized. A geoeconomic analysis will also be carried out based on relevant data from three H2 import countries, which will show that geostrategic arguments should play a greater role in the future. This to be followed by another smaller case study dealing with the future European steel industry, including the question of new dependencies.

4.1. Requirements for the hydrogen market

H2 Demand

The fact that the production cost especially for green hydrogen are expected to decrease drastically over the next decades, as Figure 9 illustrates, several demand calculations by various institutions have been conducted for 2050, and they all expect a significant increase in demand (Figure 9). Besides the overall growing demand for hydrogen, the share of green hydrogen should increase and ultimately phase out grey hydrogen.

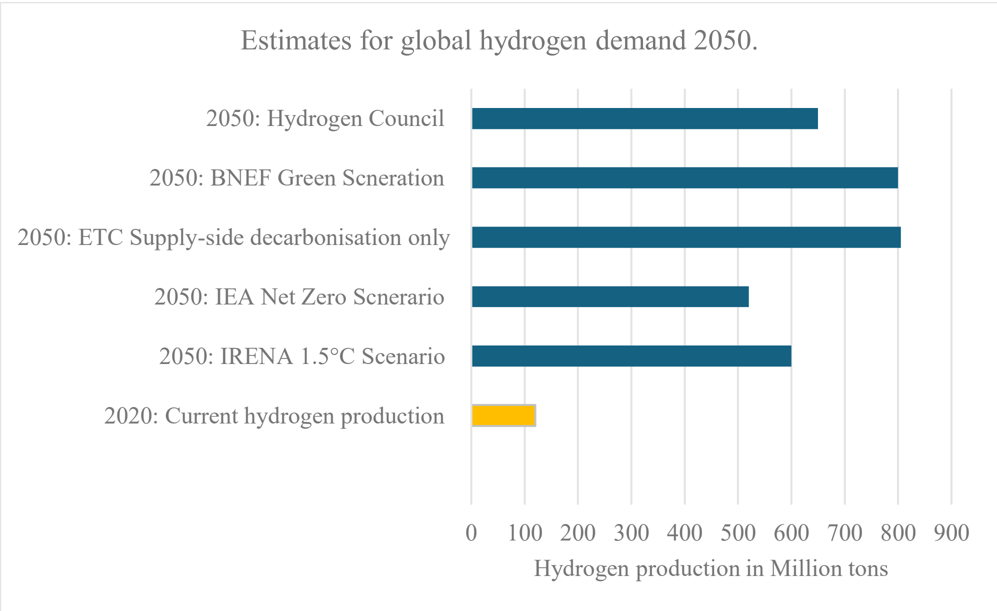

Figure 9. Estimates for global hydrogen demand 2050. Own illustration based on IRENA 2022

For Europe the following projections were calculated (Figure 10). Like on a global level, also the hydrogen demand in Europe is expected to grow significantly, with 51 percent from 2022 to 2030, 127 percent from 2030 to 2040, and 63 percent from 2040 to 2050 (EHO 2023).

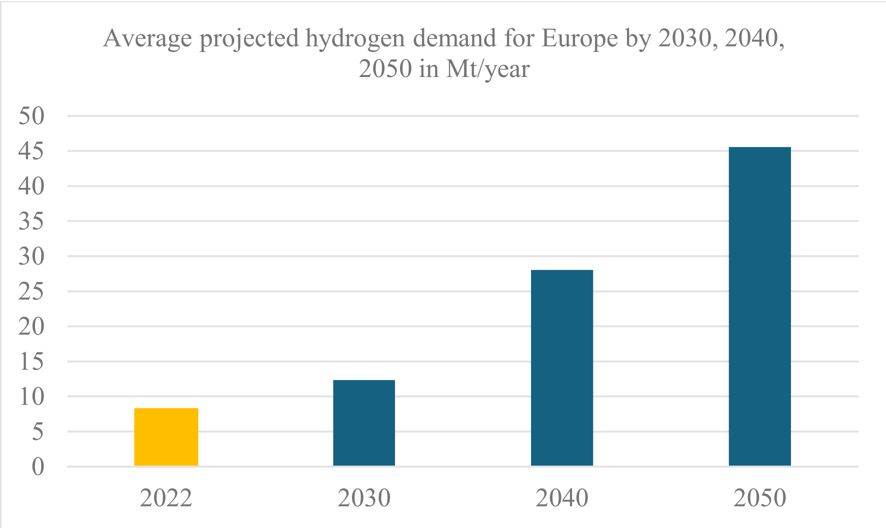

Figure 10. Average projected hydrogen demand for Europe. Own illustration based on EHO 2023

It is also worth looking into the different sectors and examining how they influence the growing demand for hydrogen (Figure 11). Currently, the industry sector, mostly fertilizer production and petroleum refining, is the only H2 demanding sector, however it is expected that especially transport demands high amounts of hydrogen in the future. It is even expected that it will nearly meet the H2 demand of the industry in 2050 of approximately 17 Mt/year. The remaining sectors building, and power will also increase their demand, however with enhanced acceleration only after 2030 (EHO 2023).

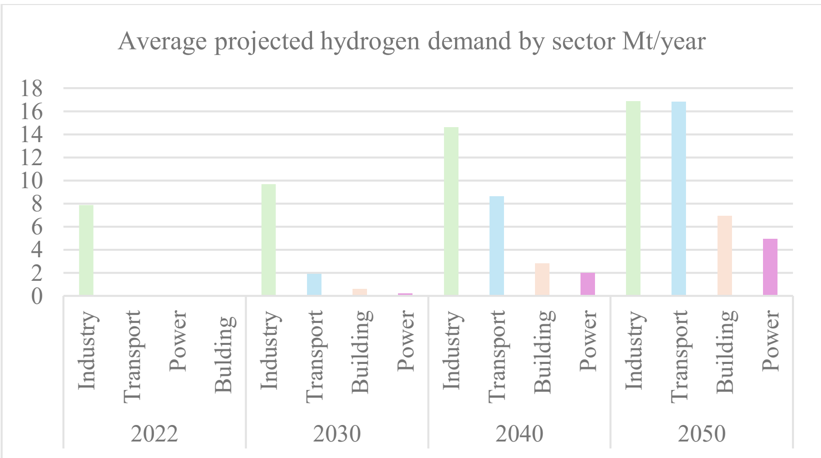

Figure 11. Average projected hydrogen demand by sector. Own illustration based on EHO 2023

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H2 Production Infrastructure

Beside projected demand calculations including those for various sectors, the establishment of **production infrastructure** for hydrogen generation is essential for widespread utilization and mainly encompasses the construction of electrolysis. In this regard, there are several well-known and new technologies, which will be briefly discussed below: The technical process that currently has the highest efficiency is water electrolysis. In this tried-and-tested process, water is decomposed by electrical energy into its two main components, H2 and O, in an electrolysis cell and with the help of two electrodes. The two electrodes are separated from each other by a membrane. Currently, there are three technically applicable models of water electrolysis (DiLiCo Engineering, n.d.)

Alkaline electrolysis (AEL) has lower investment costs and high long-term stability as advantages, an efficiency of 65% and a service life of approximately 90.000 operating hours. This form of electrolysis has a power range of up to 130 MW and is used all over the world.

Polymer electrolyte membrane electrolysis (PEM) has a similar efficiency as AEL, but its advantage is that it can react quickly to fluctuations in the energy supplied. However, this technology is rather new, so its investment costs are much higher than those of AEL, and its power range is significantly lower with values up to 6 MW.

Solid oxide electrolysis (SOE) with its operating temperature of 600-900 degrees Celsius becomes high-temperature electrolysis and it´s currently in the transition to industrial application. Their advantage is a very high efficiency of over 80%, but has high investment costs, like PEM electrolysis. However, the power is significantly lower, up to 250 kW.

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H2 Transport

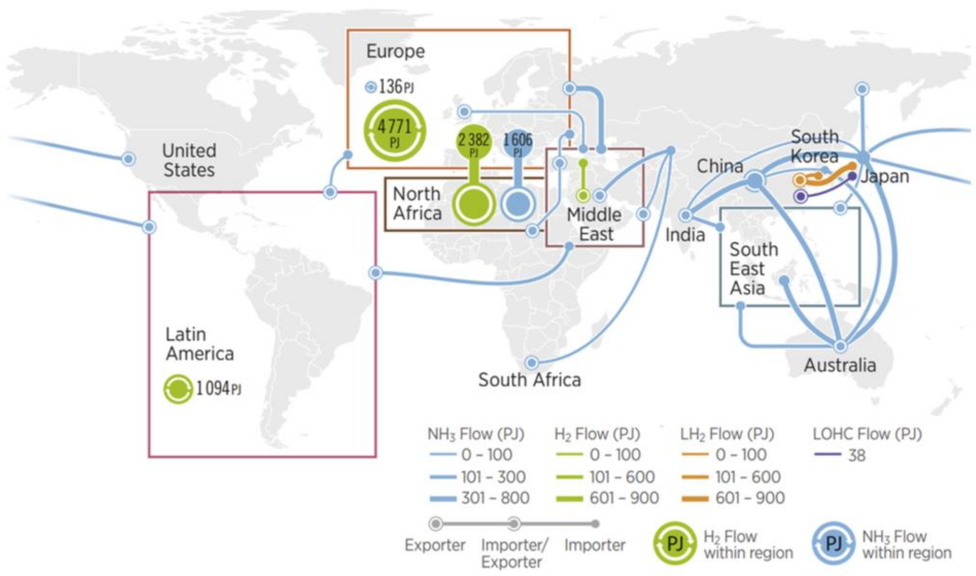

Figure 12. Global H2 trade flows 2050. Note: Optimistic scenario. Source: IRENA, n.d.

IRENA estimates that by 2050, around 150 Mt H2 is traded globally, which would account for one third of global hydrogen demand, while the rest will be produced and consumed domestically. Compared to the oil market, this represents a significant difference, as nearly three quarters of oil is traded globally, however being rather similar when compared to the gas market, which accounts for 33 percent of gas being trade internationally (IRENA, n.d.-a).

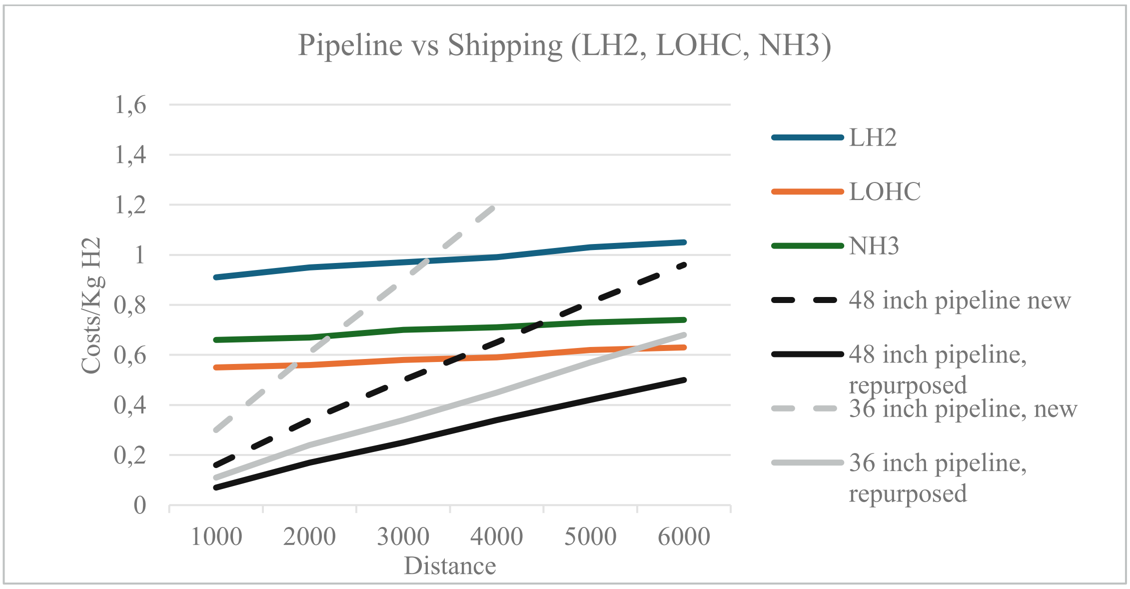

Figure 13.Levelized costs of delivering hydrogen by pipeline and by ship as LH2, LOHC and NH3. Own illustration based on IEA 2022a; EHB 2021

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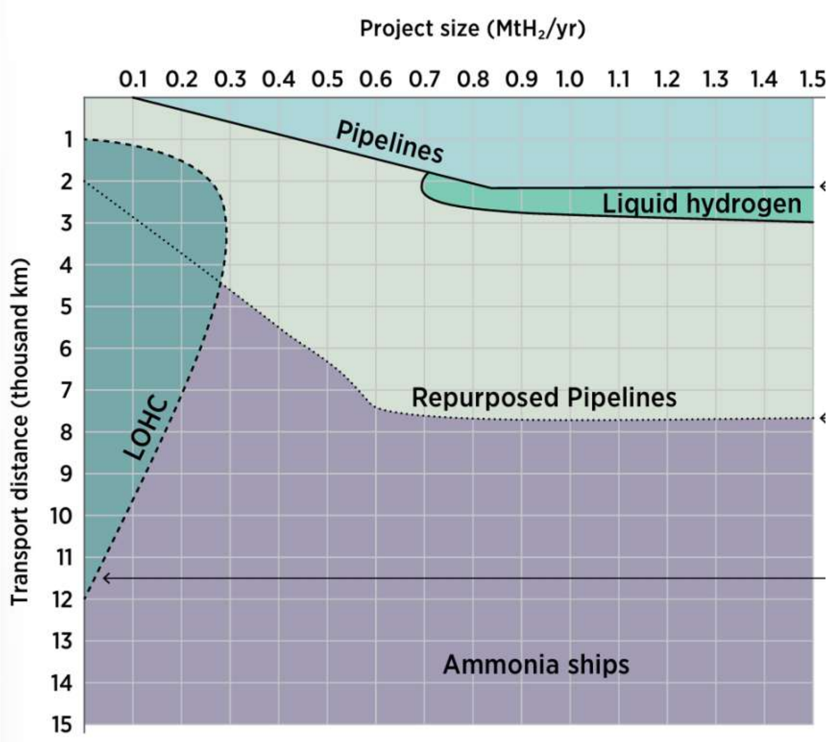

Figure 14: Most cost-effective hydrogen transport pathway in 2050 as a function of project size and transport distance. Source: IRENA (H. Blanco 2022)

A pipeline infrastructure for hydrogen transport is like the current pipeline network containing natural gas. Those pipelines currently used for natural gas transport differ in diameter, ranging from 20-48 and operate at different pressures ranging from 50-80 bar. Increased diameter and higher pressures allow for increased transportable amount (EHB 2021).

In general, as figure 14 illustrates transport costs depend on two factors, the size of the production plant and the length of the transport route. From that it can be derived that (new) pipelines are meaningful for smaller distances, repurposed pipelines are attractive for a distance up to 8.000 km, and that longer distances favor shipping. LOHCs gain advantage when production capacity is relatively small (H. Blanco 2022; IEA 2022a; EHB 2021)

When it comes to the costs for pipeline, there are certain differing aspects to consider when compared to shipping. Pipeline´s cost increase linearly with distance, however making them the cheapest variant when it comes to distances up to 3.500-4.500km, however depending on the pipe diameter and the hydrogen carrier transported by ship (Figure 13). The diameter of the pipe is another cost-influencing aspect is, as double costs occur when the diameter is doubled as well. However, in turn, a doubled diameter also

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leads to four times the flow, yielding reduced costs per unit H2 transported. Also, considering the possibility to repurpose existing natural gas pipelines makes them even more cost-efficient compared to shipping. Smaller costs associated with repurposing pipelines compared to new pipelines (65-94 percent lower investment costs) lead to increased distance in terms of attractiveness of the pipeline to 8.000 km, or even more as IEA estimates (H. Blanco 2022; IEA 2022a).

However, it is very important to account for the hydrogen´s distinct and unique properties when a pipeline network is designed which should transport that energy carrier. Bare steel is vulnerable to embrittlement when high-pressure hydrogen is being carried. Oxide Layers however can prevent this form of damage. Furthermore, pressure fluctuations should be reduced to prevent hydrogen embrittlement. Apart from embrittlement risks, hydrogens small molecule size increases the risk of leakages and permeation, hence reused existing gas pipelines for hydrogen require solid assessments of their valves and fittings. Moreover, it is likely that that different compressor designs will be needed to adapt to the low molecule weight of hydrogen. Repurposing existing natural gas infrastructure is generally possible even with lower associated costs, compared to building new pipelines (EHB 2021).

<u>Hydrogen transport by ship: LH2, LOHC, NH3</u>

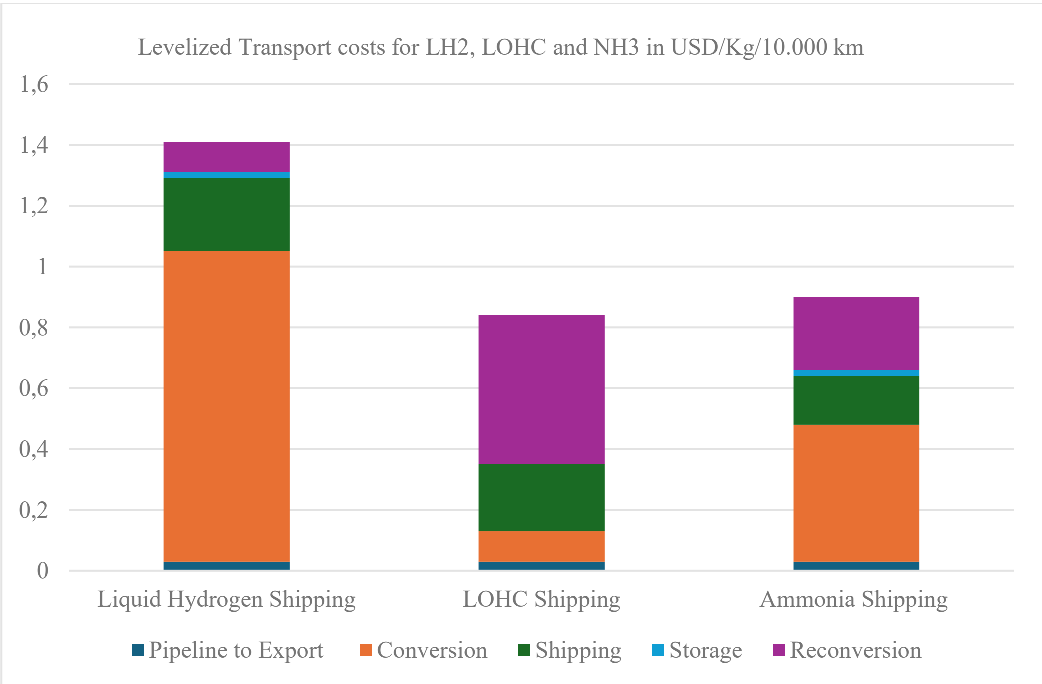

Figure 15: Levelized shipping cost breakdown for LH2, LOHC, and NH3 over 10.000km. Own illustration based on EHB 2021

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Transporting hydrogen economically by ship is challenging due to its low energy density. Still, three promising methods are being explored: **Liquid hydrogen (LH2)**, **Liquid Organic Hydrogen Carriers (LOHCs),** and **Ammonia (NH3)**. These procedures include transforming gaseous hydrogen into a denser liquid for transportation The shipping process consists of multiple stages: from pipeline transport from the production site, over actual shipping, to the pipeline transport to the demand location (EHB 2021).

Liquid hydrogen is generated when gaseous hydrogen is compressed and cooled (-253°C), leading to a significantly increased energy density. However, this method consumes a very high share of hydrogen´s energy content, roughly one third. Furthermore, strong insulation is required for storage and transport containers to significantly reduce boil-off, which increases the costs. In turn, a small portion of the boil-off can be used fuel for ships, whereas the rest is usually flared to avoid tank pressure build-up. Those aspects make the shipping of LH2 attractive when it comes to relatively short transport routes especially when pipelines are not possible, as less ships are required for a permanent LH2 flow (EHB 2021; H. Blanco 2022).

LOHCs are organic chemicals / oil derivatives that, if undergoing a chemical reaction with hydrogen, allows for an easier transportation. Promising candidates are derivatives of toluene, which form methylcyclohexane after a reaction with hydrogen. A downside, however, is that shipping LOHC consumes more fuel because of to the heavier nature of LOHCs, which also have a very low hydrogen content (4-7 percent per weight). Additionally, as LOHCs cannot be used without the emission of greenhouse gases, a carbon-neutral fuel is required for ship propulsion. Also separating the hydrogen from its carriers requires a high amount of heat, approximately the equivalent to 30-40 percent hydrogens energy content. The degradation of LOHCs adds to the cost, with approximately 0.1 percent lost per conversion/reconversion cycle (EHB 2021; H. Blanco 2022).

Ammonia is produced through a reaction of gaseous hydrogen with gaseous nitrogen, a process which is known as the Haber-Bosch process. With a boiling point of -33 °C, insulated vessels are needed for shipping, though boil-off is less of a concern compared to liquid hydrogen. Furthermore, NH3 also can be used as fuel for ship propulsion, with excess boil-off also not posing a significant risk. However, reconversion of NH3 back to hydrogen is very inefficient and currently unproven at scale. Nevertheless, despite those

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downsides' ammonia transport can rely on existing shipping infrastructure and widespread use as a chemical, potentially reducing the need for full reconversion to hydrogen. Furthermore, NH3 ships benefit from relatively small shipping costs compared to conversion and reconversion, leading to limited cost increases when transport distance increases (EHB 2021; H. Blanco 2022).

Most expenses for all three shipping methods stem from fixed costs associated with conversion and reconversion, accounting for 60% to 80% of overall shipping costs over a 10.000 km distance (Figure 15). While marginal cost increases per kilometer are small, **longer distances favor shipping**. The figure 13 analyses the estimated costs for the three methods, taking a hypothetical 10.000 km route with 100 km pipelines connecting the first and the last stage (EHB 2021). To sum up, the following is estimated: Transporting hydrogen by ship costs **USD 0.9-1,41/kg/10.000km** (optimistic calculation).

- Liquid hydrogen is the costliest due to energy-intensive liquefaction.
- LOHC and ammonia shipping have similar costs, but LOHC is less mature.
- The important point here is that, liquid hydrogen's high cost is offset if the export country has cheap renewable energy, due to the fact that the most energy intensive step – the **liquification** – takes place there (EHB 2021).

<u>Comparison of Hydrogen Transportation Costs</u>

For hydrogen transport routes within or close to mainland (Europe), pipelines prove more cost-efficient than shipping, provided there are sufficient volumes to justify pipelines at least 36 inches in diameter. Shipping remains viable for long-distance, intercontinental trade between the oceans. Pipelines face challenges in unstable regions, while shipping routes can adapt to market shifts. This reality is more closely discussed in one of the following chapters. When shipping hydrogen, selecting export and import locations closer to production and demand sites is preferred due to lower marginal shipping costs compared to pipelines (EHB 2021).

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Hydrogen Storage Facilities

Besides appropriate production sites, there is also the need for a hydrogen storage infrastructure. The absence of hydrogen storage possibilities currently slows down the development of a viable hydrogen market in Europe. However, this not the only reason, because additional storage facilities mitigate the need for costly overcapacity in production and transport. Very well suited are former oil and gas reservoirs which must be repurposed, as the Austrian company RAG Austria has demonstrated impressively (USS 2023). Furthermore, hydrogen storage functions as a safeguard, serving as a backup during crises like infrastructure failures, adverse weather, or spikes in demand (Wietfeld 2021).

When it comes to hydrogen imports due to trade, also the repurposing of LNG terminals must be considered. Many European countries have announced the construction of new LNG terminals to reduce their dependencies on Russian gas supplies (CEER 2024). However as the as the REPowerEU plan plans to reduce overall fossil fuel derived energy consumption (European Commission 2022d), it has to be ensured that those LNG terminals currently planned or under construction are also suitable hydrogen imports. As IEA points, a later conversion for the especially liquified hydrogen might be technically challenging. Also repurposed import of ammonia would require technical challenges, however they are less significant (IEA 2022a). This is why it will be essential that the construction of new LNG terminals is already in line with ammonia and liquified hydrogen impots.

CO2 Storage Facilities

Additional Infrastructure is needed encompassing CO2 storage is needed. This especially aims for Carbon Capture and Storage (CCS) which is needed to obtain blue or turquoise hydrogen as mentioned earlier. Disadvantages, however, might be the costs regarding those facilities on the one hand, and possible local resistance on the other hand. Nevertheless, as a major project of Shell, Equinor and Total Energies in Norway demonstrates, CCS can be implemented successfully (Habibic 2023). The prerequisites for solid CSS might be given, as the European Union's geological CO2 storage capacity is estimated at over 100 billion tons, compared to global CO2 emissions of around 38 billion tons in 2021(Bukold 2020; Statistisches Bundesamt 2022).

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Hydrogen-based value chains

Forming the needed hydrogen infrastructure poses a significant challenge, as it demands the coordination of various aspects, involving production, storage, transportation, and the final application. The challenging part is that a hydrogen-based value chains is needed that connects all those different steps together, as for example a hydrogen fueled vehicle depend on the accessibility of a cost-effective supply network. Without dependable demand, there is no supply, and without reliable supply, there will be no demand. This chicken-and-egg problem is critical to be tackled and will engage numerous economic activities, including private and governmental stakeholders. (Grimm 2020). In addition to those coordination challenges, significant investments are required, both private and public. However, beyond economic costs, it's also essential to account for greenhouse gas emissions apart from the final product H2, namely those regarding to energy and resource consumption during the development of the infrastructure and the final operation, as well as for those regarding eventual disposal or decommissioning of facilities (Petersen 2023).

4.2. BENEFITS OF THE HYDROGEN MARKET

A central and immediate advantage of using hydrogen instead of fossil fuels is the promotion of climate neutrality. If it is green hydrogen, no greenhouse gas emissions are produced. In addition, according to an honest assessment of greenhouse gas emissions, all activities necessary for the establishment of the required hydrogen infrastructure and the operation of this infrastructure must also be CO2-free, or at least must be accounted for. This primarily concerns the necessary production facilities for hydrogen production as well as the storage and transport infrastructure (Petersen 2023).

Moreover, it must be mentioned that hydrogen offers remarkable resource efficiency, notably surpassing traditional fuels. Comparing fuel cells to combustion engines, fuel cells achieve higher efficiency rates. While combustion engines typically operate at 20 percent efficiency, hydrogen fuel cells in mobile applications can reach up to 60 percent efficiency, depending on the fuel technology (SFC Energy, n.d.). Additionally, fuel cell systems require fewer mechanical components, which reduces wear and maintenance requirements. This leads to significant energy and resource savings associated with maintenance and repair tasks (Weider, Metzner, and Rammler 2004).

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Estimated job-growth

Beside technical advantages, it is also estimated that a functional hydrogen economy offers a dual benefit, creating both jobs and income (Horng and Kalis 2020). Direct employment opportunities will emerge from operating hydrogen facilities, whereas related economic activities will secure additional employment. Those include research and development, infrastructure construction, consulting, and investments in renewable energy production. (Merten et al. 2021).

According to a study, conducted in 2021 (by the Wuppertal Institut für Klima, Umwelt, Energie GmbH / DIW Econ GmbH) the Germany's hydrogen economy could offer to substantial job growth which however depends on multiple factors like hydrogen demand, in-house production, hydrogen imports, and international competitiveness which also explain the gap between the estimated values: Macroeconomic effects ranging from €2 billion to €30 billion in gross value added annually by 2050, with potential job increases ranging from 20.000 to 800.000 across the hydrogen production value chain are anticipated, both- direct and indirect (Merten et al. 2021).

4.3. A CRITICAL VIEW ON A HYDROGEN ECONOMY

A balanced hydrogen discussion, including economical and economic arguments, also includes critical views that might also have geopolitical implications and reveal the dimension of a future hydrogen economy.

First, the question regarding the required amount of hydrogen is repeatedly asked, however, bearing the assumption that the natural gas used so far will be *completely* substituted by hydrogen. For the European Union, this would mean the following:

Required H2 to replace all natural gas in the EU:

In 2022, the EU recorded natural gas consumption of 343 billion m3/year (Statista 2024b), which corresponds to a volume of 3.590.181.000.000 kWh[5]. [6]If all-natural gas consumption is to be replaced by hydrogen, the EU would need a total of 108.793.363.636,3636 kg of hydrogen, **almost 109 Mt**.

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[5] Calculation based on the unit converter *Unit Juggler*: https://www.unitjuggler.com/energy-umwandeln-von-kWh-nach-GcmNG.html?val=343

[6] One kilogram of hydrogen has an energy content (Lower Heating Vaue) of 33 kWh (Enapter, n.d.).

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Required electricity to produce the H2 the EU would need:

The production of green hydrogen in Europe today is not only very expensive, but also very energy intensive. The assumptions regarding the exact electricity demand to produce one kg of H2 cannot be fully narrowed down, as estimates differ. This is primarily due to the operating mode and the performance of the electrolysis. Accordingly, the Zentrum für Wasserstoff.Berlin expects a required amount of electricity between 40 and 80 kWh/kg H2 (H2. B, n.d.). Die GASAG[7] mentions a realistic value of 53 kWh/Kg H2 in this context (GASAG 2022), corresponding to an efficiency of around 63 percent. Therefore, to produce the required 109 Mt of H2, 5.766.048.272.727,271 kWh, or **5.766 TWh**, would be needed.

This amount raises the question of where the electricity for green hydrogen production will come from.

Net electricity generation in the EU amounted to 2.785 TWh in 2021, of which around 913 TWh was contributed by renewable energies (wind, solar, hydro power) (Eurostat 2023). To produce 109 million tons of hydrogen, the capacity of renewable energies would have to increase by **more than six times**. Figure 10 estimates total H2 demand by 2050 of 46 Mt, considering those sectors which will increase its H2 demand significantly. This would still require an increased capacity of renewable energies by factor of nearly **three**, only for H2 production.

These data impressively show the dimensions that a hydrogen economy could have to deal with and, above all, raise the question of where this green hydrogen should come from, now that fully covered in-house production within the EU is not possible.

In Europe, it is currently possible to cover around 44 percent of the electricity demand with renewable energies (Solar Power Europe 2024). A closer look at current legislative decisions, such as the ban on combustion engines from 2035 onwards decided by the EU (European Parliament 2023), or the gradual introduction of heat pumps in Germany (BMWK and BMWSB 2023), yields that the demand for electricity in Europe and its Member States will not fall so quickly, on the contrary, it will increase. In addition, compared to the climate targets for 2030 in the field of renewable energy expansion,

[7] GASAG is an energy company headquartered in Berlin and one of the largest regional energy-suppliers.

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progress in renewable energy consumption is progressing too slowly (European Environment Agency 2024)[8].

When narrowing it down to one of the EU member states, namely Germany, a country that is playing a pioneering role in the climate transition, the challenges become particularly clear. A comparison with the 2030 target values for renewable energy is useful here, as provided by the German Institute for Economic Research (DIW):

- In the area of on-shore wind farms, the current rate of annual expansion would have to roughly triple in order to reach the target of 115 GW by 2030 (Schmidt, Roth, and Schill 2023).
- In the field of photovoltaics, too, the average pace of expansion would have to be increased by a factor of 2.5 in order to achieve the target of 215 GW (Schmidt, Roth, and Schill 2023)

However, these results must also be evaluated by the fact that behind them are huge subsidy programs. To draw a link back to hydrogen, these growth regarding only the renewable electricity generation could well become a realistic challenge for an integrated and EU-wide hydrogen economy, which should mainly be based on green hydrogen.

The green hydrogen supply chain is crucial for meeting the rising demand for electricity, particularly in the EU, where electrolysis is expected to contribute significantly. To compete in this growing green hydrogen market, secure and affordable electricity, as well as substantial increases in wind and solar energy capacity, are essential.

However, on a global scale replacing all grey hydrogen with green hydrogen would require utilizing all installed wind and solar potential globally (Gielen, Lathwal, and Lopez Rocha 2023). Additionally, the production of green and blue hydrogen requires significant amounts of water (Ramirez et al. 2023), which may lead to conflicts over water usage or necessitate energy-intensive desalination, however this is discussed further in the following chapters.

[8] The EU has set itself the goal of achieving 42.5% of energy consumption covered by renewable energies in 2030, up from around 23% in 2022.

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Hydrogen leakages

Besides the beneficial environmental impact of an increased hydrogen use there is also recent scientific research indicating that the estimated H2 impacts on water vapor (H2O), ozone (O3) and methane (CH4) concentration in the atmosphere are higher than expected (Warwick et al. 2022). In fact, hydrogen is an indirect greenhouse gas, as it interacts with other gases in the atmosphere, like H2O, O3 and CH4, greenhouse gases with an extreme global warming potential (GWP). The International Energy Agency estimates that hydrogens GWP is around 11 (+/- 5) (IEA 2022a), which however is still more than double compared to previous estimations (Field and Derwent 2021). It is important to note that the decarbonization potential of (green) potential is still higher than its harmful effects regarding global warming. However, to reach its full decarbonization potential measures must be taken to discover premature hydrogen leakages.

4.4. Hydrogen: Geopolitics and Geoeconomics Matter

Geopolitical dimension

The current energy revolution brings a unique set of geopolitical considerations, like the still fossil fuel-dominated system. However, this "new" energy frontier is distinguished by an increased reliance on technology, the strategic importance of crucial raw materials, and a determined attempt to build regulatory frameworks and technological standards while competing for industrial leadership (Scholten et al. 2020). Therefore, in the wake of achieving the goals of the European Hydrogen Strategy it can be assumed that this will drastically change Europe's energy landscape. While researchers understand the economic and technological problems, the geographical dimension is frequently disregarded in EU strategy and political debates. Energy sources, especially raw materials such as coal, oil, natural gas, biomass, or hydrogen, can be traded globally on the energy market. Hydrogen´s geopolitical landscape will be formed by the fundamental traits of the emerging hydrogen market, similar to the hydrocarbons´ s geopolitical map, which was also influenced by the market dynamics, in its case containing the market characteristics of oil, gas, and coal. However, there certain differences.

First and foremost, due to its properties, it is not possible to extract hydrogen, rather it is manufactured. Therefore, it´s production via electrolysis is not bound to special

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locations which means that it can be generated from any location worldwide, however at different costs. Those countries with lower hydrogen production costs have comparative advantages compared to others. This is why this paper anticipates that initially nations with access to inexpensive gas for producing blue hydrogen will hold a competitive edge in pricing. But nevertheless, the widespread availability of low-cost hydrogen production, which even is expected to improve until 2050 (H. Blanco and Taibi 2022), implies that the global energy framework won't be reliant on a limited group of producers anymore, as we have seen with the OPEC countries for instance.

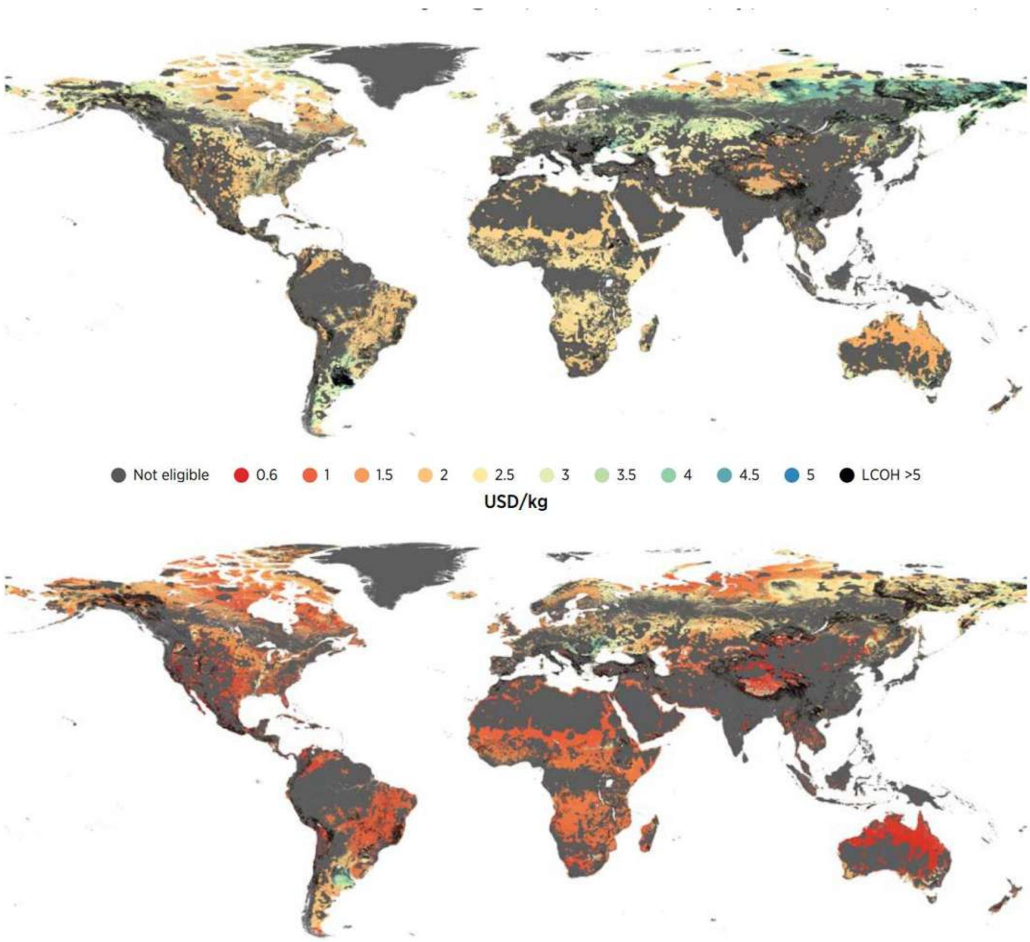

Figure 16: Levelized Costs of Hydrogen in 2030 (top) and 2050 (bottom). Source: IRENA (H. Blanco and Taibi 2022)

Therefore, the **second notable distinction** between these two eras lies in the **distribution of power**. While oil incorporated in the concentration of power within OPEC, big oil companies, and strategic chokepoints, the shift towards hydrogen will prompt a dispersal of power. This shift can be attributed to the distinctive features of hydrogen and its evolving future value chain (Behr 2023). On the other hand, important raw elements required (Nickel, or Platinum) for hydrogen production (mainly for the electrolysis) are more concentrated (Ruprecht 2022), which increases the risk potential again. Moreover, infrastructure expansion, including ports, freighters, and pipelines, will necessitate major resources and investment, influencing long-term interdependence and power dynamics in the hydrogen industry. A distribution of power of renewable energy resources also leads to a more diverse supply chain structure than for fossil fuels. Green hydrogen´s value and supply chains will therefore be **longer and more complicated**. These networked systems will create linkages across many stages of the value and supply chains, as well as geographical regions, potentially increasing their complexity (Pepe, Ansari, and Gehrung 2023). This in turn offers more energy suppliers, which in turn can reduce dependencies.

Geoeconomic dimension

> *"The concept of (critical) geopolitics is a key inventory of International Relations research. Geoeconomics, as a relatively new concept, urges us to think beyond classical geopolitical imaginaries in many aspects of the international sphere. The manifold ways in which globalized networks of corporate power and control can be weaponized, manipulated, and instrumentalized, challenges and at the same time complements geopolitics."*(European Consortium of Political Research, n.d.)

Geopolitics considers geographical elements in foreign policy, whereas **geoeconomics examines** the spatial relationship between economic and energy policies, stressing interactions between state and non-state players. In an era of rising power bloc conflicts, geoeconomics not only heightens military force projection but also competition for control over industrial output and value creation. Rising geopolitical tensions among key powers may result in protectionist measures, stifling global hydrogen market growth. Mercantilist policies, such as public investment and import security agreements, can help to expand the hydrogen market, but they must be balanced with institutional complexity. The competition for energy resources, transportation routes, and market supremacy highlights the significance of technological innovation and strategic positioning in the hydrogen production ecosystem (Grinschgl, Pepe, and Westphal 2021).

Historically, technological transformations and shifts in energy production procedures have triggered substantial changes in geoeconomic dynamics. Both nations and industries have typically settled towards hydrocarbon reservoirs, competing over access points of geostrategic importance. Political transitions paired with power realignments in global affairs have often caused domestic tensions as a redistribution of gains and losses

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occurred. The ongoing energy transition, albeit driven by the distinct attributes of hydrogen, is projected to follow a similar trajectory. Consequently, it can be anticipated that geoeconomic implications will play a significant role during shift towards a hydrogen economy (Behr 2023).

Moreover, the cost of hydrogen-derived products like ammonia can impact food costs (Food System, n.d.). The complexity of the hydrogen value chain is evident, especially in how it intersects with various industries like chemicals and steel, highlighting both its complexity and economic significance. Hydrogen consumption not only influences energy trade patterns but also reshapes economic structures globally as industries like steel and chemicals, are likely to undergo significant transformations due to the increasing influence of renewable energy (Grinschgl, Pepe, and Westphal 2021). This potential shift is further examined in chapter 4.7, but this trend heralds a broader industrial revolution driven by sustainability and energy efficiency imperatives.

Price Setting: Possible pricing systems for a global low-carbon hydrogen market

The establishment of a new market for global hydrogen trading raises the question of which price mechanism will reflect the value of hydrogen in the future.

Currently, the global demand for hydrogen is around 120 million tons per year globally (IRENA 2022), and around 8 million tons per year in European terms (Figures 9 and 10) (EHO 2023). However, this is likely to change. Depending on the estimate and global warming scenario, the forecasts vary, but assume H2 production of up to 800 million globally, and about 45 million tons in European terms (IRENA 2022; EHO 2023). The greatest demand is still determined for domestic production, but in the view of the enormous increases in production in the coming decades, certain sectors will also increase their hydrogen demand, especially the industry and transport (Figure 11) (EHO 2023). Pricing is therefore still relatively local, as long-term supply contracts between two parties reflect the value of the hydrogen traded. If such an increase in production does indeed occur, it can be assumed that this pricing mechanism will no longer be represented (Wakim 2022). Europe's future dependence on hydrogen imports is also likely to lead to the market demanding a new pricing system for hydrogen. Europe expects to import 10 million tons of renewable H2 in 2030, which corresponds to 50 percent of its demand (European Commission 2022d).

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The complexity of H2 supply chains, encompasses not only the repurposing of existing gas infrastructure (especially ships, ports, and pipelines), but also the construction of new hydrogen pipelines, and will be an essential element of future hydrogen trade and therefore can be assumed to have a significant impact on pricing. Figure 16 suggests that there are significant cost differences in hydrogen production costs globally, which will manifest themselves over the next few decades.

Due to the young and immature H2 market, hydrogen pricing will in all likelihood not be based on a spot price, as is customary in oil trading, for example (Erdöl-Vereinigung 2005). This is because this part of the commodity trade is naturally carried out where products meet their direct transport, e.g. in ports. Since the infrastructure required for the hydrogen market does not yet exist to this extent, a similar approach cannot be assumed for the time being (Wakim 2022). However, there are first attempts in this direction, such as the HyXchange project in the Netherlands, which combines the ports of Ghent, Rotterdam, Amsterdam and Groningen in a pilot project (HyXchange, n.d.).

Netback: This pricing model is one that is also common in commodity trading, including oil and natural gas, and one that is based on efficient production. According to this model, the H2 price in the exporting country would be the same as the H2 price in the importing country, but minus transport costs, insurance, and customs duties. This would only make sense for the producing country as long as their H2 production costs are significantly lower than those of the demanding countries (Wakim 2022). Both countries close to the EU such as Morocco and Algeria, as well as remote regions such as Chile, benefit from significantly lower H2 production costs compared to the EU. These countries have also developed large export plans, as will be discussed in more detail later.

Import parity: In this pricing model, the hydrogen price in the importing country corresponds to the production costs of the exporting country, but plus a margin, transport costs, customs duties, and insurance. It is likely that the price in the exporting country is based on marginal costs. Due to technological, financial, and economic uncertainties in the markets for low-carbon hydrogen, long-term supply agreements could be a solution to guarantee collateral that would also further promote the production of low-carbon H2. However, a challenge for marginal costs could be incentives for the industry in the exporting country, which further promote H2 production, but cannot be passed on to the

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consumer countries and thus do not lead to price formation on the international market (Wakim 2022).

Uncertain factors

However, much is also to be regarded as uncertain. Measured by the projected hydrogen demand at the global and European level, hydrogen trading is still in its infancy. It can be assumed, without further ado, that technological advances along the entire hydrogen supply chain – production, transport, storage, application – are to be expected. However, it is difficult to estimate when these technological achievements will arrive and, above all, when they will be used on a large scale. Nevertheless, they will influence global hydrogen trade and therefore also the hydrogen price.

Difference to gas and oil markets

However, when it comes to differences to the gas market, this thesis anticipates that the cost differentials for hydrogen production are expected to be not as stark as those for gas or oil.

This major advantage over to the recent fossil fuel dominated energy markets is possible to assume due to projections that indicate that by 2050, hydrogen production costs will span from approximately 1 USD/kg in regions like Latin America, Africa, and the Middle East – among the lowest cost producers – to 1.8–2.5 USD/kg in areas such as Europe, Japan, and South Korea. Additionally, the expense of transporting hydrogen could amount to as much as 1 USD/kg, significantly narrowing this disparity (Hydrogen Council and McKinsey & Company 2022). Those aspects points to a more competitive landscape in the hydrogen economy. The establishment of a functional global market could vastly expand consumer choices, thereby enhancing competitiveness and this could lead to hydrogen prices, more based on a level playing field compared to previous energy market, mainly determined by fossil fuels.

However, this argument could be counteracted in the initial phases of a hydrogen ramp up. Global hydrogen trade reduces the likelihood of disruptions and shortages but also has the potential to introduces price risks. Especially in the initial phase when electrolysis capacity is still a lower level, consumers may face fluctuating market prices, potentially affecting hydrogen import affordability. With growing market volumes, liquidity improves, and price volatility decreases. Like other commodities, hydrogen import-needs,

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as Piria et. al (2021) argues, could be met through a mix of stable-priced long-term contracts and short-term trading on spot markets. On the journey to climate neutrality, the balance between supply and demand may temporarily sway. Also, stronger international climate policy engagement could expedite the development of a liquid and competitive global hydrogen market. As infrastructure expands, hydrogen availability and affordability will increase as post-completion of pipeline projects (expected after 2030) as H2 supply stabilization is anticipated (Piria et al. 2021).

At the same this means that practices such as rent-seeking behavior, which was incentivized in the hydrocarbon economy, are expected to be less feasible in the hydrogen economy. It is rather, that producers are poised to become price-takers once a well-functioning level playing field is in place. Given hydrogen's pervasive availability, the prospect of forming a producer group akin to OPEC to determine prices can be assumed as nonexistent. Furthermore, margins resulting from hydrogen are anticipated to be substantially lower compared to fossil fuels margins, as they are distributed across various stages of the value chain. This circumstance may alter the energy market as could facilitate to proceed against rentier economies.

Establishing H2 Markets – EU´s influence

Transitioning to the geopolitical landscape, the variables influencing the EU's leading role in the field of hydrogen exhibit a degree of uncertainty. Although, on the one hand certain EU member states, notably Germany, Spain or Portugal, are destined with favorable condition for renewable hydrogen production, the EU's reliance on hydrogen imports could reach approximately 50 percent by 2050 (Perra 2021). This estimation might be quite accurate, as also the REPowerEU plan accounts for 50 percent imports.

With respect to this, a study by Fraunhofer ISI, RIFS Potsdam and the German Energy Agency concluded that hydrogen production capacities in certain European countries (EU, Norway, Switzerland, and Great Britain) are not fully utilized and that they revealed multiple mismatches. On the one hand, Germany cannot even cover half of its demand through its own production. Also, investments are not high enough compared to the production potential, especially in Spain, even though it has set itself the highest electrolysis capacity targets and has implemented the most projects alongside France. In addition, there are other EU states that are also favored, such as e.g. Portugal or Italy which huge investment deficit compared to their potential (Quitzow et al. 2023)

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Various nations, including those which are geographically far away from the EU such as Namibia in sub-Saharan Africa, the Middle East, Chile in South America, or Australia in the Asia-Pacific region, may find themselves in advantageous circumstances for producing and exporting competitively priced renewable hydrogen. But these countries´ export abilities to the EU are also relying to a great extent on their capacity of a fast scale up renewable energy production (and desalination plants in water-scarce areas), as well as uncertainties surrounding transportation methods and costs that are yet to be fully clarified (Jerzyniak and Herranz-Surrallés 2024).

The EU's ability to secure a leading role in global hydrogen trade (importing and exporting) is also very contingent upon the geoeconomic preferences of other major players. Both the US and China find themselves in favorable production conditions to rise as leading actors (Eicke and De Blasio 2022). Especially, the US Inflation Reduction Act may confer privileged status on American companies, enabling them to export hydrogen at reduced costs (US Department of Energy 2022). In fact, the US offers a better funding model here as far as hydrogen is concerned. The Biden administration's IRA apparently not only promotes domestic companies, but also attracts European companies to the other side of the Atlantic, a development which already has begun due to very high energy prices in Europe. (Zachová 2023). Especially for SMEs, the EU's funding programs are obviously too complicated, whereas in the US the funding instruments are understood in a few simple steps. This is certainly also related to the fact that the IRA includes a USD 700 billion program that provides far-reaching financial support for green technologies. In terms of green hydrogen production, this means a tax credit of 3 US dollars. Assuming an average price of EUR 5-7 per kilo, this subsidy allows for a competitive level compared to other types of production, in particular blue hydrogen (Matthews 2022). Competitiveness, which was already under pressure due to the sharp rise in energy prices in Europe, is now also being challenged by the IRA from a regulatory point of view.

The impending race for pivotal technologies which are crucial to the hydrogen supply chain is inevitable. It is very likely that this race will primarily revolve around electrolysis and fuel cells. Given the fact that hydrogen is a manufactured resource, substantial economic gains can be anticipated for the manufacturers of electrolysis and fuel cells, with electrolysis being explicitly critical (Behr 2023).

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Meanwhile, China currently holds the top spot in global hydrogen production, albeit predominantly derived from coal (IEA 2022b). However, China advances in big steps. As the IEA's recent Global Hydrogen Review 2023 report, half of the world's available electrolysis capacity for green hydrogen production was located on Chinese territory in 2023, or 1.2 GW. In the EU, it was just a little more than 0.5 GW (IEA 2023). A similar development can also be seen in other areas that are also important for green hydrogen production in their value chain, namely the solar energy sector. According to studies in 2022 Germany imported almost 87 percent of the imported PV systems, including China (Statistisches Bundesamt 2023). In geopolitically challenging times, the EU should focus more on independence and diversification of its supply chains.

Therefore, China presents a formidable challenge to the EU in the electrolysis market. Despite the ambitious plans of the EU deriving from the EU Hydrogen Strategy and the REPowerEU plan in increasing electrolysis manufacturing capacity, China outpaces Europe in electrolysis production, boasting significantly lower costs. Additionally, the EU still faces constraints due to limited access to critical resources – Nickel or Platinum - all essential for electrolysis, and their majority located or at least hold by China and Russia as major exporters (Clarke 2022). While alternatives exist, the EU will face intense competition and Europe must be cautious not to cause new dependencies.

Europe will import significant amounts of hydrogen in the long term, as the presented REPowerEU plan has postulated. Due to Europe´s limited renewable energy potential (compared to other regions of the world), purely domestic production of green hydrogen is not possible. Global trade in hydrogen is therefore necessary and economically sensible, since despite high transport costs, importing green hydrogen is cheaper than domestic production in the future. However, it is not yet possible to fully predict what a global hydrogen market will look like, as it´s ramp up has just began. Numerous countries are striving to become hydrogen exporters, other countries are focusing on being able to meet hydrogen needs through imports.

Similarly, Gulf states aspire to claim enormous market power in future hydrogen trade, although too not necessarily in the realm of clean hydrogen (Ansari 2022). On the one hand there exists a degree of goal alignment between the EU and entities positioning themselves as big H2 exporters into the European Union. Here Morocco and Egypt shall be mentioned. However, on the other hand there might also be risks in this emerging level

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playing field, especially when it comes to colliding objectives. This is especially true when considering the whole hydrogen value chain, where certain rivalries may arise between EU importers and non-EU exporters. The latter may have economic incentives to enhance their stance in the value chain and attract certain, hydrogen involving industries like steel, ammonia, or methanol production. Heightened risk of industrial relocation outside the EU could be a consequence of such dynamics (Eicke and De Blasio 2022). The EU's diplomatic efforts in the hydrogen sector reach to establish partnerships that align with various objectives. One facet of this diplomatic activity revolves around possible hydrogen-exporting nations into the European Union. In 2022, the EU entered Memoranda of Understanding (MoUs) or joint statements, laying the political foundation for the import of renewable hydrogen from countries such as Egypt (including a trilateral agreement involving Israel), Kazakhstan, Morocco, Namibia, and Norway (Romano 2022; European Commission 2022b; 2022c; 2023). Notably, in 2023, those countries, with the exception of Norway, became receivers of energy-related investment projects under the Global Gateway, in particular focusing on hydrogen or renewable energy.

The second cornerstone of diplomatic ambitions is more intricately directed at the regulatory aspects of global hydrogen markets. This includes a MoU with Japan signed in December 2022 (European Commission 2022a). However, given the hydrogen ambitions of major players such as China and the US, coupled with their considerable global market influence, the emergence of alternative rules—whether technical, regulatory, financial, or environmental—is probable. This could result in both, either in a fragmented international hydrogen market or in imposed standards & regulations implemented by non-EU countries.

However, the diplomatic endeavors of the EU in the field of hydrogen remain limited overall. All arrangements at EU level lack binding commitments, and in certain instances, hydrogen is only integrated into broader energy collaborations, such as critical raw materials, as in the Memorandum of Understanding with Kazakhstan (Romano 2022). Furthermore, bilateral agreements between member states and other nations may not necessarily in alignment with the EU's objectives, particularly in terms of prioritizing renewable hydrogen. This division within the EU member states undermines the EU's cohesive intent to establishing a joint global hydrogen market. The situation draws parallels with natural gas policies over the past decades (Jerzyniak and Herranz-Surrallés 2024).

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4.5. ASSOCIATED RISKS REGARDING HYDROGEN IMPORTS

Supply chain risk

Global supply chains as well as energy imports are confronted with a variety of potential risks. In addition to natural disasters and technical or human error, various geopolitical risks also pose a threat to security of supply. Security of supply is ensured by preventing or minimizing risks (Piria et al. 2021). The assessment of a country's energy supply security should therefore take into account aspects such as the stability of energy producers and transport and transit risks in addition to the share of energy imports in the energy supply and the replaceability of individual energy exporters (Wietschel et al. 2020).

The term geopolitical risk is based on the broad understanding of geopolitics in the public discourse. Geopolitical risks are defined as the endangerment, realization, and escalation of conflicts and tensions between states or political actors (Caldara and Iacoviello 2022). It assumed that geopolitical aspects of hydrogen will not only follow, but also increase the dynamic of a more complex energy supply network (Pepe, Ansari, and Gehrung 2023). The hydrogen supply chain under consideration includes input production, hydrogen production, cross-border transport, and export infrastructure up to reaching Europe’s external borders. While global hydrogen trade will not have the same volume as today's oil and gas trade, risks may still arise that leave affected countries vulnerable (IRENA 2022).

The risk potential of hydrogen trading is determined by the structure of hydrogen supply chains, i.e. from the hydrogen producer to the consumer. Dependencies allow political actors, domestic actors in exporting countries, international groupings, or actors in third countries to use the supply of energy as a means of exerting pressure to pursue political interests. Therefore, regardless of developments in the global energy market, supply disruptions pose a risk to energy importers (Muñoz, García-Verdugo, and San-Martín 2015). Geopolitics and energy markets have a close interlinkage that impacts global order. Energy exports are repeatedly used as a means of exerting political pressure. In this context, there was also talk of “energy as a weapon” (Metsola 2022). Even the threat of withholding energy exports for political reasons can lead to strong uncertainties with effects on the energy price (Fattouh 2007) as Europe experienced in the last years.

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Geopolitical risks are closely related to a country's political, economic, and social risks. In addition, bilateral relations (political and economic) between the countries directly involved in the hydrogen trade are another dimension of risk. The individual risk dimensions assess the geopolitical security of hydrogen producers and transit countries and routes (Muñoz, García-Verdugo, and San-Martín 2015).

Risk: Undersupply

It must be stated that the current understanding of the potential for a structural deficit in hydrogen supply still relies solely on assumptions. Yet, a notable contrast to the dynamics observed in fossil energy markets is already apparent. The volatility in global oil and gas production, influenced by economic cycles and strategic decision-making by producers, underscores this contrast. During periods of high market prices, even the most capital-intensive extraction facilities are brought online to. Conversely, during lower price periods, production is often scaled back as producers strategically adjust their output, poised for potential future sale at more favorable prices. This however aligns with sound business logic. In times of low prices, producers not only incur the marginal costs of extraction, including significant energy expenditures, but also struggle with the opportunity costs of selling at a discount (Piria et al. 2021). Akin to their counterparts in fossil energy, the exporters of blue hydrogen are likely to encounter similar challenges in the future, albeit complicated by the additional requirements of CCS infrastructure, which could impede supply regulation flexibility.

However, those dynamics might not apply for green hydrogen which is sourced from wind and solar energy. This is mainly due of the fact that marginal costs of renewable energy are expected to approach zero as technology advances ("The sun won´t send us a bill" (Detail 2009), but also due to anticipated lower opportunity costs, as unused energy today remains inaccessible the day after. This on the other hand represents a challenge as potential implications for importers are hard to predict. Here hydrogen storage facilities become essential again, as they have the potential to mitigate price changes and make it possible for importers and exporters to accumulate reserves during low-price periods for future use when prices increase again (Piria et al. 2021). As for example Germany, endowed with favorable geological conditions for expansive hydrogen storage, stands to gain a competitive edge in this arena and the importance of large-scale hydrogen storage is poised to ascend in the long term (Statista 2024c).

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4.6. CASE STUDY: H2 GEOSTRATEGIC ANALYSIS

Table 1. H2 Geoeconomic Indicators

INDICATORS	CHILE	MOROCCO	ALGERIA	RESOURCE[9]
Economic Factors				
Economic Growth (real GDP)	2.1	1.4	3.6	FE
Index of Economic Freedom 2024	71.4	56.8	43.9	HF
Business Freedom Index 2024	79.2	68.5	54.4	HF
Regulatory Quality Index 2022	0.98	-0.09	-1.06	GE
Unemployment rate 2024 in % (2024/2024/2022)	8.7	13.7	11.6	TE & FE
Poverty rate 2024 in %	10.8	4.8	5.5	WPR
Bilateral Factors				
EU-Imports in € B 2023	7.7	23.4	35.4	EU
EU-Exports in € B 2023	10.7	33	14.9	EU
FDI from EU in € B 2022	64.9	19.9	19.3	EU
FDI to EU in € B 2022	5.5	1.9	1.3	EU
Political Factors				
Government Effectiveness Indicator 2022	0.5	-0.1	-0.5	WB
Corruption Perception Index 2023	66	38	36	TI
Geographical Factors				
Distance to Europe in km	Very high	Very low	Very low	
Water Stress 2023	<10%/>80%	60-80%	>80%	ARA
H2 Factors				
Hydrogen Targets	25 GW Electrolysis Capacity 2030	14 TWh 2030	30-40 TWh 2040	IEA, HI
H2 Production costs US$/kg in 2030	1.5	2-3	2-3	ME, IC, CORFO, McKinsey & Co
H2 Production potential	very high	high	high	
H2 Transport potential	Ship	Pipeline/Ship	Pipeline/Ship	
H2 (NH3) Delivery costs	low	higher	higher	EHB
H2 Export Potential to EU	high	high	high	Rikabi 2024
H2 Transport routes	Atlantic	Corridor B	Corridor A	EHB
Geopolitical concerns	Low	Low	high	Own perception

[9] Abbreviations: Focus Economics = FE, The Heritage Foundation = HF, The Global Economy = GE, Trading Economics = TE, World Population Review = WPR, European Union = EU, World Bank = WB, Transparency International = TI, Aqueduct Risk Atlas = ARA, International Energy Agency = IEA, Hydrogen Insight = HI, Ministerio de Energía = ME, Invest Chile = IC, European Hydrogen Backbone = EHB

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Hydrogen has been identified as an essential component in the global energy transition, having the potential to decarbonize the hard to-abate sectors of the economy. However, as the EU tries to integrate hydrogen into its energy mix via various strategies and investments, it faces numerous both geoeconomic challenges and opportunities, especially due it´s future reliance on imports. In the following an analysis provides a detailed examination of the geoeconomic landscape surrounding hydrogen trade incorporating production and transport. To narrow this analysis down, three different countries were selected, differing in both geographics and political circumstances: Chile, Morocco, and Algeria. Additionally, a specific focus is laid on the fact why traditional economic principles, such as those outlined by David Ricardo regarding comparative advantage, may face limitations due to rising geopolitical tensions.

David Riccardo & Hydrogen production potential

Comparative Advantage: When it comes to trade, Ricardo's economic theory brings forward that countries should specialize in producing those goods and services in which they gain a comparative advantage over other countries, due to lower opportunity costs. Riccardo also argues that a specialization in certain markets would lead to greater efficiency and to an overall higher welfare. Therefore, when it comes to the product hydrogen, countries should focus on production methods that are most efficient and cost-effective, whether it's through renewable energy sources (Green Hydrogen) or natural gas reforming (Grey Hydrogen). Consequently, certain countries, as Chile, Morocco, or Algeria with abundant renewable energy resources such as strong solar irradiation or strong and steady on shore wind conditions certainly have a comparative advantage in producing green hydrogen over other countries. In turn, countries with vast reserves of natural gas may find it more economical to produce blue hydrogen (BPB, n.d.).

International Trade: Presumably hydrogen will play an important role as a future key commodity in international trade. This trade according to Riccardo´s theory might therefore occur between hydrogen exporting countries benefiting from rich energy resources and hydrogen importing countries demanding for high amounts of renewable energy.

This theory forms the basis of much of international trade theory and has been very influential in shaping global trade policies in the past. Cheap Russian gas for served as a good example regarding Europe´s gas supply. However, the bill in the end was high. Therefore, when considering trade of products like hydrogen and considering geopolitical tensions several factors might challenge the applicability of Ricardo's economic aspects.

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Chile, Morocco, and Algeria benefit from significant natural resource endowments, in particular renewable energy sources including solar and wind power, both essential for green hydrogen production. Chile, benefits from the highest solar radiation worldwide in the north (Atacama Desert) and extraordinarily strong and steady winds in the south (Patagonia) on shore. Those factors enable favorable conditions for renewable energy generation, needed for an electrolysis. Morocco also has all the requirements needed to become a major player in green hydrogen production. Algeria, neighboring Morocco, is also benefits from the sun-rich North African region, and therefore also holding substantial potential for solar-based hydrogen production. Those benefits originating from abundant renewable energy resources also enable exceptionally low levelized H2 production costs for 2030, although they differ slightly. Hydrogen production costs for in Morocco and Algeria are higher compared to Chile due to slightly better production conditions in the Atacama Desert and Patagonia than in the northern African region. By 2030, McKinsey estimates the production costs in Morocco and Algeria to be around USD 2-3/kg, whereas the levelized costs in Chile aims are even below USD 1.5/kg (Ministerio de Energia, InvestChile, and CORFO, n.d.). As all three countries have the possibility to produce at relatively low and very low costs, they also have committed themselves to play future role in hydrogen trade, as they want to export vast amounts of hydrogen and its derivatives.

Own assessment based on provided data: Production costs

Chile	Morocco	Algeria

Note, also for upcoming assessments: green = high, orange = medium, red = low

<u>Economic and Political Factors</u>

Chile, despite social and political turmoil in 2019 (Müller 2023) and the pandemic, has regained economic growth and recorded a GDP growth of 2.1 percent in 2022 (Focus Economics, n.d.). Besides economic strength Chile also stands for a favorable business environment for investment and innovation, especially for foreign investors. This is underpinned by high values regarding certain indexes, like the Economic Freedom Index (EFI), 71.4 in 2024, or the Business Freedom Index (BFI), 79.2 in 2024 (The Heritage Foundation, n.d.). Additionally, when it comes to institutional stability Chile benefits from a transparent and trustworthy government. According to the World Bank (2022) it´s

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value regarding the Government Effectiveness Indicator (GEI) is 0.5 and it´s Corruption Perception Index (CPI) score of 66 is reflecting Chile´s integrity in its governance practices (For comparison: Germany currently (2023) has a CPI of 71) (World Bank, n.d.; Transparency International 2024).

Although **Morocco** and **Algeria** also have economic growth (1.4 percent and 3.6 percent in 2022), both countries demonstrate comparatively lower scores on economic and governance indicators (Focus Economics, n.d.). Morocco's EFI score of 56.8 and BFI score of 68.5 highlight challenges related to economic freedom and foreign investment attractiveness. Similarly, Algeria's EFI score of 43.9 and BFI score of 54.4 indicate areas for improvement in economic governance and transparency, representing the lowest values in this regard compared to the other two countries (The Heritage Foundation, n.d.). Additionally, when it comes to unemployment, Morocco faces the highest rate with 13.7 percent, followed by Algeria with 11.6 percent and Chile with 8.7 percent (Trading Economics, n.d.-b; n.d.-a). When it comes to political indicators measuring governance especially Algeria has potential for improvement. Both selected indicators, GEI, and CPI, show the lowest values, -0.5 and 36 respectively (Transparency International 2024; World Bank, n.d.). Especially Algeria, which plans to export 10 percent of its clean hydrogen production (blue and green) to Europe (Collins 2023a), might be well advised to enhance its economic and economic and governance performance in this regard. At the same time Europe might have to act cautious not to intensify these bilateral ties to avoid negative dependencies.

Chile´s governance, which is characterized by democratic and rather stable conditions, enhances the country´s attractiveness as hydrogen supplier for future trade. On the other hand, both North African countries fell short compared to Chile. While Morocco maintains a stable monarchy, Algeria's, although geographically being a favorable trading partner for the EU, currently needs to deal with democratic institutions that are increasingly characterized by repression and a deterioration in the efficiency of governance (Mersch 2023).

Own assessment based on provided data: Economic and Political Factors

Chile	Morocco	Algeria

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Transport and delivery costs

Regarding the costs of delivery, as already mentioned in chapter 4.1, it is important to distinguish certain points. The delivery costs depend not only on the chosen transport method but also on the chosen form of transport of hydrogen. The different transportation methods are ship or pipeline transportation. The different forms of transport are liquid hydrogen, LOHC, and ammonia. These also include necessary intermediate steps, all of which are associated with costs, such as conversion prior to export & pre-export storage, shipping, post-import storage and reconversion at import country (only in the case of carriers). The capital investment and operating costs are also included in the actual transport costs. In the following, only delivery costs of NH3 are calculated. This seems to be plausible, as there is already an existing market for ammonia. Figure 17 is important as it illustrates the current gas pipeline between North Africa and Europe. This grid will presumably be used for future hydrogen trade, although with probable limitations.

Figure 17. The existing gas pipeline network between Europe and North Africa can be used for H2 transport. Source: Research Gate, n.d.

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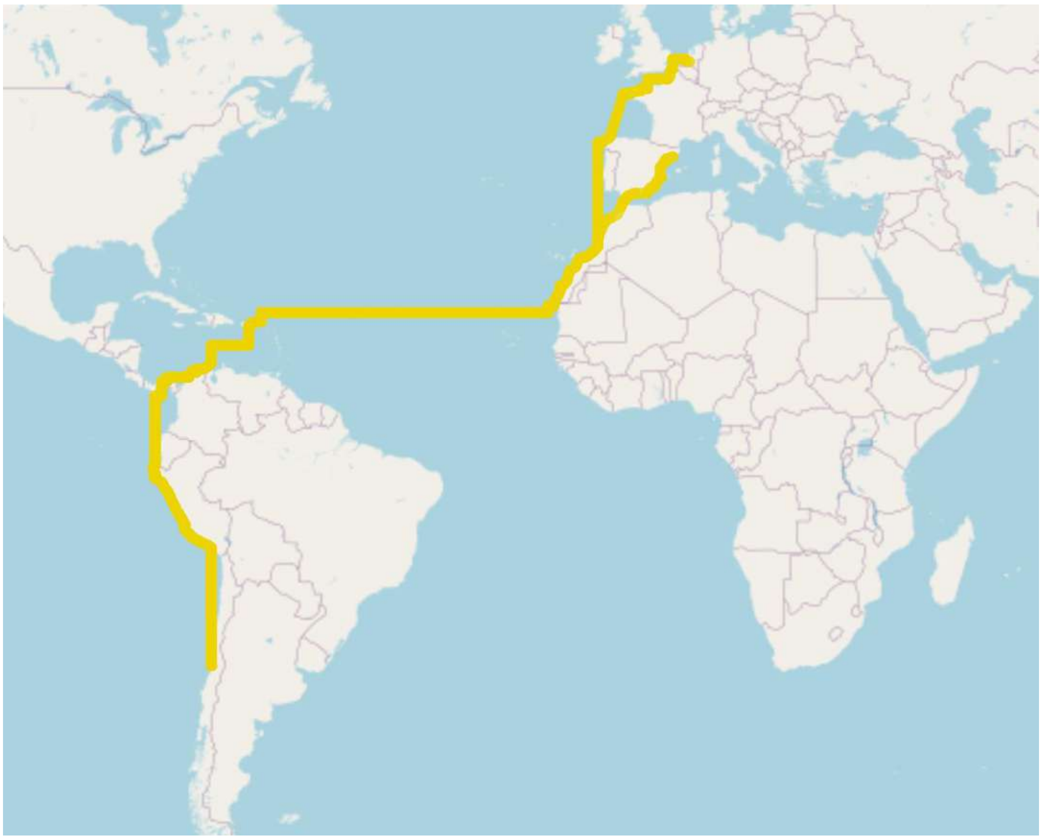

Figure 18. Puerto San Antonio (Chile) - Port of Barcelona/Port of Rotterdam. Source: Ports 2024a; 2024b

As there is no pipeline connecting the **Chile** with mainland Europe, Chile´s hydrogen will rely on ships. The distance between Chile and Europe varies, depending on the H2 demanding location, however considering the port of Barcelona a future H2 distribution center within Europe, it would amount to 16.653 km. As figure 13 illustrates, the costs for transport costs by ship for NH3 increases almost linearly. Considering Chile as a future green ammonia exporter the transport costs, for 16.653 km the transport costs would account for USD 0.98/Kg NH3. When hydrogen production costs of USD 1.5/Kg H2 as it is estimated by McKinsey&Company for 2030 are added, this would account for delivery costs from Puerto San Antonio to Port of Barcelona of **USD 2.48/Kg NH3**. Considering the Port of Rotterdam as final destination and its distance of roughly 18.000 km (Ports 2024b), transport costs would account for USD 1.003/Kg NH3, which ends up in overall delivery cost of **USD 2.50/Kg NH3** in 2030.

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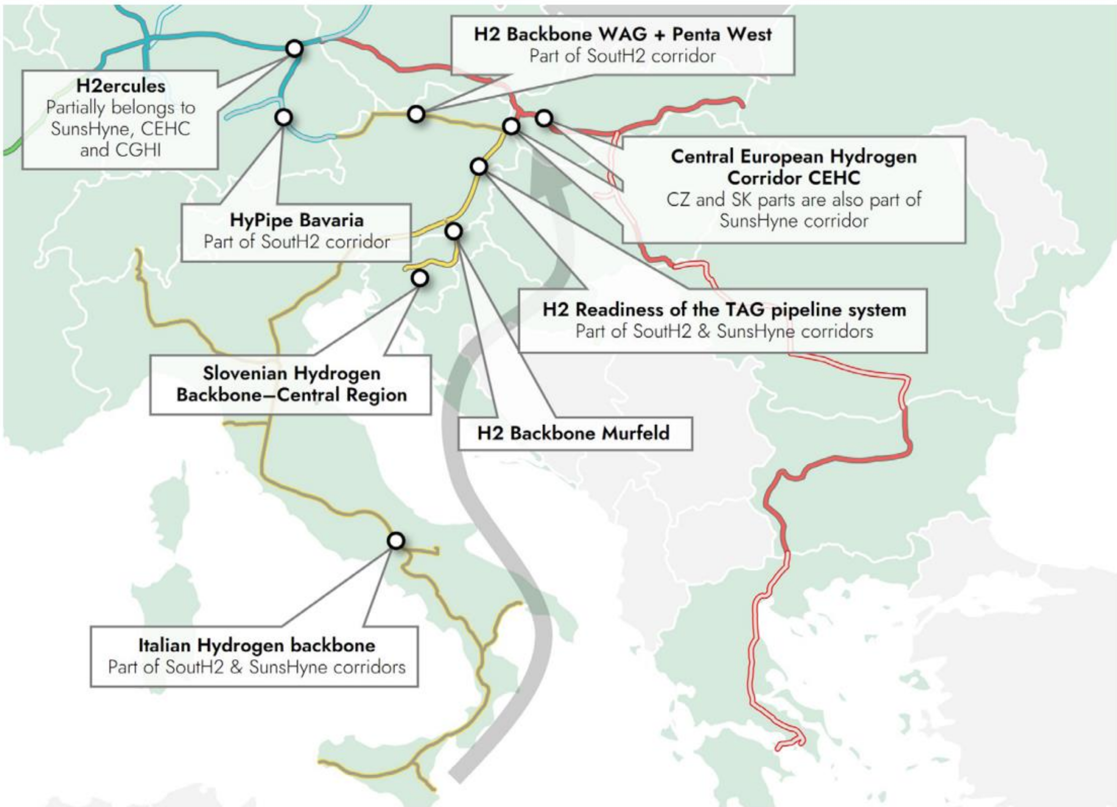

Figure 19: Corridor A - North Africa and Southern Europe. Source: EHB 2023

Algeria will use Corridor A "North Africa and Southern Europe" where the supply route runs from Algeria over Tunisia to Italy (SunHyne and SouthH2 corridor), before it reaches Central Europe including Austria, and Germany (EHB 2023). Algeria benefits from an already existing gas pipeline, the Trans-Mediterranean pipeline, which is connected to Tunisia (Figure 17) and allows for further hydrogen export to Europe, as 70 percent will be repurposed from former gas transport (Collins 2023b; Research Gate, n.d.). As figure 17 illustrates there is another already existing gas pipeline connected to Europe – the Medgaz Pipeline, which ends up in Almeria, Spain. However, in contrast to previous plans, this pipeline will not be used for trans-mediterranean hydrogen transport (FuelCellsWorks 2023). Algeria has one decisive advantage over Morocco, as additionally to the transport route via Tunesia, it also has an advanced domestic gas grid (Global Energy Monitor 2024). This will enable more decentralized hydrogen distribution within the country, but also facilitated hydrogen exports.

For the calculating delivery costs, repurposing the Trans-Mediterranean pipeline with a length of 2.475 km and diameter of 48 inch (most of the time) is presumed. It starts in the Algerian town Hassi R´mel and ends in Northern Italy, close to Slovenia. For a

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repurposed 48-inch pipeline Figure 13 indicates transport cost of approximately USD 0.25/kg NH3 for a length of 2.475 km. This has to be added to the H2 production costs of USD 2.5/kg NH3 which results in a delivery cost of **USD 2.75/kg NH3**. Taking the Port of Rotterdam as transport destination, and considering its shipping route of 3839km distance, would result in transport costs of USD 0.767/Kg NH3. Since the H2 production costs have to added, total delivery costs by ship yield to **USD 3.26 Kg/NH3**

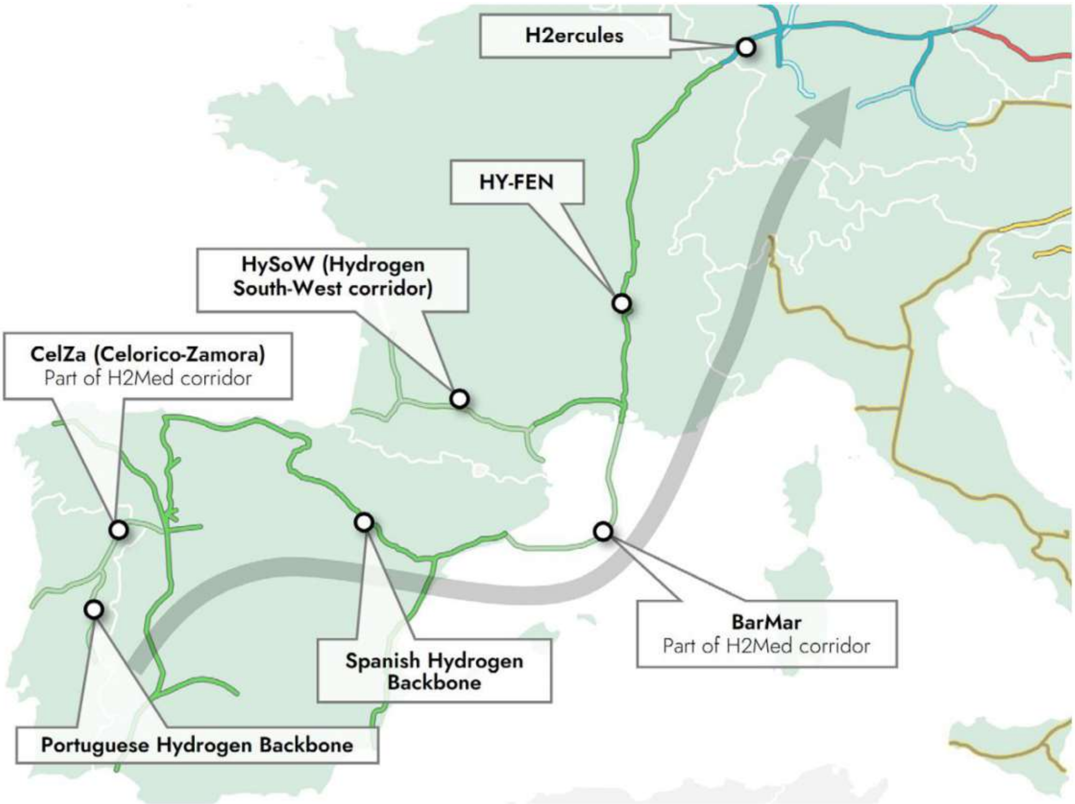

Figure 20: Corridor B - Southwest Europe and North Africa. Source: EHB 2023

Morocco will most probably use Corridor B – the Southwest Europe & North Africa route. From there onwards, the imported hydrogen will be distributed over Spain and Portugal (H2 Med corridor) and further to Central Europe over a sub-sea pipeline from Barcelona to Marseille (Bar Mar project) before it finally reaches Germany (H2 Hercules) (EHB 2023). Morocco also has a direct pipeline connection to Spain via the Maghreb-Pipeline, as figure 17 illustrates. However as or right now there are no concrete plans yet presented to reuse this existing gas pipeline as future hydrogen carrier, an neither if it is technically possible. Apart from that, there is another factor which hinders short term H2 exports to the EU. As of right now, Morocco is heavily lacking of a wide spread domestic gas grid, in contrast to Algeria (Global Energy Monitor 2024). This however is essential when hydrogen transport should be connected to the Maghreb-Pipeline Despite this open

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questions and possible hindrances, potential costs of delivery for NH3 from Morocco can be calculated as followed. As the Maghreb-Europe Gas pipeline has a diameter of 48 inches, it would be very attractive in terms of cost effectiveness, as Figure 13 illustrates.

Analysist from the European Hydrogen Backbone have compared the transport route between Marrakesh and Cologne using ships and pipelines. Pipeline transport over distance of 2.700 km using a repurposed 48-inch pipeline is by far the most attractive one in terms of cost effectiveness, yielding transport costs of USD 0.14 – 0.27/Kg. Using the ports of Casablanca and Rotterdam for shipping, which also would require short pipelines from Marrakesh to Casblanca and Rotterdam to Cologne, would lead to costs of USD 0.74/Kg NH3 (EHB 2021). Adding now the anticipated H2 production costs for Morocco in 2030[10] of USD 2.5/Kg H2 this would yield to delivery costs **USD 2.64/Kg NH3** (re-purposed pipeline) and **USD 3.24/kg NH3** (ship).

Comparison: Delivery Costs 2030: NH3 Imports to Europe. Assessment based on provided data.

Chile	Morocco	Algeria
Ship: USD 2.5/Kg	Ship: USD 3.24/kg Pipeline: USD 2.64/kg	Ship: USD 3.26/kg Pipeline: USD 2.75/kg

When it comes to transport, and the European Union considered as hydrogen demanding export market, Morocco, and Algeria surprisingly do not benefit from its distances. For Chile export costs are expected to be lower than its North African competitors.

[10] Estimated production costs for Morocco by 2030 are anticipated to be between USD 2-3/Kg H2 (Ministerio de Energia, InvestChile, and CORFO, n.d.). For simplicity the mean of USD 2.5/Kg H2 is taken

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H2 transport: Balancing economic efficiency with geopolitical realities

The debate over the optimal method for transporting hydrogen – via ship or pipeline – is interesting, especially when discussing economic efficiency with geoeconomic considerations. While the economic argument often favors pipeline transport for its cost-effectiveness, especially for short distances, geopolitical risks associated with pipelines raise relevant questions about overall viability. So, it is necessary to dissect both economic and geoeconomic factors to provide a nuanced understanding of this critical decision-making process.

First of all, pipelines allow economies of scale (Molnar 2022), offering large volumes of hydrogen to be transported over long distances at relatively low costs per unit. Secondly, once pipelines are established, their operational costs tend to be lower compared to alternative modes of transport, like shipping (Weihs, Kumar, and Wiley 2014). Unlike ships, which require ongoing maintenance, fuel, and labor costs, pipelines have relatively fixed operational expenses. Moreover, generally a continuous and reliable means of transport is provided by pipelines, which minimizes disruptions and ensures a steady hydrogen flow to demanding countries. This assumption however only remains valid until no political actor decides to conduct an attack on such critical infrastructure. Then the ships suddenly gain importance again, as they can circumvent such hazardous zones.

Therefore, the economic argument in favor of pipeline transport must be balanced against geoeconomic realities. As Europe witnessed in 2022 with the attack on the North-Stream Pipelines (Schürpf et al. 2024), pipelines are vulnerable to disruptions caused by geopolitical tensions, including sabotage attacks, which have far-reaching consequences for supply reliability and energy security. Pipelines passing through cross border politically unstable regions or areas prone to conflicts face increased risks of disruption. Moreover, the pipeline structure is rather centralized, which increases negative consequences, as a single disruption leads to major damages along hydrogen supply chain. Shipping routes on the other hand are rather decentralized where multiple vessels and ports offer resilience in the face of disruptions. Algeria serves as good example in this regard. Politically unstable itself on the on hand, it also plans to export hydrogen to Europe via Tunesia, another country characterized by political and social turmoil (Dokso 2023; Carbonaro 2023). So, pipeline´s susceptibility to geopolitical disruptions highlights the need for diversified transport options.

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Bilateral Factors

It is safe to say, that bilateral relations between future H2 exporting markets and the EU, as an importing partner, are essential for enabling and facilitating both trade and investment regarding hydrogen. As the data provided indicate all three countries have modest to increased trade ongoing with the EU.

Chile, despite being on the other side of this globe, pursues strong economic ties with the EU, with remarkable imports and exports on the one side, but also foreign direct investment flows on the other sides. EU´s FDI in Chile with a volume of 64.9 billion Euros is by far the highest compared to the other countries. This dynamic is underpinned by the fact that, as of 2022, the European Union has been Chile´s third biggest trading partner (European Union 2023). Beside trade related agreements with the European Union (EEAS 2023), Chile also does approach direct partnership with individual EU Member States, amongst other including Germany and The Netherlands (Bnamericas 2024; Chilean Government 2022). Chile might benefit from strong economic ties with the EU, as put forward by representative advanced flows, covering both trade and investment. Chile adopted its national green hydrogen strategy in 2020 and set out the goal to become the global leader of green hydrogen export by 2040. Additionally, Chile has the potential exceed its domestic renewable energy demand by 70 times and therefore could also support to meet significant shares or Europe’s demand (GH2, n.d.-a). This positions Chile as a reliable trading partner for the EU in the future global hydrogen market.

Morocco and Algeria also enjoy economic relations with the EU, albeit to varying degrees (European Union, n.d.). Morocco's rather stable governance make it an attractive trading partner for hydrogen and investment. Out of all three other countries Morocco imports the most from the EU with a volume of 33 billion euros. However, FDI flows are significantly lower compared to Chile. Like the Chilean government, Morocco also uses direct trading channels with EU member states. This includes amongst others direct collaborations with Germany, Belgium and Spain (The North Africa Post 2024; Enterprise 2024; 2023). Similar to Chile, Morocco has outlined ambitious trade related hydrogen targets, as they account for 10 TWh for the export market by 2030, which makes them attractive for the EU (GH2, n.d.-b)

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Algeria, having the highest export volume to the EU amongst the three selected countries (35.4 billion euros in 2023), but the lowest inward FDI from the EU. It has also set up various frameworks for future export. Via a joint task force, together with Germany it already has laid the groundwork for a future hydrogen flow up (Kurmayer 2024). When it comes to future hydrogen trade, Algeria is also quite attractive due to its presented targets in the national hydrogen roadmap. As of 2040 the North African country wants to produce and export 30-40 TWh of liquid and gaseous H2 derivatives (Collins 2023a), which is around 1 million tons H2[11]. Therefore, based on its significant export potential Algeria already reached to out to Europe and offered 10 percent of its clean hydrogen domestic demand. However, Algeria faces political difficulties which could have the potential to jeopardize bilateral relations, despite abundant resources in the field of renewable energy.

Own assessment based on provided data: Bilateral Factors

Chile	Morocco	Algeria

Hidden risk: Water stress for Morocco and Algeria

In examining the viability of hydrogen production, it's crucial not only to consider diversification but also to assess the sustainability and reliability of water sources. Unlike many other processes, water electrolysis consumes water instead of recycling it, posing unique challenges. Surprisingly only little literature is available in this regard. However, looking ahead to 2040, projections from the World Resources Institute indicate that regions with significant potential for green hydrogen, particularly those leveraging solar-based methods, are already grappling with water scarcity. This highlights the imperative of managing water resources judiciously to ensure that hydrogen production does not further strain already-stressed water supplies (Kuzma, Saccoccia, and Chertock 2023; Franzmann et al. 2023).

The production of green hydrogen is directly linked with the consumption of approximately 9 liters water per kg hydrogen (Hydrogen Europe 2020). The water needed

[11] 33 TWh corresponds to a million tons H2 (Collins 2023a)

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solely for hydrogen production in regions with high or extreme water risks exceeds Europe's (EU's) total water withdrawal in 2019 by over 1.8 times (Franzmann et al. 2023).

Remaining with the selected countries both Morocco and Algeria already do have to deal with severe water issues. This is clearly indicated by the presented values which were evaluated through the latest version of the Aqueduct Risk Atlas by the World Resource Institute, representing water stress. Algeria and Morocco already have concerning high-water stress values: Morocco having 60-80 percent, while Algeria has already reached the highest level, with more than 80 percent [12]. Additionally both countries have experienced a negative development in recent years and it is expected to remain, as estimations indicate that Morocco will reach extremely high waters stress levels in 2050 (Kuzma, Saccoccia, and Chertock 2023). Regarding Chile, however it is important to note, that due to the Atacama Dessert the overall statistic might be distorted, as the northern part also faces extremely high-water risks. Chile´s south experiences less water stress. So, upon initial examination, the challenge of achieving large-scale, cost-competitive clean hydrogen production appears to be rooted in the fact that the lowest levelized cost of hydrogen can typically only be attained in regions abundant in sunlight yet lacking in water resources.

According to Hydrogen Europe this problem can be effectively addressed with a relatively minor investment by incorporating desalination plants at the electrolysis sites to alleviate water stress. The expense of water desalination amounts to approximately 0.8 EUR/m3 water, thereby adding a mere 0.007 EUR/kg to the total hydrogen production cost (Hydrogen Europe 2020).

Nevertheless, out of a geoeconomic and geostrategic perspective the EU must take, those circumstances might have great risk potential due to enhanced water stress levels which result through water intensive electrolysis. Algeria and Morocco could therefore face considerable problems in the coming decades if the water stress rate maintains the dynamics, which unfortunately can be assumed due to climatic change. In the future, both countries could be forced to use their water resources more efficiently to meet not only the domestic demand for electrolysis, but also the basic needs of the population. If no trend reversal can be achieved, hydrogen trade with Morocco and Algeria would also face

[12] Water stress: "A country facing **extreme water stress** means it is using at least 80% of its available supply" (Kuzma, Saccoccia, and Chertock 2023).

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major challenges, as hydrogen production for exports may face shortages. When assessing the potentials and opportunities for hydrogen imports from these countries, the sustainable use of water resources must therefore be taken into account in addition to renewable energy resources, political and economic developments.

Own assessment on provided data: Water Stress

Chile	Morocco	Algeria

<u>Geoeconomic Analysis and Limitations of Traditional Economic Principles</u>

Traditional economic models, such as David Riccardo´s comparative advantage may apply in theory however might also face some limitations especially when it comes to geopolitical tensions which cause **friction**. While current representative data does not imply any future conflicts with Chile and Morocco, Algeria pose a risk to European hydrogen trade and investment.

Bilateral relations can be undermined by geopolitical tensions as supply chains are easily disrupted or even the announcement can result in short-term supply shortages. This means that increased political instability and bad governance in exporting countries indirectly affects importing countries as they are reliant on continuous exports, like the EU. These dynamics have been seen in the last couple of years and there are no indications that those dynamics will we put aside soon. Therefore, it can be argued that David Riccardos trade theory may not fully account for the geopolitical complexities and their consequences for trade and hence do not apply to certain countries as for Algeria when it comes to future hydrogen trade. Besides worsening political indicators of Algeria, both North African Countries will have to deal with severe water scarcity levels, as they already have high and extremely high levels of water stress. This in turn has also the potential to undermine hydrogen trade relations with the EU as electrolysis consumes high amounts of water.

Therefore, out of all three selected countries Chile holds tops spot in all categories which have been scrutinized. Surprisingly, besides having lowest production costs, also delivery costs have trumped both North African countries. Backed with good governance and economic strength, the EU is recommended to intensify relations with Chile when it comes to future hydrogen trade. Out of both North African countries, the EU should focus

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more on Morocco, despite the fact NH3 delivery might be cheaper from Algeria as calculations illustrate. However, trading with a country which is reflecting values of democracy and freedom similar to the EU, should also be determinants in the price structure. As the energy crisis in Europe has shown impressively economic and policy profiles should play critical roles in determining the attractiveness of each country as a potential hydrogen supplier.

Overall assessment: Based on provided data

Indicators	Chile	Morocco	Algeria
Production Costs			
Economic and Political Factors			
Delivery Costs			
Bilateral Factors			
Water Stress			
Geoeconomic Analysis: Result Decisive: Economic and Political Factors			

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4.7. CASE STUDY: FUTURE IRON AND STEEL PRODUCTION

The following a little case study has been conducted which should serve as an example, which illustrates the potential of hydrogen with regards to reshaping trade patterns, as major industries are affected by the climate transition. As Europe grapples with the challenges of the green transition, particularly in its steel industry, the question arises, if importing steel from countries with lower production costs for hydrogen might be a more viable option. This analysis explores the arguments for and against both scenarios, evaluates their implications, and includes geoeconomic considerations, again with also including David Ricardo's theory of comparative advantage.

Recent studies by PIK[13] and IRENA highlight the potential for significant cost savings in energy-intensive industries. Specifically, importing green steel from green hydrogen could lead to savings of up to **20** percent. This is also because an electricity-price disparity of 40 EUR/MWh between renewable-scarce industrial production sites, e.g. Germany, and favorable locations, e.g. Australia or Chile, is expected by 2040. Steel producers, as the VOEST in Austria or Thyssenkrupp in Germany, have outlined plans to replace blast furnaces with a process called *direct reduction* using green hydrogen (VOEST 2022; ThyssenKrupp, n.d.). Given Australia's status as a major supplier of iron ore and its potential to become a significant producer of green hydrogen through electrolysis IRENA suggests that Australia should handle the DRI process and only export the resulting pre-steel product, sponge iron, to European countries (Verpoort et al. 2024; Durrant et al. 2020).

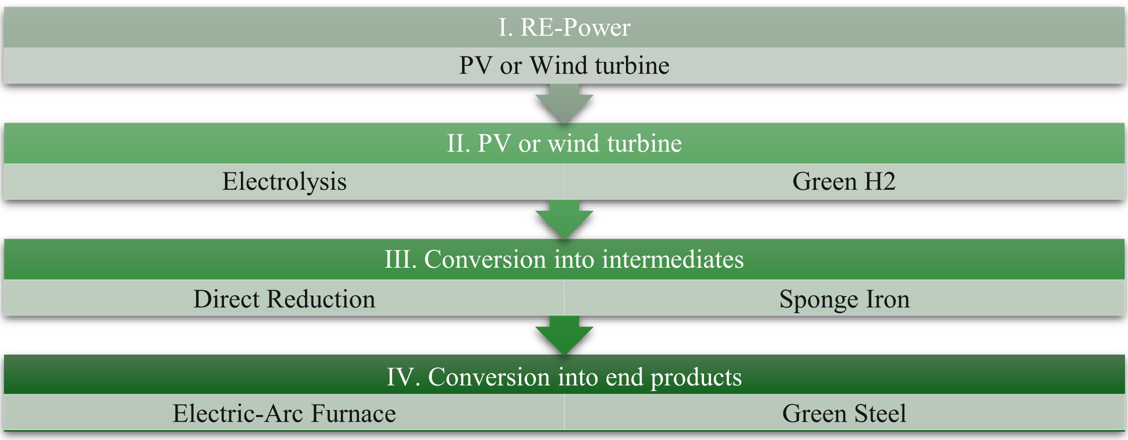

Figure 21: Value Chain of Green Steel. Own illustration based on Verpoort et al. 2024

[13] Potsdam Institute for Climate Impact Research (PIK)

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Iron and Steel production (Wirtschaftsvereinigung Stahl 2020a)

Traditional iron and steel production involves the use of blast furnaces, which are fueled by coke to convert iron ore into pig iron, however releasing significant CO2 emissions. Decarbonizing methods aim to reduce/eliminate these emissions by using alternative processes such as the DRI-EAF Method.

Direct Reduction (DRI): Involves using natural gas or hydrogen to directly reduce iron ore into sponge iron, bypassing the need for coke. This process emits less (natural gas), or no (hydrogen) CO2 compared to traditional methods.

Electric Arc Furnace (EAF): Utilizes electricity to melt scrap steel, reducing the reliance on coke as a fuel source. EAFs can be powered by renewable energy sources, further reducing emissions.

However, this industry shift would have to deal with social and economic challenges. Especially, Germany's specialization in high-tech steel production for industries like automotive manufacturing has been a cornerstone of its economic strength. However, with over 70% of global steel production still relying on traditional blast furnace methods (Wirtschaftsvereinigung Stahl 2020b), and therefore the transition towards climate neutrality poses a significant challenge for the industry.

Table 2. Relevant data regarding Europe´s steel industry. Own illustration

Relevant data regarding Europe´s steel industry	Data	Resource
Direct employment 2022 in K	306	Statista 2024
Value added 2019 in B EUR	83	McKinsey & Company
Share of GDP in percent in %	9	McKinsey & Company
Exports of finished steel products in M tons 2021	19,40	EUROFER 2022
Steel Imports of finished steel products in M tons 2021	30,3	EUROFER 2022
Dependencies of external markets in %	35,9	Own calculation based on imports & exports

In the wake of the current global geopolitical situation, it may sound incomprehensible that, on the one hand, that Europe aims for more resilience and more autonomy, but on the other hand, fails to recognize that its steel industry is of immense importance for its resilience. The pandemic and Ukraine War have exposed the vulnerabilities of global supply chains and have also revealed negative dependencies. The steel industry is almost the basis for every value chain, as in Germany, two-thirds of exports are steel-intensive (Wirtschaftsvereinigung Stahl 2024).

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On the other hand, the conventional European steel production is already suffering under current conditions. This is primarily due to low-cost steel from China, falling prices and increased raw material and energy costs, according to the Ifo Institute[14] in 2018 (Döhrn et al. 2018). In 2020, the German Steel Association concluded that an increase in the CO2 price in Germany would result in a massive drop in production by 35 percent. This would lead to a loss of 200.000 jobs and would decrease in value added by 114 billion euros (Wirtschaftsdienst 2020). This could further impact the competitiveness of European steel manufacturers in the global market, leading to reduced market share and profitability.

Europe´s steel production has ever since been a major driver of economic growth. This not only created jobs and added value, but also created an industrial base that enabled Europe to become competitive in the international market. In 2022, 306.000 people were employed in the steel sector, while the European steel industry was responsible for a value added of 83 billion euros in 2019. This, in turn, accounted for 9 percent of Europe's GDP (Statista 2024a; McKinsey & Company 2021).

A relevant consideration in the field of geoeconomics is the question of dependencies. Although Europe has a significant production capacity, it is already dependent on significant imports of steel products. Exports in 2021 of around 19 million tons of steel products were offset by around 30 million tons of imports necessary to meet demand (EUROFER 2022), yielding to a dependency of approximately 36 percent. On the one hand, imports reduce the risk of shortages in the European market and can support the European consumer through lower prices, however trade conflicts and geopolitical tensions, pose a threat to supply security. Moving the steel production to Australia as they have comparative advantage in green steel production, could therefore further increase dependencies which might lead to serious economic but also social difficulties.

Furthermore, also regarding the climate goals a European (green) steel industry is essential. To achieve the energy transitions globally it is calculated that almost 5 billion tons of steel is needed, which accounts for 75 percent of total material requirement (Energy Transition Commission 2023). The most powerful onshore wind turbines require almost 1000 tons of steel per MW of capacity, "*No electricity without steel*" (VOEST 2024).

[14] Leibniz Institute for Economic Research at the University of Munich e.V.

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Also, it is important to remember that those studies regarding future steel production are only projections. In the wake of geopolitical turmoil, accurate estimates are hard to make. Steel supply will have to be always guaranteed, which is why Europe must keep steel manufactures to absorb supply disruptions. Besides comparative advantages of other regions, there is a major benefit Europe has. Knowledge, an asset which dates back decades. This should not be underestimated and shall be seen as a chance to gain strength in this economic challenging times.

To sum up, from geostrategic viewpoints it might seem as and additional and avoidable risk to outsource specific parts of Europe´s steel industry. Especially Australia has not only to deal with long transport routes, but also the need to pass certain chokepoints like the Suez Canal. The happenings of the ran aground container ship *Ever Given* in 2021 and the attacks in the Red-Sea of the Iran-backed Houthi rebels in 2024 serve as unprecedented examples of today's risks to supply chains. The latter, according to *Reuters* has led to a drop of more than 45 percent regarding commercial traffic in just two months (Blenkinsop 2024). Hence, the need for maintaining domestic steel production might be seen as important to secure Europe´s supply chain security, particularly in times of geopolitical uncertainty or trade disputes.

Economic policy aspects of the hydrogen market

A hydrogen economy will require some sort of government intervention due to the current disparity between private and societal benefits of green hydrogen. Currently grey products are cheaper in production. So, processes and products based on green hydrogen are not competitive in the international market, although they bring significant societal benefits due a considerable reduction of greenhouse gas emissions. Therefore, it is important that strategies are carried out to answer the question how the market for green steel can be established After all, the production of green steel will compete with the prices of conventional steel during a transitional phase and will have a technical disadvantage in terms of costs. To keep this bridging period as short as possible, the use of certain policy instruments is being considered:

<u>Carbon Contracts for Difference - CCfDs</u>

CCfDs could help to eliminate the price disadvantage of hydrogen technologies, as the agreement involves the government and investing companies, with the European emissions trading system serving as a reference point. CCfDs ensure a price differential,

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supporting emission reduction initiatives like hydrogen steel production. Initially, the government subsidizes projects if the contract price exceeds the CO2 price, but companies must reimburse any excess if CO2 prices surpass the contract price (V. J. C. Richstein and Neuhoff 2019). Moreover, CCfDs offer a significant advantage by reducing the financing costs of investments in climate-friendly products and processes. This makes investments in clean technologies profitable even when CO2 prices are low (J. C. Richstein 2017). By stabilizing revenue streams from fluctuating CO2 prices, investors can secure loans and lower financing costs (Helm and Hepburn 2005).

One big disadvantage of CCfDs is that since the associated risks are covered by the state, the individual company does not have the incentive to drive for innovative and cost-efficient solution anymore. Should the risk become real, the cost have to be absorbed by the tax payer (BMWK 2022).

Green Lead Markets

Another form policy intervention is the establishment of Green Lead Markets. The main goal is to generate new sales markets for green products, in case of steel products they are called green premiums (Urban and Zaccaro 2024). Hence Green Lead Markets differ from CCfDs as they do not promote the supply of green products, but rather the demand for them.

How are such sales markets generated? By means of green lead markets, the state can commit itself to demand only steel products that contain a fixed amount of green steel, however, taxpayers will be charged with the costs of climate-neutral production. This is to be avoided when the state e.g. prescribes that cars have be produced entirely from green steel, and the resulting additional costs are charged to the buyer, i.e. the "polluter". This would ease the burden on taxpayers and comply with the polluter-pays principle (BMWK 2022). Another incentive that can be set through Green Lead Markets are preferential treatment that can be granted to producers or buyers in the event of a decision in favor of green steel (BMWK 2022).

However, a disadvantage is the fact that considerable uncertainties regarding the costs could arise. This is primarily because steel companies must conclude long-term contracts even before new steel production facilities have been constructed and certain price developments for specific goods cannot yet be estimated. In addition, there may be some uncertainty when the duration of Green Lead Markets is not known, as this can be decisive

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for investment decisions. Also, market intervention in this form could only succeed at the European level, which furthermore requires universal definition of green steel (BMWK 2022; Urban and Zaccaro 2024).

On the other hand, Green Lead Markets have the effect, especially in steel production, that the additional costs measured against the end-product prices are rather low compared to other industries but are likely to have a great impact in terms of CO2 reduction. If a mid-size car is taken as an example, the use of green steel saves about a quarter of the total emissions (in production) (Wirtschaftsvereinigung Stahl 2022).

To conclude this chapter, Green Lead Markets are likely to be the more successful instrument to reach climate neutral production and therefore trump CCfDs. This is because they do not interfere with production processes and remain open to new technologies. Moreover, it is possible to apply the polluter pays principle, as the costs are automatically by the consumer and not the taxpayer.

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5. Findings and recommendations

5.1. Findings

Hydrogen has regained prominence as it is seen to play a pivotal role in the energy transition. Being discovered in the 16th century by Phillip von Hohenheim and named the "coal of the future" by Jules Verne in 1874, it has found itself assigned with key technologies for the decarbonization of the hard-to-abate sectors in the European Hydrogen Strategy and REPowerEU Plan.

Especially green hydrogen and its derivatives like green ammonia stand as beacon of hope, as they are produced with green electricity from renewable energy source like wind and solar power. However, the production costs of green hydrogen are still high, giving alternative production methods like grey and blue a competitive edge in pricing. This price disparity is expected to be offset in the future as costs for green electricity will decrease. By 2030 the cost for green hydrogen will be around USD 1.3 in the most favored regions. This will put green hydrogen in a competitive position with blue and grey hydrogen. It will be important however to use blue hydrogen as a transition technology using CCS and taking advantage of reduced costs.

Demand is expected to increase drastically on European and global level, which is mainly due heightened H2 demand in the industry and transport sector. This will result in an estimated trade volume of 150 Mt H2 globally, which would account for one third of global hydrogen demand. This raises the question after the most suitable transport method for H2 and its derivatives. Short distances up to approximately 8.000 kilometers favor pipeline transport, however when it comes to longer distances transport by ship is recommended However it is important to distinguish between new and repurposed pipelines since their construction costs influence the transport distance in terms of cost-effectiveness compared to shipping. Liquid hydrogen is the costliest due to energy-intensive liquefaction. LOHCs and NH3 shipping have similar costs, but LOHCs are less mature, and only attractive for short distances. The big advantage of NH3 transport is the already existing infrastructure regarding ports and ships. However, besides considerations regarding cost-effectiveness, geostrategic aspects also must be accounted, as especially pipelines bear the risk of becoming a weaponized tool.

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The global hydrogen market will be determined by supply and demand, however also the coordination of various aspects, involving production, storage, transportation, and the final application. The infrastructure poses a significant challenge. For Europe the European Hydrogen Backbone is essential as it will enable a hydrogen-based value chain throughout Europe. However, this project is expected to make its biggest advancements in 2030, the year the EU already plans to produce and import 20 Mt renewable hydrogen.

There are significant differences to the present oil and gas market, when compared with the emerging hydrogen market. Hydrogen is not extracted, is it manufactured through electrolysis, meaning it is possible to produce at any place, however some countries have more favorable conditions. This yields to the perception that future power over hydrogen trade is limited as it is more distributed and not as concentrated as in the oil market (OPEC). This will also lead to more a competitive price setting as the number of suppliers will be higher.

Low production costs are also essential for the global hydrogen market, as low-cost production will only be possible in certain countries. Transport costs, including the transport mode and the form of hydrogen, is another crucial factor. Those are especially relevant for the European Union it is planned to import 10 Mt hydrogen. Two pricing models, netback and import parity have been presented as they are possible for future hydrogen price mechanism, as both have been used in the oil and gas market.

Despite having a clear hydrogen strategy, the EU must secure international competitiveness regarding hydrogen technologies. China already is the leader in grey hydrogen production, and by 2023 it owned half of the world´s available electrolysis capacity for green hydrogen. The US has offered significant benefits for companies regarding investments and production of renewable hydrogen originating from the US Inflation Reduction Act. The European Union needs local investment for financing its green transition and therefore must avoid further overseas migration of companies.

Morocco and Algeria, being considered as future hydrogen and hydrogen derivative trade partners for the EU, are benefiting from significant low-cost green hydrogen production potential and already announced high level hydrogen production and export plans. However, both countries are dealing with increased water stress levels and those are expected to worsen in the future even more. This represents a major threat regarding hydrogen supply for Europe in the future. Chile on the other hand might reveal itself as

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potent future trading partner as the case study yielded high levels of political and economic freedom paired with low hydrogen production and delivery costs.

The iron and steel industry has proven to be the backbone of Europe´s economy in the last decades, however, is now facing the risk of migrating to other regions of this world. Hydrogen being the pivotal element for green steel can be produced at lower costs in e.g. Australia which furthermore has high amounts of iron ore. Letting this industry migrate to remote areas will increase the Europe´s dependency on foreign markets and would stand in contrast to its open strategic autonomy. Carbon Contracts for Difference and Green Lead Markets might be economic policy instruments which could help to support Europe´s green products involving hydrogen and its derivatives, like green steel. In particular Green Lead Markets are expected to be most effective as they do not interfere with production decisions of the producing companies and do not require the taxpayer to absorb the risks.

Limitations

In the following limitations of a holistic approach are discussed. As mentioned in the beginning, holistic approaches most of the time consider multiple aspects of a general topic, as in this case hydrogen. However, this complexity may lead to difficulties in determining exact causes and consequences for specific topics. Hence, by including a variety of different aspects, there is the risk of lacking focus on specific areas. This can lead to circumstances where certain elements are overemphasized, while at the same time others are overlooked. In this Master Thesis especially the societal aspects were not evaluated. Hydrogen trade will demand new infrastructure, from production facilities to new pipelines and distribution centers. This is certainly a field of further research as the green transition also depends on societal acceptance. It might be also obvious that holistic approaches face challenges when it comes to effectiveness measurements, however this becomes more difficult when it is dealt with interdependent and interconnected fields and elements. Geoeconomics in general can be seen as the study encompassing international economic and political aspects of resources in the temporal and spatial dimension. This in turn is also the reason why this holistic approach was initially chosen and why it is well suited.

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5.2. ECONOMIC POLICY RECOMMENDATIONS

1. The EU should ensure that those European regions with cheap hydrogen production are financially supported to fully exploit their potential. Also, a limitation of hydrogen usage to the so-called hard-to-electrify sectors seems meaningful, especially for those countries with less production capacities. Especially in the beginning, this will lead to reduced supply risks, and will also enable targeted use of hydrogen and its derivatives in certain industries (Quitzow et al. 2023). In other sectors, such as heating, further technologies, such as heat pumps, should be used.
2. In addition to the development of transport and storage infrastructure, special focus should also be laid on technologies such as CCS (Pepe, Ansari, and Gehrung 2023). Blue hydrogen will likely offer a transitional technology but will still be necessary to allow the green hydrogen economy to develop. This back-up technology could also become more important, especially if there are delays in the establishment of the green hydrogen economy.
3. An important aspect of the future hydrogen economy will be to identify new dependencies at an early stage, to always monitor them intensively and, if possible, to reduce them to a minimum without risking supply shortages. However, it is particularly important here that Europe is always aware of the geopolitical situation and that negative dependencies are also priced into hydrogen trading. According to the motto: Europe cannot afford cheap imports in the long run.
4. In addition to CCS plants, electrolysis in particular plays an essential role, without which no green hydrogen can be produced. The EU has already lost track with China regarding electrolysis capacity. To catch up, the rare earths required for this, such as nickel or platinum, should therefore become part of extensive recycling programs and central trading elements of new free trade agreements. The EU's strategic partnership with the ASEAN states, which was intensified in 2022, could offer itself as an opportunity here (Bundeskanzleramt 2022).
5. The European Union must devote itself to a target-oriented import policy. There are various strategies such as the REPowerEU plan which envisage 50 percent hydrogen imports to meet demand in 2030 and strategic MoUs with various countries such as Chile or Algeria, but those are not legally binding agreements.

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Europe will be dependent on hydrogen imports and should therefore design a more in-depth import strategy to avoid supply gaps in the future. However, when hydrogen trade will eventually accelerate, as the green transition demands it, the EU must act cautiously when it comes to select suitable trading partners! Morocco and Algeria are both considered as future H2 import countries, however both face enormous risk regarding water stress, with the latter additionally dealing with political turmoil and worsening rule of law.

6. It will also be important not to experience competitive disadvantages through overregulation. With its US Inflation Reduction Act, the USA has shown how tax programs based on subsidies have an attractive effect on investors. The migration of many European companies to the various regions of the USA has already begun due to high energy prices (Zachová 2023). Hydrogen and the entire Clean Tec sector offer an opportunity for a trend reversal here. But Europe must also use this opportunity to stop this development and initiate a turning point.
7. The European steel sector is facing enormous challenges due to geopolitical circumstances and the transformation of the industry. Important regulatory support measures are needed here to protect Europe from the steel industry from leaving. Measures such as the CBAM were a successful start, but the introduction of Green Lead Markets should also be pushed forward to guarantee sales markets for companies.

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6. SUMMARY

Hydrogen, especially green H2, is regaining attention, after it´s hypes have repeatedly subsided throughout history. However, the large-scale technical use in a variety of industries, combined with the realistic hope that green hydrogen can be produced at competitive costs in the future, like its counterpart grey H2, makes it possible to assume that this time the hydrogen euphoria came to stay. Noteworthy here are the industries in the field of iron and steel production, fertilizer production and transport, especially climate-neutral shipping. Apart from the technical and environmental advantages that hydrogen brings there are also enormous risks to be considered that have received too little echo in previous literature and political decisions. Although there are ambitious plans such as REPowerEU or a European Hydrogen Strategy, geoeconomic aspects have to play bigger role. The number of supply chain bottlenecks and supply difficulties have increased significantly in recent years due to crises, leading to strategic realignments, including within the EU. As far as hydrogen is concerned, it should be noted that new advantages and new disadvantages will arise if you compare them with energies from the fossil age. Oil and gas resources, in particular, were trapped in the power of a few states due to their geographical concentration, and the resulting dependencies deepened over decades. With hydrogen, there is justified hope for the EU to gradually escape these dependencies and establish new trade relations. But also, as far as hydrogen trading is concerned, it can be assumed that new dependencies will arise due to the amount that the EU will need in the next few decades to achieve its climate targets. These are likely to be more complex on the one hand, but more diversified on the other, and could therefore create geopolitical advantages compared to oil and gas imports of the past decades. Nevertheless, caution is recommended regarding those countries Europe selects for hydrogen trading in the future. The case study, encompassing Algeria, Morocco, and Chile, shows that not only the most cost-effective option should be used, but also that dependencies with weakening democratic states also have a price. This has been demonstrated by Russia, and the EU must act cautiously when it comes to future hydrogen trade with Algeria. Also, hydrogen has the potential to pose new challenges for entire industries. Europe´s steel industry a reallocation of its production facilities should be prevented, and new dependencies avoided. However, this is only possible through certain measures. The establishment of Green Lead Markets as economic policy measures is essential to achieve green sales markets and reach price competitiveness with grey steal.

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ANNEX

Interview I

Mag. Drazen Maloca, Austrian commercial Attaché,

Advantage Austria Santiago de Chile, Chile

Mag. Drazen Maloca represents the interests of the Austrian economy in Santiago de Chile. In addition, he serves same function in the countries of Peru and Bolivia. His immediate tasks are as follows (WKO 2024b):

- Individual advice for Austrian companies on market entry, market development, and all matters relating to internationalization,
- Market information, reports, customs law and standards
- Organization of events and trade fairs
- Networking of Austrian companies locally

I would like to thank him and his team for taking the time to answer the questions.

This interview was conducted in written form and in English. The following questions were answered in Santago de Chile and send back via email on the 20th of March 2024.

In the following the questionnaire with the answered questions is presented.

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1. **Can you provide an overview of Chile's current stance on green hydrogen development and its strategic importance in the country's energy agenda?**

   Chile has made the development of the Green Hydrogen Industry a national priority. Due to this, it published a national hydrogen strategy. Among the goals stated in this strategy is that the country strives to provide the world's cheapest green hydrogen by 2030 with an approximate cost of 1,5 USD / kg and to become the world's leading green hydrogen exporter by 2040. You can download a summary here:
   https://energia.gob.cl/sites/default/files/national_green_hydrogen_strategy_-_chile.pdf
   Chile also recently took the next step and developed an Action Plan with input from the country's citizenry. This doesn't seem to be available to the public yet, but you can download the working document for the participants here (Spanish):
   https://energia.gob.cl/sites/default/files/documentos/plan-h2v-consulta.pdf
   Chile has understood that it can play a big role in the energy transition plans of the industrialized nations and is poised to use its unique geography as well as political stability to become the number one trading partner to the countries of the western hemisphere. Chile is also trying to diversify their export portfolio by developing this industry and make it less dependent on their main export copper and its derivates.

2. **What specific projects or initiatives has Chile undertaken to promote the production and use of green hydrogen?**

   Apart from the development of the strategy and the action plan, there are programs to incentivize the development of GH2 projects. However, it should be noted that most of the funds provided for these programs are not coming out of the pocket of the Chilean government, but rather from the coffers of international institutions such as the World Bank, the Inter-American Development Bank, the German KfW, as well as from some state and interstate organisms that have a stake in Chile's development in this sector, such as the European Union and the German government though organizations such as the GiZ. However, most of the funds are being bundled and managed by the Chilean agency for economic development Corfo, which is also in charge of publishing and executing tenders. More Info here: https://www.hydrogeninsight.com/policy/chile-unveils-728m-fund-to-de-risk-green-hydrogen-projects-backed-by-european-and-us-banks/2-1-1466607

A few programs worth mentioning here is the H2-Upp Program for early stage programs as well as the RH2 program for more developed projects. Both programs are being carried out by the GiZ. The RH2 program is (at least partially) funded by the Team Europe Initiative (TEI) with funds from the EU.

3. **How does Chile perceive the strategic alignment of its green hydrogen initiatives with the economic goals and priorities of the EU?**

   I think it is fair to say that Chile's entire GH2 strategy has been based on the EU's economic and climate goals. Many European delegations have been incentivized to visit Chile, moreover, Chile has already signed agreements with the ports of Antwerp, Rotterdam and Hamburg. There is a close collaboration between the Chilean government and local GiZ branch office to also make sure that the green hydrogen will be in compliance with the EUs regulations.

4. **From a geoeconomic standpoint, what specific economic benefits does Chile anticipate from fostering partnerships with the EU in the green hydrogen sector?**

   Chile is looking to position itself as a reliable trading partner for the EU. Just recently, Chile signed the Advanced Framework Agreement, which is hailed to be the most progressive of trade agreements that the EU has made with any partner country so far. This goes to show how much importance Chile places on its relationship with the EU. I think one can make the point that especially since Russia's invasion of Ukraine, Chile has placed an emphasis of being one of the most economically and politically stable countries in South America (while South America as a whole is currently becoming more popular for investors) as well as being a "likeminded state" that upholds democratic values as much as the EU does. From a more economic standpoint, Chile hopes to not only secure long term supply agreements of Green Hydrogen with the EU, but also of other export goods, such as copper and soon also lithium. Moreover, Chile aims to attract more foreign direct investment from Europe as well as technology transfers. It is very likely that this focus on the EU is also Chile trying to make itself less dependent

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from the waning demand of its main trade partner China and therefore divest the risk of a potential shock, shall demand from China suddenly break in.

5. **How does the geoeconomic climate in Chile facilitate or hinder foreign investments, particularly from EU countries, in green hydrogen projects?**
   Chile has a clear geological advantage for the production of green hydrogen: an extremely long coastline (i.e. access to water for production and shipments), intense radiation for the production of PV energy in the norther Atacama Desert and very strong winds for the generation of wind energy in the southern Magallanes Region. It also benefits from successfully projecting the political will to develop this fledgling industry and therefore attracting international funding and foreign direct investment (Chile was among the first LATAM countries that drew up a Green Hydrogen Strategy). On the other hand, the fact that Chile is very far away from the EU puts it at a disadvantage vis a vis countries in Northern Africa or even EU countries like Spain that aim to produce their own green hydrogen. Talking to industry insiders, the famous "1,5 US-Dollar per kg hydrogen" has already widely been accepted as being a pipe dream. Moreover, there haven't been any presentable advances in planning the necessary infrastructure, the high level of bureaucracy has slowed down many projects to be (and scared off potential international investors) and it is still not clear how Chile will meet the growing demand for a workforce specialized in green hydrogen all along the value chain.

6. **In the context of geoeconomics, how does Chile plan to integrate its green hydrogen products into the broader regional and global energy markets, especially considering EU markets?**
   For now, Chile plans on exporting mainly Green Hydrogen itself and its derivates: Mostly green ammonia, but also green methanol and to a certain extent e-fuels. So far, there are no significant agreements with Chile's neighboring countries, chiefly because most of them are competing with Chile in producing this resource. However last year, Chile has signed an agreement with the European Union to secure their supply of Chilean green hydrogen and their derivates, while receiving funding for GH2 projects in return. Specifically about e-fuels: one of the very few already operating projects in this sector in Chile, is the pilot plant for e-fuels Haru

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Oni, operated by HIF. HIF is a conglomerate with participation by Porsche, that is the sole off-taker of the e-fuels produced in this plant. While Haru Oni is not an industrial scale plant, HIF is currently developing another e-fuel project that is, and is closing off-taker deals with, among others, European companies right now.

7. **What geoeconomic strategies has Chile implemented to encourage the transfer of green hydrogen technologies from the EU, and how does this contribute to economic development?**

   As mentioned in the previous paragraphs, Chile has struck many bilateral deals with the European Union (see point 6), as well as with private entities such as ports (see point 3) which will ensure reciprocity: Chile will supply the raw materials, Europe will grant access and provide funding.

8. **How does Chile approach geoeconomic risk management in the green hydrogen sector, considering factors such as market dynamics, geopolitical uncertainties, and investment risks?**

   For Chile developing the green hydrogen industry is a divestment in and of itself to mitigate the risk of being overly dependent on its main export, which is copper and its derivates (up to 45% of the country's total exports). Its strategy to hedge against price fluctuations in the green hydrogen market seems to be ramping up production on a massive scale to minimize the cost per kg as much as possible. In terms of geopolitical uncertainties, as mentioned before, Chile's main focus seems to be the EU as a target market for its green hydrogen and it strives to secure long term access to these markets through binding bilateral agreements. Nevertheless, it is very likely that Chile will also try to develop a second market in Asia, which is geographically closer than Europe which will give Chile a price advantage.

9. **Are there specific geoeconomic models or frameworks in place to encourage collaborative investments between Chilean and EU entities in green hydrogen projects?**

   The recently ratified Advanced Framework Agreement between the EU and Chile particularly mentions green hydrogen with Chile being the supplier and the EU buyer and investment partner in this context

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10. **How does the development of the green hydrogen sector impact Chile's trade balances, and what geoeconomic considerations are taken into account in this regard?**

    Since virtually the entire industry is still in the planning phase, it is a bit early to speculate on this. However, it is fair to assume that once the industry reaches a viable stage and domestic demand is met, Chile will transition from being a net importer of hydrogen and ammonia to a net exporter. Moreover, the local hydrogen production could significantly reduce Chile's dependance on natural gas imported mainly from Argentina. However, this will depend on technological developments and implementations, such as the proliferation of heat pumps which would reduce its dependence on gas powered heating overall (natural gas as well as GH2).

11. **From a geoeconomic perspective, how does Chile assess the potential regional economic impact of its green hydrogen initiatives, particularly in collaboration with the EU?**

    Chile has a lot riding on the successful execution of its national green hydrogen strategy, especially considering that most other countries in the region, specifically Brazil and Colombia, are directly competing with Chile and that the EU is dancing on more than one wedding by naturally also dealing with Chile's regional competitors.

12. **To what extent does the green hydrogen sector contribute to Chile's geoeconomic strategy for economic diversification, and how does this align with EU economic interests?**

    As mentioned above, one goal, albeit a secondary and not explicitly stated one, for Chile is to reduce its dependance on its main export good copper, as well as its main export partner China. This aligns with the EU's interests in two ways: first, with Chile they are securing a reliable and likeminded trade partner, this weakening China's influence in the region and second, if Chile delivers on its promises, the EU will have a reliable source of sustainably produced hydrogen helping them to reach their climate goals.

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13. **What financial instruments or incentives has Chile implemented to attract geoeconomically significant investments in green hydrogen, especially from European financiers or institutions?**

    Chile has implemented a number of programs (see point 2), however, it bears repeating that most the funds for these programs are not coming out of Chile's coffers, but from transnational banks and institutions, the EU as well as private equity funds.

14. **How does Chile position itself geoeconomically in the global competition for green hydrogen markets, and how does collaboration with the EU enhance its competitive edge?**

    Chile strives to become the world's leading and cheapest supplier of GH2 by 2040. This vision has occasionally been referred to Chile becoming the "Saudi Arabia of Green Hydrogen". Slow progress in regulatory reforms and infrastructure investments have dampened this enthusiasm a little bit. Nevertheless, Chile's political campaign still goes strong and it put Green Hydrogen on the agenda at its annual Chile Day Events in the UK, USA and recently also Canada, as well as established the Chile Green Hydrogen Day which took place for the 4th time in Germany (Hamburg and Duisburg) last year.

15. **From a geoeconomic standpoint, how does Chile plan to integrate itself into the green hydrogen value chain, considering both upstream and downstream activities, in collaboration with the EU?**

    So far the main focus is on upstream activities, i.e. the production of the raw hydrogen and its derivates for subsequent export (although the government is actively promoting domestic demand of GH2 through programs such as Aceleradora H2). There have been calls to seize the opportunity and develop a "downstream industry" alongside, such as fuel cell production. However, this has not gained much traction so far as it is unlikely that Chile will be able to compete with industry giants from the US, China and the EU on the merit of producing cheap hydrogen alone.

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16. **How does the geoeconomic perspective influence Chile's approach to job creation and skill development in the green hydrogen sector, especially in alignment with EU workforce considerations?**

    This is one of the biggest challenges that Chile will be facing the coming decades. The estimate is that by 2050 Chile will need more than a million skilled workers to run this industry. That's 5% of Chile's overall population today. This means that on the one hand, Chile needs to heavily lobby for future students to major in one of these fields, so they are available to this burgeoning industry in the medium term. This is an issue that the Spanish Agency for International Development Cooperation AECID is currently working on, as part of a mandate by the EU Global Gateway Initiative. However, Chile will also need to import a lot of these skilled workers, all this considering that immigration has already become a very contentious issue throughout the last couple of years due to mass immigration from Venezuela and other poverty stricken countries of the region. A challenge related to this is that most of the green hydrogen hubs will be located in areas with an un- or at least underdeveloped civil infrastructure. In the case of the Magallanes region, they will have to build a lot of new roads in order to be able to build the GH2 projects in the first place, and they will have to be on good terms with neighboring Argentina, because it is not possible to reach the Magallanes region overland without crossing into Argentina. Regional governor Jorge Flies recently said during a panel discussion that if they were relying on the current infrastructure, the road to Argentina would clog up for 5 straight years. Moreover, the Magallanes region will experience a massive influx of people, such as engineers, construction workers, and everybody providing ancillary services to a region of 165.000 people. To compare, Santiago has about 5,6 million people, 34 times more than the entire Magallanes region. The civil infrastructure will need to be bolstered in a massive way to prevent collapse.

17. **How does Chile engage in geoeconomic diplomacy to promote its green hydrogen agenda, particularly in building partnerships and collaborations with EU nations and entities?**

    See points 3, 4, 9 and 14

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Interview II

Dr. Albrecht Zimburg, Austrian comercial Attaché

Advantage Austria Casablanca, Morocco

Dr. Albrecht Zimburg represents the interests of the Austrian economy in Casablanca (WKO 2024a)

I would like to thank him for taking his time for the interview, which was hold in German via MS Teams on the 29th of February 2024.

In the following a transcript of this interview is presented.

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Frage: Herr Dr. Albrecht Zimburg, es gibt in der öffentlichen Meinung in Österreich den Eindruck, dass Wasserstoff das Allheilmittel für unsere Energieprobleme ist, besonders als Ersatz für russisches Gas. Welche Strategien verfolgt Österreich in Bezug auf Wasserstoff aus Nordafrika?

Dr. Albrecht Zimburg: Wasserstoff wird tatsächlich als wichtiger Bestandteil unserer zukünftigen Energieversorgung gesehen. Österreich hat eine Strategie entwickelt, um Wasserstoff aus Nordafrika zu importieren. Ein zentraler Punkt dieser Strategie ist Tunesien. Von dort führen mehrere Gasleitungen nach Italien, und eine dieser Leitungen könnte für Wasserstoff umgerüstet werden, um diesen dann nach Europa und schließlich nach Österreich zu transportieren. Dies ist die kürzeste und infrastrukturell am besten erschlossene Route.

Frage: Tunesien selbst wird aber nicht der Hauptproduzent von Wasserstoff sein, oder?

Dr. Albrecht Zimburg: Genau, Tunesien wäre in diesem Fall eher ein Hub. Die eigentliche Produktion könnte in Ländern wie Algerien stattfinden, die bereits großes Interesse an Wasserstoff gezeigt haben und über die notwendigen natürlichen Ressourcen verfügen. Algerien hat sowohl Erdgas als auch Potenzial für Wasserstoffproduktion. Es gibt aber politische und infrastrukturelle Herausforderungen, vor allem wegen der Spannungen zwischen Algerien und Marokko, die den Gasfluss zwischen diesen Ländern behindern.

Frage: Welche Länder könnten neben Algerien noch relevante Produzenten werden?

Dr. Albrecht Zimburg: Libyen und Ägypten könnten in der Zukunft auch bedeutende Rollen spielen. Aber beide Länder sind politisch instabil, was langfristige Energieprojekte schwierig macht. In Nordafrika ist Marokko das stabilste Land mit einer engen Verbindung zu Europa und einer positiven Einstellung gegenüber erneuerbaren Energien.

Frage: Marokko hat also großes Potenzial für die Produktion von grünem Wasserstoff?

Dr. Albrecht Zimburg: Ja, absolut. Marokko hat ideale Bedingungen für Solar- und Windenergie, insbesondere in der marokkanischen Westsahara, wo konstant starke Winde vom Atlantik wehen. Diese erneuerbaren Energiequellen sind entscheidend für die Produktion von grünem Wasserstoff. Marokko plant große Solarkraftwerke und Windparks, um diese Ressourcen zu nutzen.

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Frage: Es gibt aber noch viele Herausforderungen, besonders in Bezug auf die Infrastruktur, richtig?

Dr. Albrecht Zimburg: Genau. Eine der größten Herausforderungen ist der Transport des Wasserstoffs nach Europa. Derzeit gibt es Diskussionen über den Bau einer Pipeline von Marokko nach Spanien, aber das ist noch nicht finalisiert. Es gibt auch Pläne für eine Pipeline von Nigeria nach Marokko, das Gas transportieren soll, aber das dauert Jahre, bis es umgesetzt wird.

Frage: Wie sieht es mit der finanziellen Seite aus? Solche Projekte sind sicherlich sehr kostspielig.

Dr. Albrecht Zimburg: Die Finanzierung solcher Projekte ist komplex und erfordert massive Investitionen. Unternehmen wie die OCP in Marokko haben bereits eigene Projekte gestartet und verfügen über die nötigen Mittel. Für andere Projekte sind internationale Investoren notwendig, und Marokko arbeitet daran, die Rahmenbedingungen für solche Investitionen zu schaffen. Der Staat allein kann diese Kosten nicht tragen.

Frage: Wie sieht die langfristige Vision für Marokko in Bezug auf Wasserstoff aus?

Dr. Albrecht Zimburg: Marokko hat das Ziel, 8 % des weltweiten Wasserstoffmarkts zu bedienen. Sie haben eine Roadmap, um dieses Ziel zu erreichen, aber es gibt noch viele offene Fragen, wie z.B. die regulatorischen Rahmenbedingungen für ausländische Investoren und die genaue Verteilung der produzierten Energie zwischen Inland und Export.

Frage: Das klingt nach einem sehr ambitionierten Plan. Gibt es bereits konkrete Projekte oder Partnerschaften, die umgesetzt werden?

Dr. Albrecht Zimburg: Ja, es gibt bereits konkrete Projekte. Marokko besitzt die weltweitgrößten Phosphatvorkommen, welche von dem Unternehmen OCP abgebaut werden. Sie planen, ihren Wasserstoffbedarf selbst zu decken und grünen Wasserstoff für die Produktion von Ammoniak zu nutzen. Dieser grüne Wasserstoff wird dann entweder als Ammoniak exportiert oder zur Düngemittelproduktion im Land verwendet. Das ist ein Projekt, das bis 2027 abgeschlossen sein soll.

Frage: Und wie sieht es mit den politischen Beziehungen aus? Gibt es Hindernisse oder Konflikte, die die Zusammenarbeit erschweren könnten?

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Dr. Albrecht Zimburg: Politische Stabilität und gute Beziehungen sind in dieser Region von entscheidender Bedeutung. Marokko und Algerien haben leider sehr angespannte Beziehungen, was den Bau und die Nutzung von Pipelines betrifft. Die bestehende Gasleitung zwischen Algerien und Marokko wurde von Algerien gekappt, was bedeutet, dass Marokko alternative Routen nach Europa finden muss. Das macht die Situation natürlich komplizierter. Tunesien hingegen ist ein relativ stabiler Partner, aber auch dort gibt es immer wieder politische Unruhen, die sich auf langfristige Projekte auswirken könnten.

Frage: Das klingt nach einer sehr komplexen geopolitischen Lage. Wie beurteilen Sie die Chancen, dass diese Projekte erfolgreich umgesetzt werden können?

Dr. Albrecht Zimburg: Die Chancen stehen gut, aber es erfordert Geduld, Flexibilität und diplomatisches Geschick. Die Marokkaner sind sehr ambitioniert und haben bereits gezeigt, dass sie in der Lage sind, große Projekte umzusetzen. Ein Beispiel dafür ist das Noor-Solarkraftwerk in Ouarzazate, eines der größten Solarkraftwerke der Welt. Solche Erfolge geben Anlass zur Hoffnung, dass auch die Wasserstoffprojekte erfolgreich sein können.

Frage: Welche Rolle spielt die Europäische Union in diesen Plänen? Gibt es Unterstützung oder Partnerschaften mit der EU?

Dr. Albrecht Zimburg: Die EU spielt eine wichtige Rolle, sowohl in finanzieller als auch in strategischer Hinsicht. Es gibt mehrere Initiativen und Programme, die darauf abzielen, erneuerbare Energien in Nordafrika zu fördern und die Integration in den europäischen Energiemarkt zu erleichtern. Die EU unterstützt diese Projekte durch Investitionen und politische Kooperationen. Es gibt jedoch auch Herausforderungen, wie die unterschiedlichen regulatorischen Rahmenbedingungen und die Notwendigkeit, die Interessen aller beteiligten Länder in Einklang zu bringen.

Frage: Was sind die größten technischen Herausforderungen bei der Umstellung von Erdgas auf Wasserstoff in den bestehenden Pipelines?

Dr. Albrecht Zimburg: Eine der größten Herausforderungen ist die Materialverträglichkeit. Wasserstoff ist ein sehr kleines Molekül und kann Materialien durchdringen, die für Erdgas undurchlässig sind. Dies kann zu Leckagen und Sicherheitsproblemen führen. Außerdem müssen die Kompressoren und anderen

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technischen Komponenten der Pipelines angepasst oder ersetzt werden, um mit den spezifischen Anforderungen von Wasserstoff umgehen zu können. Diese Umstellungen sind technisch anspruchsvoll und kostenintensiv.

Frage: Wie sieht es mit der lokalen Bevölkerung aus? Gibt es Widerstände oder Bedenken bezüglich dieser groß angelegten Energieprojekte?

Dr. Albrecht Zimburg: Bisher gibt es überwiegend positive Reaktionen, da diese Projekte wirtschaftliche Vorteile und Arbeitsplätze bringen. Die marokkanische Regierung bemüht sich, die lokale Bevölkerung einzubeziehen und ihnen die Vorteile der erneuerbaren Energien und der Wasserstoffproduktion zu vermitteln. Es gibt jedoch auch Bedenken hinsichtlich der Umwelt und der sozialen Auswirkungen, insbesondere in ländlichen Gebieten. Es ist wichtig, dass diese Bedenken ernst genommen und adressiert werden, um langfristige Akzeptanz und Unterstützung sicherzustellen.

Frage: Wie wird die Zusammenarbeit zwischen öffentlichen und privaten Sektoren in diesen Projekten gestaltet?

Dr. Albrecht Zimburg: Die Zusammenarbeit zwischen öffentlichen und privaten Sektoren ist entscheidend für den Erfolg dieser Projekte. Die marokkanische Regierung schafft die regulatorischen Rahmenbedingungen und Anreize, während private Unternehmen die Investitionen und das technische Know-how einbringen. Es gibt auch internationale Partnerschaften und Kooperationen, die diese Zusammenarbeit unterstützen. Ein gutes Beispiel dafür ist das erwähnte OCP-Projekt, das sowohl staatliche Unterstützung als auch private Investitionen umfasst.

Frage: Welche langfristigen wirtschaftlichen Auswirkungen erwarten Sie von diesen Wasserstoffprojekten für Marokko und die gesamte Region?

Dr. Albrecht Zimburg: Langfristig könnten diese Projekte Marokko zu einem führenden Exporteur von grünem Wasserstoff machen und signifikante wirtschaftliche Vorteile bringen. Dies könnte zu einer Diversifizierung der Wirtschaft, einer Verringerung der Abhängigkeit von fossilen Brennstoffen und einer Stärkung der wirtschaftlichen Beziehungen mit Europa führen. Für die gesamte Region könnte dies ein Modell für nachhaltige Entwicklung und internationale Zusammenarbeit darstellen. Es gibt jedoch auch Herausforderungen, wie die Notwendigkeit, die lokale Wirtschaft zu diversifizieren und sicherzustellen, dass die Vorteile breit verteilt werden.

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Frage: Welche weiteren Schritte sind notwendig, um diese Vision Wirklichkeit werden zu lassen?

Dr. Albrecht Zimburg: Es braucht weiterhin erhebliche Investitionen in Infrastruktur und Technologie, eine klare und stabile regulatorische Rahmenbedingung, sowie eine enge Zusammenarbeit zwischen allen beteiligten Parteien. Bildung und Ausbildung der lokalen Arbeitskräfte sind ebenfalls entscheidend, um sicherzustellen, dass die Bevölkerung von den neuen Arbeitsplätzen und wirtschaftlichen Möglichkeiten profitieren kann. Schließlich ist es wichtig, dass die politischen Spannungen in der Region gemanagt und, wenn möglich, reduziert werden, um eine stabile Grundlage für diese Projekte zu schaffen.

Frage: Herr Dr. Albrecht Zimburg, das war ein äußerst informatives Gespräch. Vielen Dank für Ihre Zeit und Ihre ausführlichen Antworten.

Dr. Albrecht Zimburg: Gern geschehen. Es war mir ein Vergnügen, über dieses wichtige und zukunftsweisende Thema zu sprechen.

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