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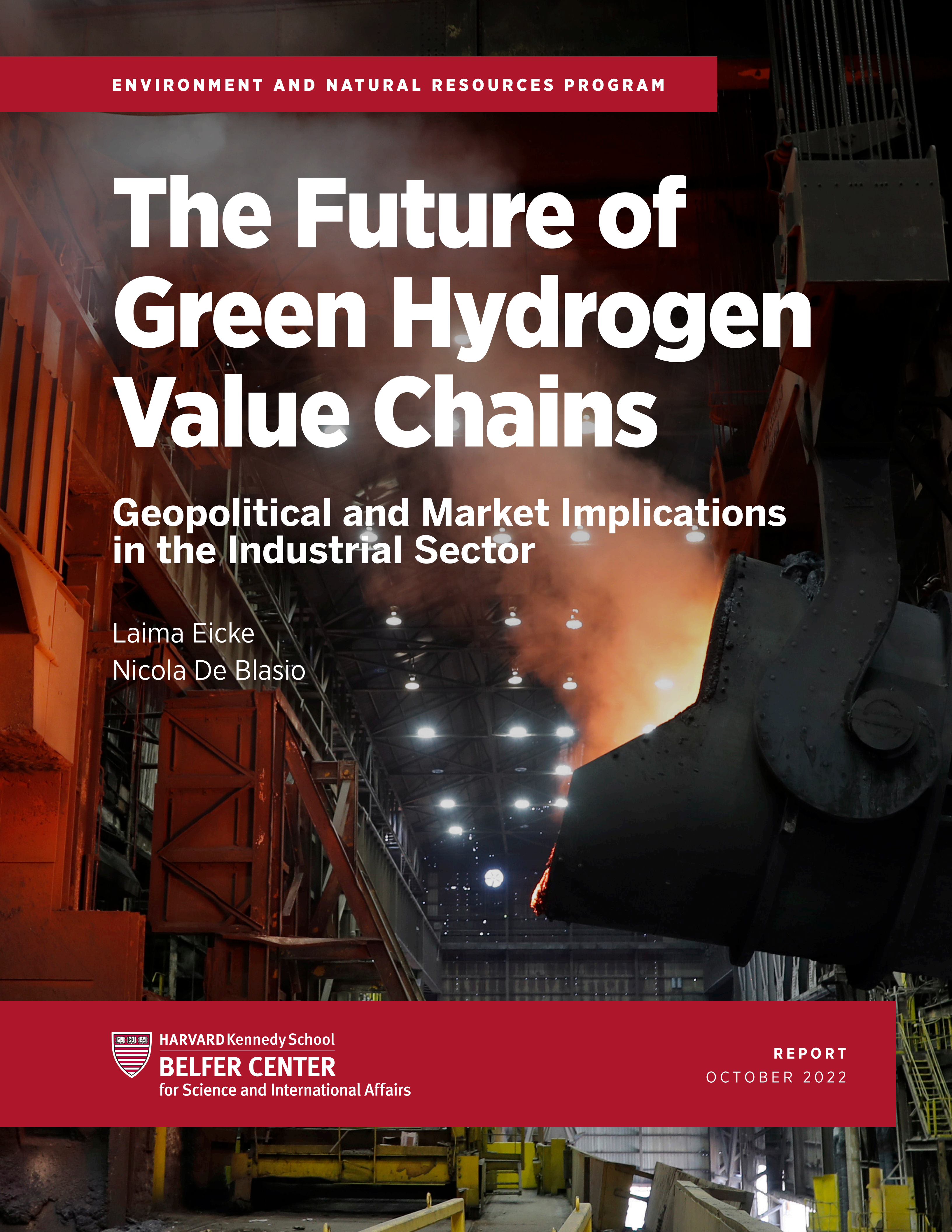

ENVIRONMENT AND NATURAL RESOURCES PROGRAM

The Future of Green Hydrogen Value Chains

Geopolitical and Market Implications in the Industrial Sector

Laima Eicke
Nicola De Blasio

HARVARD Kennedy School
BELFER CENTER
for Science and International Affairs

REPORT
OCTOBER 2022

Environment and Natural Resources Program
Belfer Center for Science and International Affairs
Harvard Kennedy School
79 JFK Street
Cambridge, MA 02138

www.belfercenter.org/ENRP

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Declaration of Interests

The authors declare that they have no competing personal or financial interests that might have biased this research.

About the Authors

Laima Eicke is a Research Fellow at the Belfer Center's Environment and Natural Resources Program and the Science, Technology, and Public Policy Program. Her research focuses on the decarbonization pathways of countries worldwide, value chains of renewable energy technologies, and how both affect geopolitics. At the Belfer Center, she specifically focuses on green hydrogen.

Eicke is currently pursuing a Ph.D. at the Willy Brandt School for Public Policy in Erfurt, Germany, and is a Research Associate at the Institute for Advanced Sustainability Studies (IASS). She holds a M.Sc. with honors in socio-ecological economics and policy from the Vienna University of Business and Economics and a B.A. in international relations and Latin American studies from the Technical University of Dresden. She previously worked at the German Corporation for International Cooperation (GIZ), the Germany Ministry for International Affairs, two NGOs, and in consultancy. Eicke is a passionate observer and youth advocate in international climate negotiations.

Nicola De Blasio is a Senior Fellow leading Belfer Center research on energy technology innovation and the transition to a low-carbon economy. With more than 25 years of global experience in the energy sector, Dr. De Blasio is an expert in navigating the challenges of strategic development and technology innovation toward sustainable commercial success at scale. Through his research and experience, he has gained considerable insight into the impact of institutional development and innovation activities on other facets of business strategy.

Dr. De Blasio spent 17 years at Eni, one of the world's leading energy companies, most recently as Vice President and Head of R&D International Development. Prior to joining Harvard, he was Senior Research Scholar in the faculty of SIPA at Columbia University and Program Director Technology and Innovation at the Center on Global Energy Policy, where he was also Director of Strategic Partnerships. Dr. De Blasio holds a degree in Chemical Engineering from the Politecnico of Milan University. He specialized at St. Andrews University, Scotland, and then at Eni Corporate University, where he focused on energy economics. He is author of the book *Value of Innovation*, and has extensively published and lectured on energy, innovation, project evaluation and catalysis.

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A giant ladle backs away after pouring its contents of red-hot iron into a vessel in the basic oxygen furnace as part of the process of producing steel at the U.S. Steel Granite City Works facility Thursday, June 28, 2018, in Granite City, Ill. (AP Photo/Jeff Roberson)

Executive Summary

The global transition to a low-carbon economy will significantly impact existing energy value chains and transform the production to consumption lifecycle, dramatically altering interactions among stakeholders. Thanks to its versatility, green hydrogen is gaining economic and political momentum and could play a critical role in a carbon-free future. Furthermore, its adoption will be critical for decarbonizing industrial processes at scale, especially hard-to-abate ones such as steel and cement production. Overall, hydrogen demand is expected to grow by 700% by 2050 (BP, 2019). Currently, the two central challenges to green hydrogen adoption and use at scale are limited infrastructure availability and cost. While recent spikes in fossil fuel prices due to the war in Ukraine have made green hydrogen cost-competitive with blue and grey hydrogen (Radowitz, 2022), from a long-term perspective, the International Renewable Energy Agency (IRENA) predicts a decline in green hydrogen costs by up to 85% by 2050 (IRENA, 2020), making it the dominant hydrogen form (IRENA, 2022).

A new framework to assess countries' roles in industrial green hydrogen value chains

This report studies the role countries could play in future green hydrogen industrial markets, focusing on three key applications: ammonia, methanol, and steel production. Today, these sectors are among the largest consumers of hydrogen, accounting for about 41% of global demand, and are expected to increase their shares due to global decarbonization efforts (IRENA, 2022). Analyzing a country's potential positioning in these markets is key to helping policymakers define strategic industrial policies. To elucidate the impact of the transition to a low-carbon economy on energy value chains, we propose an analytical framework to cluster countries into five groups based on the variables of resource endowment, existing industrial production, and economic relatedness:

Frontrunners. These countries could lead in green hydrogen production and industrial applications at scale globally. Potential frontrunners should focus on industrial policies that foster green hydrogen up-scaling to gain global leadership.

Upgraders. Countries with adequate resources for green hydrogen production and highly related economic activities could potentially upgrade their value chain positioning and attract green hydrogen-based industries. Potential upgraders could benefit from strategic partnerships with frontrunners to foster technological and know-how transfer. Policies should focus on attracting foreign capital, for example, by lowering market risk, developing public-private partnerships, and forming joint ventures.

Green hydrogen exporters. Resource-rich countries with limited upgrading potential should prioritize green hydrogen exports and would benefit from partnerships with green hydrogen importers to deploy enabling infrastructure and reduce market risk. Furthermore, coordination of international standards for green hydrogen production and use would facilitate trade on a global scale.

Green hydrogen importers. Resource-constrained countries with industrial hydrogen-based production will need to develop strategic partnerships to ensure secure and stable green hydrogen supplies. Additionally, stimulating innovation and knowledge creation through targeted policies will be critical to sustaining competitiveness and avoiding industrial relocations to frontrunners or upgraders.

Bystanders. Countries with significant constraints along all three critical variables should assess whether some of these constraints, such as limited infrastructure or freshwater availability, could be overcome to integrate into future green hydrogen value chains. Otherwise, they will continue to be the final importers of industrial products.

Countries in these groups face unique challenges and opportunities, which we exemplify through case studies focusing on the United States, Germany, and Thailand.

The geopolitical map of green hydrogen in the industrial sector

The low-carbon transition in existing energy value chains will also give rise to new market and geopolitical dynamics and dependencies. Our analysis elucidates key geopolitical trends that could shape international relations in the upcoming decades, with countries competing for industrial leadership, markets, and opportunities for job creation.

Only a few countries, including China and the United States, may emerge as clear frontrunners. These countries have vast resource endowments and considerable market shares in today's hydrogen industrial applications that would enable them to integrate the green hydrogen value chain segments of production and industrial applications. Locating industrial facilities close to low-cost green hydrogen production would create value by increasing a country's control over supply chains and minimizing hydrogen transportation costs. These countries could thus reap the most extensive benefits and become geopolitical and market winners. However, these dynamics could spur a green race for industrial leadership, creating tensions in international relations. Furthermore, competing dynamics for green hydrogen-based industries could foster market tensions between green hydrogen importers and upgraders. Resource-rich countries, such as Thailand and Mexico, have the potential for green industrialization and would likely compete with import-dependent industrial powers for market share and jobs, leading to new geopolitical tensions.

Second, new dependencies might emerge. Most countries that currently have highly developed ammonia, methanol, or steel industries, such as Saudi Arabia, Japan, and Germany, are resource constrained and would depend on green hydrogen imports to meet demand. Hence, from a geopolitical perspective, dependencies and supply disruption risks will likely persist in a low-carbon energy world, but will be different from those of today. These new geopolitical dependencies will involve new alliances and will also be a function of future market structures. Like natural gas markets, hydrogen markets will emerge as regional ones, but only global and more structured markets will allow for risk reduction.

Finally, tensions between higher-income countries in the Global North and lower-income countries, often located in the Global South, might intensify. Our analysis shows how the potential for the three industrial hydrogen applications—ammonia, methanol, and steel—is unevenly distributed across the globe. Although there are opportunities for economic gains in all world regions, most frontrunners are middle- to high-income countries. Many lower-income countries, especially in Africa, will be limited to green hydrogen exports since they cannot compete in value-added segments of the value chains. Hence the promise of 'sustainable development' and green industrialization, often associated with the energy transition, might not be replicable everywhere. This might intensify the need for technology transfer and financial support to enable sustainable development and green industrialization for all.

1. Introduction

Green hydrogen[1] could play a significant role in the decarbonization of hard-to-abate industrial sectors, such as steel and cement. Global hydrogen demand is expected to grow by 700% by 2050 (BP, 2019), from today's 70 million tons per year (IEA, 2019). The use of hydrogen at this scale will significantly impact existing value chains[2] and create economic opportunities for countries that strategically position themselves in future green hydrogen markets. To gain leadership, several countries, including the United States, Norway, and Chile, have started to adopt industrial policies; these policies support green hydrogen adoption at scale and foster innovation in key industries (IEA, 2021a).

Previous studies on the geopolitics of hydrogen have analyzed the different roles that countries could adopt in future green hydrogen markets and how the associated economic gains might affect international relations (Pflugmann & De Blasio, 2020; Van de Graaf et al., 2020). These studies mainly identified the countries with a higher potential for green hydrogen production and the associated market and geopolitical implications. In contrast, few studies have focused on the demand for green hydrogen driven by the industrial sector (IRENA, 2022). Since industrial applications drive the majority of today's fossil fuel-based hydrogen demand, this sector will most likely play a key role in shaping emerging green hydrogen value chains. This will be especially true in the early stages of adoption when fragile, nascent market dynamics will be supported by the sector's higher economies of scale and are lower risk than other potential applications (IRENA, 2022).

This study answers the question of which countries have the potential to play a critical role in green hydrogen value chains in key industries, not only for green hydrogen production but also in its industrial applications. To this end, we draw on a mixed-methods approach. First, we propose a framework to cluster countries based on three variables that would give them a distinct advantage in future green hydrogen markets: resource endowment, current industrial production,

1 Green hydrogen refers to hydrogen produced by water splitting using renewable electricity.

2 We use the term 'value chain' to define a more conceptual design of business relationships between stakeholders that support the development and adoption of a market or technology at scale. This differs from the term 'supply chain,' which is typically used to define a set of operational relationships designed to benefit a single stakeholder and deliver products or services.

and economic relatedness.[3] We then apply this framework to identify countries' potential in using hydrogen at scale for three industrial applications: ammonia, methanol, and steel production. Finally, we analyze three country case studies, illustrating the challenges and opportunities of different country groups in their strategic industrial positioning in future green hydrogen markets, and outline their concrete policy options.

Our findings highlight how the potential for green hydrogen production and associated industrial applications is distributed unevenly across the globe. We argue that countries like the United States and China, who can lead in both green hydrogen production and its industrial applications, could emerge as frontrunners in a green hydrogen economy. Other resource-rich countries, such as Thailand or Mexico, have the potential for green industrialization and will likely compete with import-dependent industrial powers for market share and jobs, leading to new geopolitical dependencies and tensions.

This paper not only contributes empirical evidence to the ongoing debate on the geopolitics of hydrogen but integrates it based on insights from the global value chain literature. Our findings demonstrate that this perspective offers new insights into both the different roles countries could assume in a green hydrogen economy and the distribution of associated economic gains and losses. Furthermore, it provides guidance and recommendations for defining strategic industrial policies.

The remainder of this paper is structured as follows: Section 2 reviews existing literature on the geopolitics of green hydrogen and the scholarly debate on global value chains and proposes a framework for understanding economic gains in a green hydrogen economy. Section 3 describes the methodology used for analyzing a country's role in green hydrogen value chains. Section 4 draws the geopolitical map of green hydrogen applications for ammonia, methanol, and steel production. Section 5 uses three case studies to analyze the opportunities and challenges for different country groups in emerging hydrogen markets. Section 6 addresses the geopolitical challenges and opportunities arising from green hydrogen adoption in the industrial sector. Finally, Section 7 addresses conclusions and policy recommendations.

3 Economic relatedness indicates the percentage of related activities in a particular location; the relatedness ω between a location c and an activity p is calculated based on the following formula: $\omega_{cp}=(\sum_{p'} M_{cp'} \phi_{pp'})/(\sum_{p'} \phi_{pp'})$, where M_{cp} refers to a matrix indicating the presence of activity p in location c; $\phi_{pp'}$ is a measure of similarity between activities p and p′; For further details on the methodology, see (OEC, 2021a).

2. Literature Review and Framework

The debate on the geopolitical implications of an emerging hydrogen economy has intensified over the past few years. Scholars have argued that the projected rapid growth in green hydrogen demand might lead to new geopolitical opportunities and challenges (IRENA, 2022; Pflugmann & De Blasio, 2020; Van de Graaf, 2021; Van de Graaf et al., 2020). New trade patterns might give rise to novel export champions, and resource-poor countries might face new geopolitical dependencies (Pflugmann & De Blasio, 2020). In this context, hydrogen has been identified as the 'new oil' (Van de Graaf et al., 2020). Authors have also warned that emerging hydrogen markets could lead to geo-economic competition and conflict (Blondeel et al., 2021). Some studies have analyzed the potential for hydrogen production worldwide to identify potential winners in future green hydrogen markets (Pflugmann & De Blasio, 2020; Van de Graaf, 2021). Others have discussed potential global trade patterns and governance (Van de Graaf et al., 2020). Few articles hint at the importance of value chains in international relations (Blondeel et al., 2021; Lebrouhi et al., 2022; Noussan et al., 2021; Van de Graaf et al., 2020). But only very few examine in detail the geopolitical implications of hydrogen adoption at scale in industrial applications and the associated impact on value chains (IRENA, 2022). Some of these studies have explored the technological and cost improvements in hydrogen applications (Chen et al., 2019; Lebrouhi et al., 2022) or examined hydrogen value chains in country-specific case studies, for example, in Germany (Coleman et al., 2020), Japan (Nagashima, 2018) and the United States (Ruth et al., 2020). However, there has not been a comprehensive, empirically driven analysis of the role countries could assume in green hydrogen value chains. Therefore, we believe that the geopolitical and market implications of hydrogen adoption at scale require further analysis.

We address this gap using insights from global value chain literature. This perspective offers new insights into the distribution of gains and losses in a green hydrogen economy among different country groups based on a country's potential to engage in green hydrogen value chain segments. In our analysis, critical segments of future green hydrogen value chains include its production, distribution, and utilization— focusing, as discussed, on industrial applications of green hydrogen, such as ammonia, methanol, and steel production (see Figure 1).

Figure 1. Green hydrogen value chain segments for industrial applications

Literature on global value chains highlights that the final value of a product increases in each manufacturing stage and varies along value chain segments. Resource extraction is the least profitable segment of a value chain, whereas the value-added in industrial applications is much higher (Gereffi & Lee, 2012; Pipkin & Fuentes, 2017). In the case of green hydrogen, this implies that industrial applications, such as ammonia, methanol, or steel production, could yield more added value than simple production and commodity trading.

In this context, it can be beneficial for countries to improve their value chain positioning by moving from lower- to higher-value activities (Gereffi, 2005, p. 171), a process referred to as upgrading. China is a successful example of value chain upgrading. In the past three decades, Beijing has supported the solar and wind green energy sectors thanks to favorable and stable policies aimed at growing its global market shares and the required skilled labor force (Binz & Truffer, 2017; Chen & Lees, 2016; Gandenberger et al., 2015). Pursuing green industrialization has been especially important for the Global South countries, where policymakers have used strategic industrial policies to try to upgrade their country's value chain position (Bazilian et al., 2020; Pipkin & Fuentes, 2017). A few studies have highlighted the importance of technology transfer and knowledge spillovers from related industries in enabling upgrading processes in renewable energy value chains (Pipkin & Fuentes, 2017; Tajoli & Felice, 2018).

Nascent hydrogen markets might provide new opportunities for countries to upgrade along value chains and attract added-value applications and sectors. Furthermore, evolving value chains have significant implications on the distribution of gains and losses, especially with respect to varying degrees of segmentation or integration. An analysis of existing energy value chains helps to highlight how stakeholders position their offerings, for example by adopting sustainable business models, specializing in critical technologies to gain a competitive advantage, or responding to regulatory constraints. However, these decisions generally result in two outcomes: segmentation or integration.

Segmented value chains consist of stakeholders specializing in single segments to gain a unique competitive advantage. On the other hand, integration refers to combining different segments in one firm or location (Gereffi et al., 2005).

Integration has usually been associated with gains in higher value accumulation and a more substantial degree of control (Gereffi, 2005; Gereffi et al., 2005). Countries could thus benefit by integrating green hydrogen value chains' production and industrial applications segments in various ways. Integration could increase the local added value and create jobs; it could reduce distribution costs (IRENA, 2020), increase control, and reduce dependencies, which can also create vulnerability. The latter has become even more apparent in the recent supply chain interruptions due to COVID-19 (Øverland et al., 2020) and the war in Ukraine (Simchi-Levi & Haren, 2022). The benefits associated with integration along value chains might incentivize carbon-intensive industries to relocate closer to low-cost green hydrogen production locations (IRENA, 2022), which strategic industrial policies might further incentivize.

We argue that combining the two research streams on global value chains and the geopolitics of hydrogen can provide novel and more granular insights into the different roles countries might assume in future green hydrogen markets. Previous studies on the geopolitics of hydrogen highlighted the countries that could benefit from the adoption of green hydrogen at scale and those that could benefit from green hydrogen applications in domestic markets. Integrating insights from global value chains literature, we argue that countries that combine both green hydrogen value chain segments—production and industrial applications—could emerge as frontrunners in future green hydrogen markets. This is because the synergies deriving from the integration of these two segments enable countries to leverage and compound the intrinsic value of each segment, while increasing control over value chains and reducing dependencies.

2.1. **Framing the Challenge**

Building and expanding existing literature on both the geopolitics of hydrogen and global value chains, this paper analyzes a country's potential in future green hydrogen markets, focusing on two segments of its value chain: a) production and b) industrial applications, using three criteria: resource endowment, current industrial production, and economic relatedness.

Resource endowment. Green hydrogen is hydrogen produced by splitting water molecules into hydrogen and oxygen using renewable electricity. The availability of plentiful renewable energy sources, such as solar and wind, together with freshwater availability and enabling infrastructure, is thus critical for producing green hydrogen at scale. Accordingly, these variables have been used by Pflugmann and De Blasio (2020) to assess green hydrogen potentials globally.

Industrial production. Existing and mature hydrogen markets increase the potential for green hydrogen adoption because they provide sectoral knowledge and skills, enabling infrastructure, strong networks, and practices that offer a competitive advantage compared to new market entrants (Lambkin, 1988). The size of existing hydrogen markets can be measured based on sectoral production figures and has been used as an indicator of future green hydrogen demand (IRENA, 2022).

Economic relatedness. The global transition to a low-carbon economy will significantly impact existing energy value chains and transform the production to consumption lifecycle, dramatically altering stakeholders' interactions. Since global value chains are not static, this dynamism must be addressed using the concept of economic relatedness. Future green hydrogen demand could diverge from current hydrogen market dynamics; for example, as hard-to-abate sectors decarbonize, economic incentives to relocate industrial green hydrogen applications closer to low-cost green hydrogen production could emerge (IRENA, 2022). Related economic activities would build up transferable skills that can increase the potential for new markets and sectoral economic growth (Hausmann & Hidalgo, 2011; Hausmann et al., 2014; Hidalgo et al., 2018; Hidalgo et al., 2007). For this reason, economic relatedness has been successfully used to predict new economic opportunities and the growth of specific products or industries at a national or subnational level (Hausmann et al., 2014; Neffke et al., 2011).

Table 1. Key criteria for assessing countries' roles in value chains for green hydrogen applications

Resource Endowment	Industrial Production	Economic Relatedness	Country Group
+	+	(+/-)	1: Frontrunners
+	-	+	2: Upgraders
-	+	(+/-)	3: Green Hydrogen Importers
+	-	-	4: Green Hydrogen Exporters
-	-	(+/-)	5: Bystanders

Using these three criteria, we cluster countries into five groups (see Table 1): Resource-rich countries with industrial hydrogen-based production show the best preconditions to emerge as frontrunners (Group 1). Resource-rich countries with high economic relatedness have the potential to become value chain upgraders by expanding their industrial hydrogen applications or developing new green industrialization opportunities (Group 2). Resource-poor countries with industrial hydrogen-based production rely on green hydrogen imports for their industrial applications (Group 3). Resource-rich countries without industrial hydrogen-based production or related economic activities could become hydrogen exporters (Group 4). Finally resource-poor countries without industrial hydrogen-based production will be 'Bystanders' (Group 5). These countries will—most likely—not be able to integrate into green hydrogen value chains and will continue to be importers of final products.

To elucidate the value chain dynamics and implications of green hydrogen adoption at scale, we focus our analysis on three major industrial applications: ammonia, methanol, and steel production.[4] Today, these applications are among the most significant consumers of hydrogen; their combined demand accounts for 41% of global hydrogen supply and is expected to further increase due to industrial decarbonization efforts (IRENA, 2022). Ammonia (accounting for about 27% of global hydrogen demand) mainly serves as a feedstock in chemical processes, especially in fertilizer production, but also for cooling systems or explosives (IEA, 2019, p. 56). Ammonia could also be used as a hydrogen carrier for the long-distance transport of green hydrogen (De Blasio, 2021; IEA, 2019). Most methanol (accounting for 11% of global hydrogen demand) is used in the chemical industry (IEA, 2019). Like ammonia, methanol could further enable global hydrogen

4 Refining would be another prominent hydrogen application, accounting for 33% of current demand [IRENA (2019). *Hydrogen: A renewable energy perspective*. International Renewable Energy Agency. (Excluded from the analysis.)]

markets as it can be used as a fuel or as a carrier for the transport of hydrogen (IEA, 2019). Finally, steel production (accounting for 3% of global hydrogen demand) represents a hard-to-abate sector requiring high-heat processes, which cannot be easily achieved by electrification. The IEA estimates that this sector's demand will significantly increase as hydrogen's share could grow from today's 7% to eventually cover 100% of steel production by substituting natural gas (IRENA, 2019a).

While our analysis focuses on green hydrogen, we acknowledge that fossil fuel-based hydrogen, especially in combination with CCS technologies, could play a role in emerging hydrogen value chains, especially in the early stages. While more than 99% of today's hydrogen supply is based on fossil fuels, the share of green hydrogen is expected to increase significantly. Furthermore, recent surges in fossil fuel prices due to the war in Ukraine have made green hydrogen cost-competitive with blue and grey hydrogen (Radowitz, 2022). From a long-term perspective, IRENA predicts a decline in green hydrogen costs by up to 85% by 2050 (IRENA, 2020), making it the dominant hydrogen source (IRENA, 2022).

Finally, it is important to note that our framework only elucidates a country's potential to engage in future green hydrogen value chains. It should not be seen as a prediction of the future. While high potentials indicate the expectation of future economic gains along value chains, countries may or may not live up to these expectations, depending on how market dynamics and interactions between national and international policies play out in the future.

3. Building the Geopolitical Map of Green Hydrogen Industrial Applications

Our analysis leverages a mixed-method approach to define a country's potential in industrial green hydrogen applications. Building on the framework described in the previous section, we start by clustering countries into five groups based on the critical variables of resource endowment, existing industrial production, and economic relatedness. Leveraging case studies, we then elucidate the opportunities and challenges for frontrunners, upgraders, and green hydrogen importers, the country groups that will most likely shape future hydrogen value chains, markets, and geopolitics. To define the role countries could play in future green hydrogen markets, the following coding was used:

Resource endowment: For coding green hydrogen production potentials, we use the methodology devised by Pflugmann and De Blasio (2020): 'zero' implies resources constraints, defined as either a) renewable energy sources potential[5] lower than 1.5 times a country's primary energy consumption,[6] also taking into account land constraints with population densities higher than 150 inhabitants per square kilometer; b) freshwater renewable resources lower than 800 cubic meters per inhabitant;[7] or c) limited infrastructure potential to operate hydrogen production, transportation, and distribution at scale, based on a score below 4 (out of 7) of the overall infrastructure score in the World Economic Forum's 2019 Global Competitiveness Index (WEF, 2019). Otherwise countries were coded with 'one.'

Industrial production: Existing industrial hydrogen applications will most likely improve a country's role in future green hydrogen value chains and markets. Hence this criterium is coded as 'one' if a country's existing global market share for the production capacity of ammonia (USGS, 2021) and steel (Worldsteel, 2021) is

5 The combined potential for renewable electricity production per country is calculated based on the wind power potential, which is based on NREL (2014), and the solar power potential, which is based on Pietzecker et al. (2014).

6 Primary energy consumption is based on the year 2019 (EIA, 2019).

7 Countries with freshwater resources below this threshold predominantly use them for drinking, household consumption, industrial use, and/or irrigation and have no additional capacities for increased water demand for hydrogen production (Pflugmann and De Blasio, 2020). Freshwater resource data are based on AQUASTAT (2020).

above 1%, or in the case of methanol,[8] a country's share of global net exports is above 1%.[9] Otherwise, it is coded as 'zero.'

Economic relatedness: Comparatively high economic relatedness will most likely improve a country's role in future green hydrogen value chains and markets. Hence this criterium is coded as 'one' if a country's economic relatedness to ammonia, methanol, or steel production is higher than the global average;[10] otherwise, it is coded as 'zero' (OEC, 2021a).

First we map countries' potential roles in green hydrogen value chains, looking at ammonia, methanol, and steel production separately. In a second step, we build an integrated map across these three applications. We code each criterium as 'one' if it was met in at least two of the three industrial applications; otherwise, we coded it with 'zero.' This allows us to identify frontrunners across multiple industrial applications.

Overall, frontrunners, upgraders, and green hydrogen importers are the groups that will shape future hydrogen markets and geopolitics more than others. To elucidate the associated value chain dynamics, we use three case studies: the United States for frontrunners, Thailand for upgraders, and Germany for green hydrogen importers. It should be noted that the current dominance in industrial hydrogen applications and markets was not the driving selection parameter for these case studies. For example, while China and India dominate today's steel markets, they are influenced by unique domestic dynamics that cannot be easily transferred to other countries (Goldthau et al., 2020). Therefore, we selected countries that showcase dynamics and patterns representing the entire group, and provide consistency across the three analyzed industrial green hydrogen applications. While some countries are in different country groups depending on the application, the United States and Thailand are in the same country group in all cases and Germany in two out of three. Finally, we also prioritized a geographically diverse distribution to include key regional markets. See Section 5 for a detailed analysis, including an overview of current policies promoting green hydrogen development and deployment.

8 Since we could not access methanol production global data, we rely on a positive net trade balance as a proxy for a country's methanol production. While this approach does account for countries with small productions consumed domestically or supplemented with imports, nevertheless the proxy allows us to identify key global methanol exporters. Methanol trade balances were derived from OEC (2021b).

9 This threshold was chosen to ensure that only key players in global markets are considered.

10 Based on OEC (2020), the economic relatedness global averages are 0,152 for ammonia, 0,134 for methanol, and 0,248 for steel.

4. The Potential for Industrial Applications of Green Hydrogen in Ammonia, Methanol, and Steel Production

The following section gives an overview of the roles countries could assume in future value chains for green hydrogen-based ammonia, methanol, and steel production.

4.1. The Geopolitical Potential for Green Hydrogen-Based Ammonia Production

Today's top producers dominating ammonia markets are China (26% market share), Russia (10%), the United States (10%), Indonesia (4%), and Egypt (3%). Our analysis shows that China, the United States, and Indonesia are well positioned to become frontrunners in green hydrogen-based ammonia markets. Russia and Egypt are limited in their ability to produce or distribute green hydrogen at scale, Russia because of infrastructure constraints, and Egypt due to limited freshwater availability. Other top ten producers, such as Canada (3% market share) or Poland (2%), could significantly increase their global market shares, thanks to favorable green hydrogen production potentials. Countries with high resource endowments and high economic relatedness, like Mexico, Spain, and Thailand, could evolve into green ammonia upgraders. Finally, countries with high green hydrogen production potentials but low transferrable skills could also benefit by exporting hydrogen to import-dependent ammonia producers such as Egypt or Germany (see Figure 2).

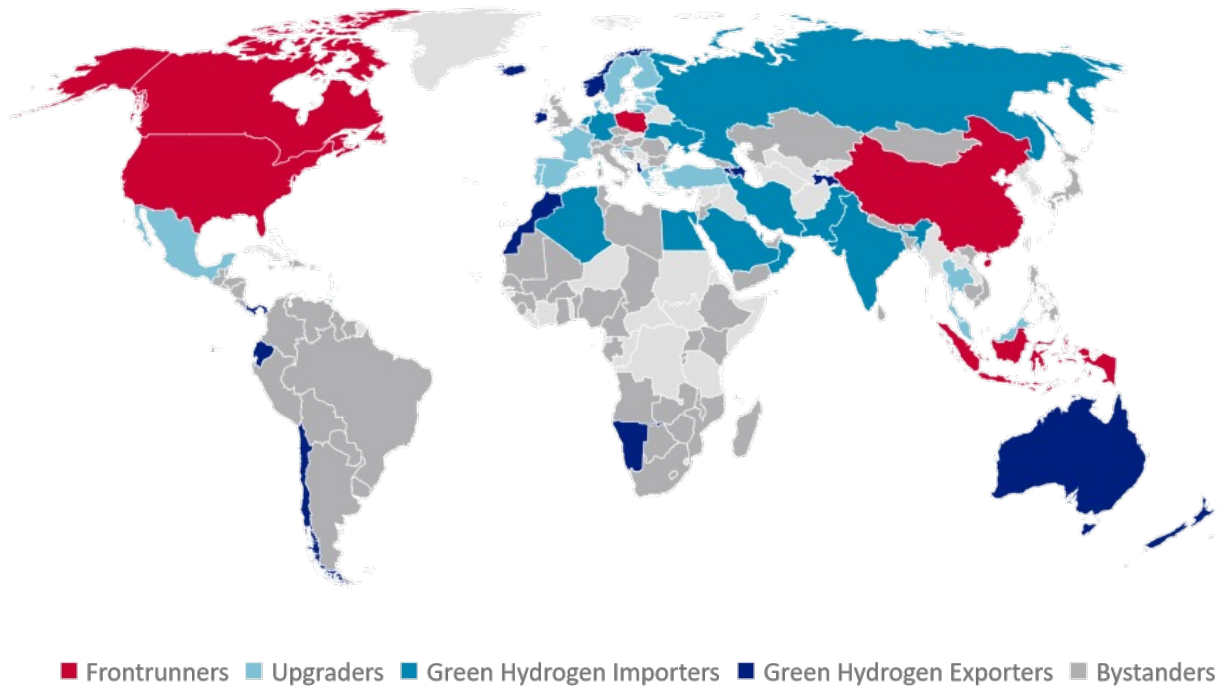

Figure 2. Geopolitical map of green ammonia production potential

4.2. **The Geopolitical Potential for Green Hydrogen-Based Methanol Production**

Four out of today's top five methanol exporters—Saudi Arabia (13% market share), Trinidad and Tobago (11%), Oman (9%), and the United Arab Emirates (6%)—are limited in their potential to produce green hydrogen. Therefore, they would need to rely on imports to maintain their predominance in future green methanol markets. In contrast, large exporters, such as New Zealand (4% market share), the United States (3%), Chile (3%), and Norway (2%), could increase their market shares and evolve into frontrunners thanks to their high resource endowments and significant economic relatedness. Countries such as China, Mexico, Spain, or Turkey with high economic relatedness indicating transferrable skills, but not the current industrial production needed to become frontrunners, could still upgrade their positioning by attracting industries using green methanol. Countries without highly transferrable skills, like Australia, Namibia, and Morocco, could still benefit by becoming hydrogen exporters to countries with extensive green methanol-based industries but low production potentials (see Figure 3).

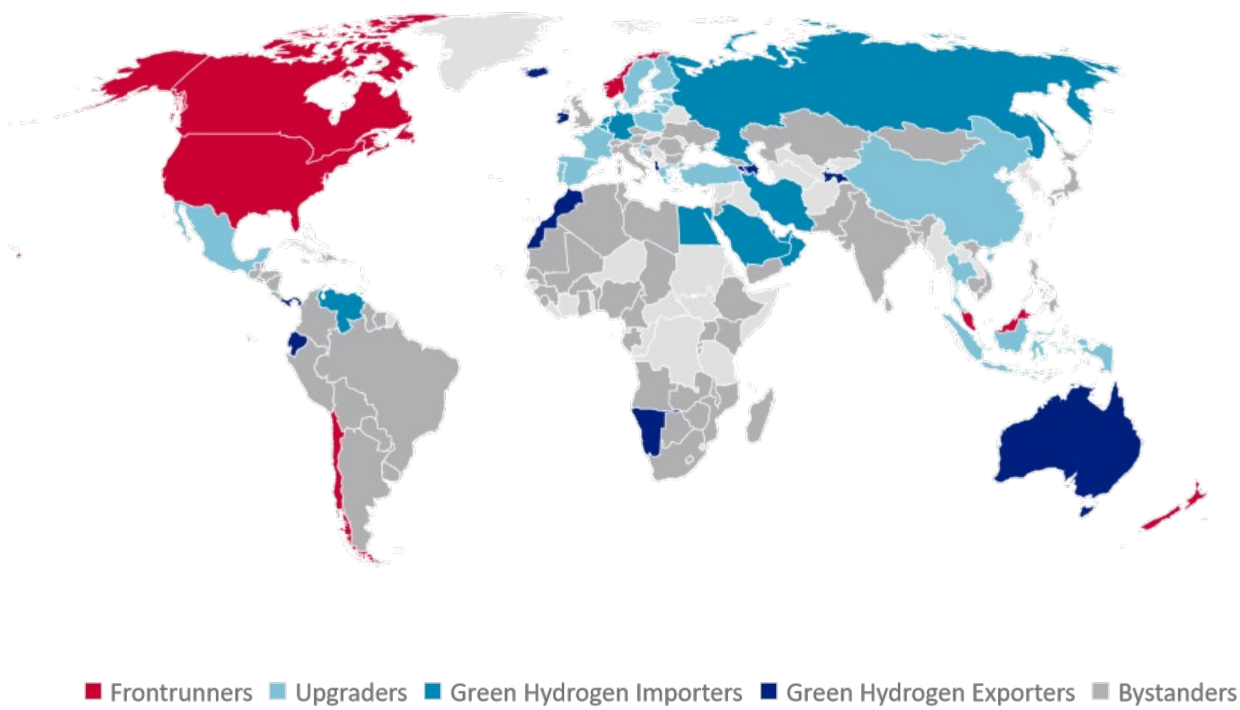

Figure 3. Country potential for methanol production based on green hydrogen

4.3. **The Geopolitical Potential for Green Hydrogen-Based Steel Production**

Today's steel production is dominated by China, which accounts for almost 57% of global markets, followed by India (5% market share), Japan, the United States, and Russia (4% each). While China and the United States are well positioned to become frontrunners in future green steel markets, Japan, Hungary, Russia, and other major steel producers face resource endowment constraints and would depend on green hydrogen imports. Smaller producers such as France (0.6% market share) or Spain (0.6%) could benefit from evolving market dynamics and increase market shares thanks to their high economic relatedness. Countries with good resource endowments and economic relatedness, such as the Baltic States, Morocco, Turkey, and Thailand, could try to attract green steel production, thus gaining new value-creating opportunities. Countries like Norway, Chile, and Namibia could become green hydrogen exporters to countries wishing to decarbonize their steel production (see Figure 4).

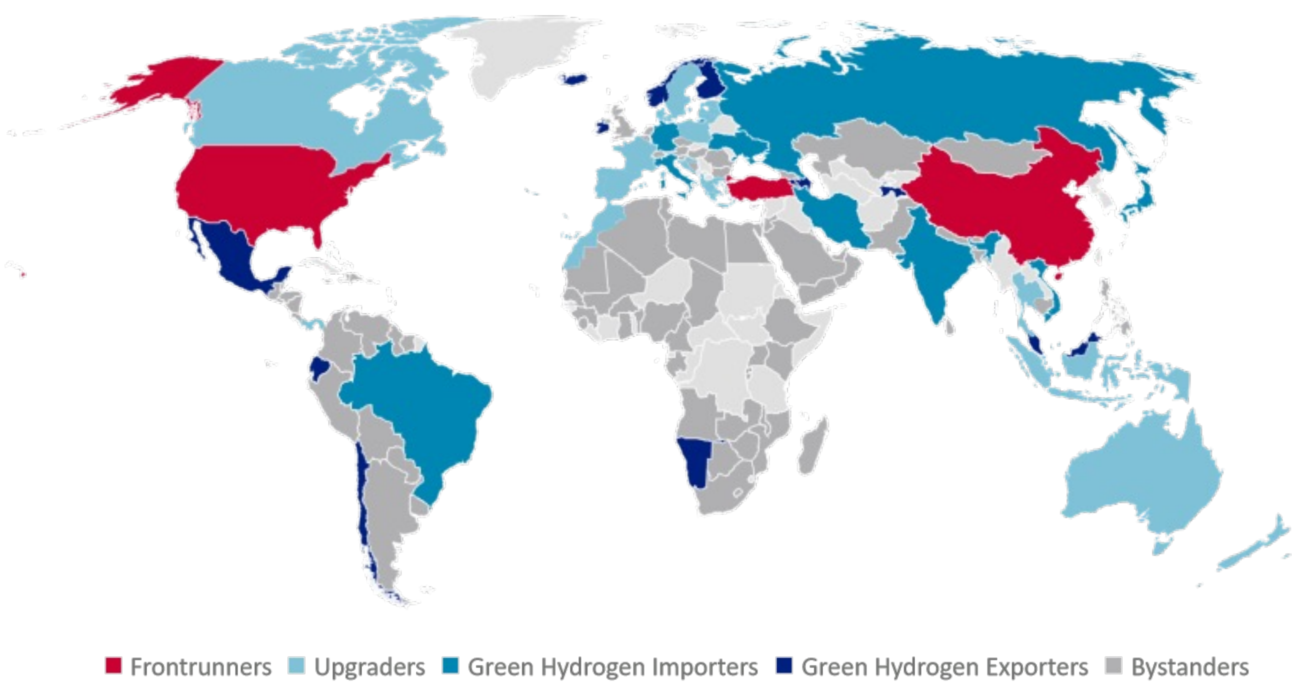

Figure 4. Country potential for steel production based on green hydrogen

4.4. **The Geopolitical Potential for Green Hydrogen Industrial Applications**

Our analysis shows how only a few countries, such as Canada, China, and the United States, have the potential to emerge as leaders in at least two industrial green hydrogen applications. The majority of current steel, ammonia, and methanol production locations face resource constraints and might depend on hydrogen imports to decarbonize. Producing nations that lead in at least one industrial green hydrogen application, like Spain and Mexico, could upgrade their value chain position based on related economic activities. Most potential green hydrogen producers are good locations for at least one of the three green hydrogen industrial applications, and might consider the integration of value chain segments, whereas countries with lower economic relatedness, such as Chile, Norway, or Namibia, could focus on green hydrogen exports. While the mapping indicates that there are opportunities for countries in all world regions, most countries in South America and Africa face constraints that limit their potential for an active role in industrial green hydrogen value chains (see Figure 5).

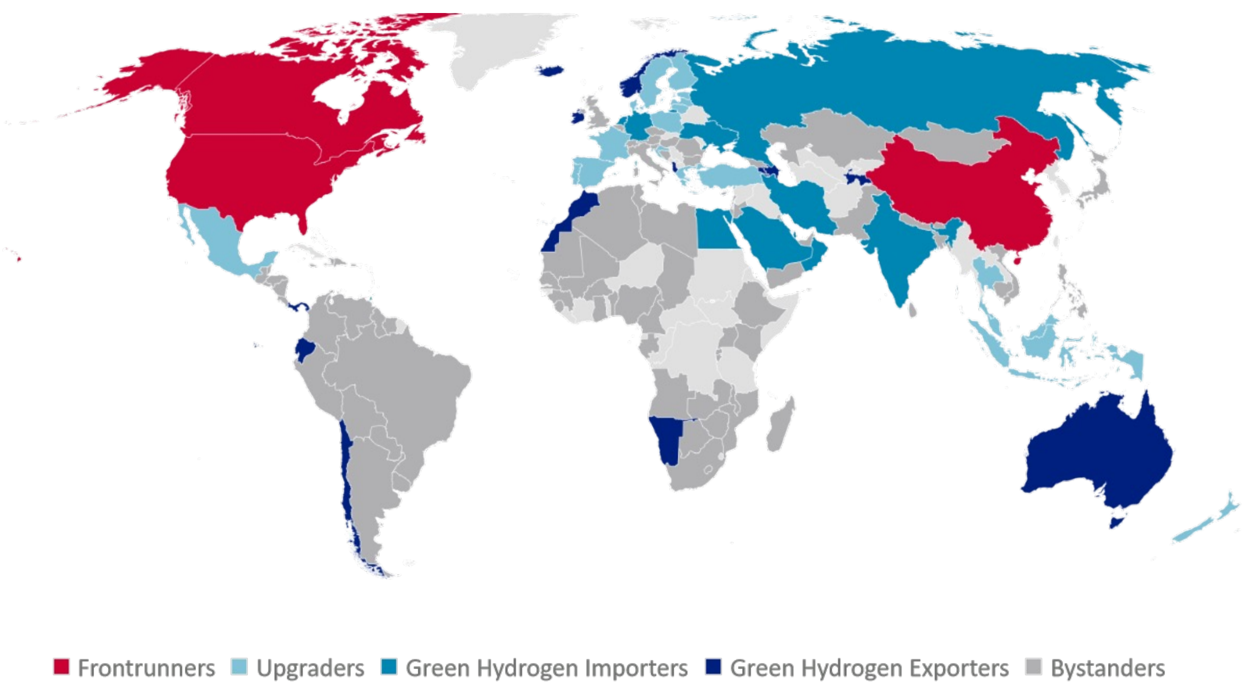

Figure 5. Country potential for at least two industrial green hydrogen applications

5. Case Studies—Opportunities and Challenges

5.1. The United States—a Frontrunner

Today the United States is one of the world's leading hydrogen producers, accounting for 13% of global demand, with 80% of this production deriving from natural gas that, even if cost-competitive compared to green hydrogen, has a much higher carbon intensity (IEA, 2019). At the same time, the country's vast solar, wind (Osmani, 2013), and freshwater endowments (AQUASTAT, 2020; Pflugmann & De Blasio, 2020) could turn the United States into a green hydrogen export champion and a frontrunner in future green hydrogen industrial applications.

Existing large ammonia and steel applications, equal to 10% and 3.9% of global production, respectively, have given rise to industrial clusters with relatively high-skilled labor forces. Stakeholders such as USS Steel Corp. are exploring decarbonization options (Reuters, 2021), while the largest U.S. ammonia producer, CF Industries, is building its first green ammonia plant in Louisiana, which should be operational by 2023 (Renews, 2021).

The U.S. government has made green hydrogen a key piece of its industrial and climate policy. The 'hydrogen program plan' supports technological innovation and green hydrogen deployment at scale (U.S. Department of Energy, 2020). One central instrument is the 'Energy Earthshot Initiative,' which aims to reduce the cost of green hydrogen by 80% to $1 per kg by 2030 (Office of Energy Efficiency and Renewable Energy, 2021). With investments of about $400 million in 2022 alone, the program provides grants to hydrogen innovation and demonstration projects focused specifically on chemical and industrial processes. One concrete example is the U.S. Department of Energy's support for projects in Texas that explore how to scale up production and industrial uses of green hydrogen (UT, 2020). These strategic industrial policies go in the direction of establishing the United States as a frontrunner in future global hydrogen value chains (Office of Energy Efficiency and Renewable Energy, 2021).

5.2. Thailand—a Potential Upgrader Driving Green Industrialization

Thailand is driving green industrialization partly as a means to create new job opportunities. Its long-term economic development plan 'Thailand 4.0' is aimed at moving the country from middle-income paying jobs to high-income ones in the next 20 years. Key measures include strengthening industrialization and spurring innovation, especially for the chemical sector, which is seen as the country's 'growth engine' (Royal Thai Embassy, 2021). Upgrading Thailand's positioning along green hydrogen value chains would highly resonate with these economic development goals.

Thailand has vast renewable resource endowments for green hydrogen production, and already leads in the ASEAN[11] region with more than 60% of the regional installed solar capacity (Hong, 2019). While biofuels still account for the majority of renewable electricity supply, government policies support the increase of wind and solar energy production (Hong, 2019; IEA, 2021b). Based on improvements in water management in the past decades, Thailand's water plan foresees no resource scarcity that would restrict green hydrogen production (Sethaputra et al., 2000). The first plants for green hydrogen production are already being built by the largest state-owned energy utility, EGAT (EGAT, 2019), and by the Chinese company Wison Engineering, which plans to start production in 2023 (Bailey, 2021).

Thailand could therefore build up green hydrogen-based industrial production. While domestic ammonia, methanol, and steel production is not yet established, Thai industries currently use imported ammonia as a feedstock for fertilizers in the food industry and refrigeration systems (Yoshimoto, 2017). Related industrial activities contribute to a high level of transferable skills; Thailand is a regional leader in chemicals and has an extensive refining base that has started to explore the use of green hydrogen to decarbonize diesel production (Bailey, 2021). These related economic activites and skills could become valuable assets for attracting green ammonia and methanol productions, but it is yet not clear whether the country could compete at scale in future green hydrogen markets and applications.

11 The Association of Southeast Asian Nations (ASEAN) includes the following countries: Brunei, Cambodia, Indonesia, Laos, Malaysia, Myanmar, the Philippines, Singapore, Thailand, and Vietnam.

Thailand has not yet developed a national hydrogen plan outlining the country's long-term vision and supporting policies. However, nascent initiatives like the multi-stakeholder 'Hydrogen Thailand Group' exist at a national level (PTT, 2020). At a cross-border level, ASEAN countries hold meetings to coordinate policies among member states and foster regional initiatives for the deployment of new hydrogen plants and enabling infrastructure (ASEAN, 2021). The production of green hydrogen and the build-up of green hydrogen industries could strengthen Thailand's role in regional trade with other ASEAN countries. However, more targeted policies will be needed to capitalize on the full potential of industrial upgrading opportunities.

5.3. **Germany—an Import-Dependent Decarbonizing Industrial Power**

Germany will need to rely on imports to meet projected green hydrogen demand due to its comparatively low solar and wind potentials and limited land availability (Nuñez-Jimenez & De Blasio, 2022; Prognos et al., 2021). Although several plants for green hydrogen production are being developed (BmWi, 2021e), recent estimates forecast that Germany could, at most, produce only a third of the needed green hydrogen demand by 2045 (See Figure 6) (Prognos et al., 2021).

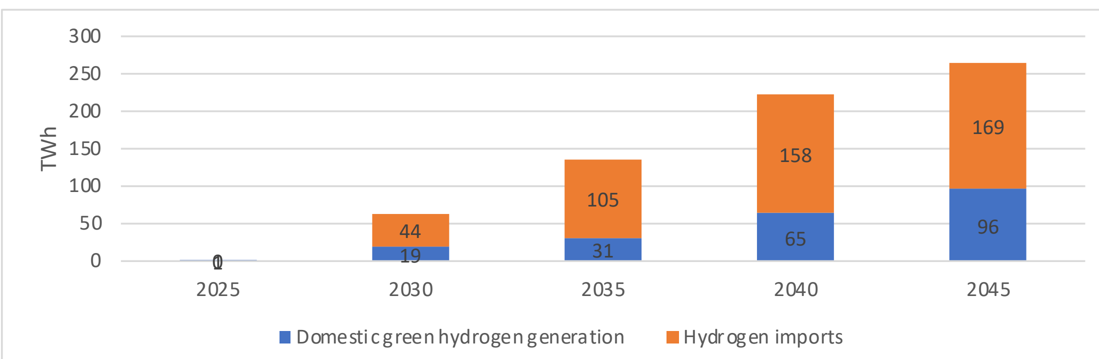

Figure 6. Projected green hydrogen production in Germany and import needs (Prognos et al., 2021, p. 23)

While Germany is not among the world's top producers of ammonia, methanol, or steel, it still accounts for considerable steel and ammonia production market shares, 2% and 1.7%, respectively (BmWi, 2021c; Statista, 2022). These industries are well established and often operate in captive markets with highly integrated infrastructure networks, including 400 km of hydrogen pipelines (IEA, 2019; Shell, 2017).

As these sectors decarbonize, a key challenge facing Germany will be how to remain competitive despite its import dependency, a challenge already seen in the chemical sector, which is under pressure due to the increasing offshoring of production facilities (Prognos et al., 2021, p. 45). On the other hand, highly specialized transferable skills, especially in the plastics sector, innovation clusters, and customer proximity, could become key assets (Prognos et al., 2021, p. 45).

The German government strongly supports a green hydrogen-based decarbonization of industrial applications. Several concrete support policies have already been introduced beyond a national hydrogen strategy that provides general guidance. These policies include a national innovation program providing up to 1.4 billion euros in public funding and 2 billion euros in private funding for hydrogen and fuel cell technologies (IEA, 2019). This program aims to build the needed know-how and skills through demonstration projects, such as the first synthetic methane production plants using green hydrogen as a feedstock being built in Werlte (IEA, 2019). On top of these national initiatives, Germany is also leveraging European Union (EU) initiatives based on the 'hydrogen strategy for a climate neutral Europe.' The EU and its member states support large-scale deployment of green hydrogen, especially in the steel and chemical industries, by uniting stakeholders in a 'European Clean Hydrogen Alliance' that provides public funding and promotes research and innovation (EC, 2022).

Policymakers at the national and EU levels are also focusing on securing stable green hydrogen imports for industrial applications. The EU hydrogen strategy aims to address the market and geopolitical implications of green hydrogen imports and the Commission prioritizes partnerships with key suppliers (EC, 2020), mainly Middle Eastern and Northern African countries (EC, 2020; IRENA, 2021). At the national level, Germany supports public partnerships and private sector collaborations with Morocco, Saudi Arabia, UAE, and Australia (BmWi, 2021a, 2021b, 2021d; Ghorfa, 2020). In addition, resource potentials for hydrogen imports have been assessed in cooperation with West and sub-Saharan African states, including Namibia (BmBF, 2021).

6. Geopolitical and Market Implications

Previous research on the geopolitics of green hydrogen has identified potential green hydrogen export champions, such as Australia, Canada, Norway, Namibia, and the United States, based on their vast resource endowments (IRENA, 2022; Pflugmann & De Blasio, 2020; Van de Graaf et al., 2020). Integrating critical insights from a value chain perspective allows us to elucidate the distribution of potential economic gains and losses and the associated geopolitical and market implications in more detail.

This study argues that the role countries will assume in future green hydrogen value chains depends not only on their resource endowments but also on their current positioning in hydrogen markets and the economic relatedness of their industrial sectors with green hydrogen applications. This implies that countries with significant renewable hydrogen potential could prioritize hydrogen exports ('green hydrogen exporters'), foster value creation opportunities by upgrading along value chains ('upgraders'), or both ('frontrunners').

Only a few countries, including China and the United States, might emerge as clear frontrunners that integrate numerous segments of value chains for various industrial green hydrogen applications. These countries have vast resource endowments and considerable market shares in today's hydrogen industrial applications that enable them to integrate the green hydrogen value chain segments of production and industrial applications. Locating industrial facilities close to low-cost green hydrogen production would create value by increasing a country's control over supply chains and minimizing hydrogen transportation costs. These countries could thus reap the most extensive benefits and become geopolitical and market winners. However, previous studies on the geopolitics of the energy transition have warned that these dynamics could spur a green race for industrial leadership, creating tensions in international relations (Fankhauser et al., 2013; Goldthau et al., 2019).

Today, most countries with highly developed ammonia, methanol, and steel industries, such as Saudi Arabia, Japan, and Germany, are resource constrained and would depend on green hydrogen imports to meet demand. Hence, from a geopolitical perspective, the past's dependencies and supply disruption risks are likely to persist in a low-carbon energy world, but will be different from today's (Bradshaw, 2009; Pflugmann & De Blasio, 2020; Toft, 2011). These new geopolitical dependencies will involve new alliances and will also be a function of future market structures; like natural gas markets, hydrogen markets will emerge as regional ones, but only global and more structured markets will allow for risk reduction (Pflugmann & De Blasio, 2020).

Furthermore, competing dynamics for green hydrogen-based industries could foster new geopolitical and market tensions and conflicts between green hydrogen importers and upgraders. The case study on Germany clearly exemplifies these potential dynamics. As discussed, Germany will need to import green hydrogen to meet demand. However, potential exporters (especially in Southern Europe and Northern Africa) could have a substantial economic interest in attracting the respective green hydrogen industrial applications instead of relying only on hydrogen exports. Countries with high resource potentials and highly skilled labor forces, like Spain, could instead aim to upgrade their value chain position and expand industrial hydrogen applications. These competing interests would likely result in trade barriers or conflicts; green hydrogen importers would protect internal markets with import tariffs on industrial products. At the same time, upgraders would support local industries with subsidies and local content requirements. Various studies on the dynamics of wind and solar value chains illustrate how countries, including China and India, have used trade barriers to strengthen the buildup of domestic industries (Bazilian et al., 2020; Chen & Lees, 2016; Dai & Xue, 2014; Hipp & Binz, 2020; Johnson, 2015; Kuntze & Moerenhout, 2013; Meckling & Hughes, 2017; Prud'homme et al., 2018; Quitzow et al., 2017; Zhang & Gallagher, 2016).

Furthermore, tensions between higher-income countries in the Global North and lower-income countries often located in the Global South might intensify. Our analysis shows how the potential for the three industrial hydrogen applications—ammonia, methanol, and steel—is unevenly distributed across the globe. Although there are opportunities for economic gains in all world regions, most frontrunners are middle- to high-income countries.[12] Our analysis shows that many lower-income countries, especially in Africa, will be limited to green hydrogen exports since they cannot compete in value-added segments of the value chains.

12 A country's income level classification is based on the World Bank (2021). Low-income countries have a gross national income (GNI) per capita below $1,045; lower middle-income countries have a GNI per capita between $1,046 and $4,095; upper middle-income countries between $4,096 and $12,695; high-income countries above $12,695.

Hence the promise of 'sustainable development' and green industrialization, often associated with the energy transition (Helgenberger et al., 2017), as, for example, in our case study country Thailand, might not be replicable everywhere. This finding is in line with existing literature on the 'uneven transition,' in which the gap between countries leading and benefiting from the energy transition and those that are not is widening (Eicke & Goldthau, 2021; Goldthau et al., 2020; Quitzow et al., 2021). This result might intensify previous debates in the United Nations Framework Convention on Climate Change (UNFCCC) on the need for technology transfer and financial support to enable sustainable development and green industrialization for all (Glachant & Dechezleprêtre, 2016; Hoekman et al., 2005; Kirchherr & Urban, 2018; Lema & Lema, 2013; Lema & Lema, 2012; McGee & Wenta, 2014).

Finally, we have identified several adjacent research topics in need of further academic focus. Potential areas include but are not limited to:

1. Apply the proposed framework to other sectors and applications. We exemplarily analyzed countries' potential for green hydrogen-based ammonia, methanol, and steel production. Further research could concentrate on value chains for other green hydrogen applications, including the transport and refining sectors.

2. Expand the analytical framework to elucidate and compare industrial upgrading and relocation from a system dynamics perspective, considering sector-specific and local factors such as regulations and labor costs. While many previous studies highlighted the importance of economic relatedness and skill and technology transfer, these complex processes seem to depend on further interdependent factors, which vary among countries and sectors (Baker et al., 2014; Gandenberger et al., 2015; Giuliani et al., 2005; Haakonsson & Slepniov, 2018; Pipkin & Fuentes, 2017; Qiu et al., 2013). Thus, further research on the specific dynamics in the chemical and steel sectors could help clarify the relative importance of these factors, in concrete country contexts. Previous research on relocations in wind and solar value chains might offer interesting entry points for a comparative analysis (Meckling & Hughes, 2017; Zhang & Gallagher, 2016).

3. Model differences in green hydrogen production costs, based on various constraints. Some of the mentioned constraints in this study could be overcome. Limited resource availability does not always imply that a country

will entirely depend on green hydrogen imports since it might still be able to produce some of its demand internally, as the case study on Germany highlights. Likewise, better water management systems and targeted training could increase freshwater availability and labor skills. At the same time, even if existing constraints were to be addressed, this would come at a cost, which could be modeled in future research.

7. Conclusion and Policy Recommendations

This paper addresses the potential for green hydrogen adoption at scale in three key industrial applications: ammonia, methanol, and steel production. Building on existing literature that assesses countries' potential for green hydrogen production (Pflugmann & De Blasio, 2020), we add critical insights from a value chain perspective. We propose an analytical framework to cluster countries into five groups based on resource endowment, current industrial production, and economic relatedness. Our findings offer more granular insights into the different roles countries could assume in future green hydrogen markets. Thus, they contribute empirical evidence to the ongoing debate on the geopolitics of hydrogen, and elucidate the distribution of potential economic gains and losses and the associated geopolitical and market implications.

Analyzing a country's potential value chain positioning in future green hydrogen markets can guide policymakers in defining strategic industrial policies for each country group:

Frontrunners. Countries with vast resource endowments and considerable market shares in today's hydrogen industrial applications could evolve into frontrunners by integrating green hydrogen value chain segments of production and industrial applications. Potential frontrunners should focus on industrial policies that foster the up-scaling of green hydrogen production and industrial applications.

Upgraders. Countries with adequate resources for green hydrogen production and highly related economic activities could potentially upgrade their value chain position and attract green hydrogen-based industries. Potential upgraders could benefit from strategic partnerships with frontrunners to foster technological and know-how transfer. Policies should focus on attracting foreign capital—for example, by lowering market risk, developing public-private partnerships, and forming joint ventures (Asiedu, 2006; Bürer & Wüstenhagen, 2009; Busse & Hefeker, 2007).

Green hydrogen exporters. Resource-rich countries without upgrading potential should prioritize green hydrogen exports and would benefit from partnerships with green hydrogen importers to deploy enabling infrastructure and reduce market risk. Further coordination among green hydrogen exporters on international standards for green hydrogen production could avoid conflict and facilitate trade at global scale.

Green hydrogen importers. Resource-constrained countries with industrial hydrogen-based production will need to develop strategic partnerships to ensure secure and stable green hydrogen supplies. Furthermore, stimulating innovation and knowledge creation through targeted policies will be critical to sustain competitiveness during the transition to a low-carbon economy and avoid industrial relocation to frontrunners or upgraders.

Bystanders. Countries with significant constraints along all three critical variables of resource endowment, current positioning in hydrogen markets, and economic relatedness should assess whether some of these constraints, such as limited infrastructure or freshwater availability, could be overcome.

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Belfer Center for Science and International Affairs
Harvard Kennedy School
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