Energy Research & Social Science 93 (2022) 102847

Contents lists available at ScienceDirect

Energy Research & Social Science

journal homepage: www.elsevier.com/locate/erss

Original research article

# Green hydrogen value chains in the industrial sector—Geopolitical and market implications

Laima Eicke [a,b,c,*], Nicola De Blasio [a]

[a] Belfer Center for Science and International Affairs, Harvard University, 79 John F. Kennedy St, Cambridge, MA 02138, United States
[b] Institute for Advanced Sustainability Studies (IASS), Berliner Str. 130, 14467 Potsdam, Germany
[c] Willy Brandt School for Public Policy, University of Erfurt, Nordhäuser Straße 84, 99089 Erfurt, Germany

ARTICLE INFO

*Keywords:*
Green hydrogen
Geopolitics
Energy transition
Industry
Energy policy
Value chain

ABSTRACT

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 could play a significant role in reaching a carbon-free future by 2050. Its adoption will be critical for decarbonizing industrial processes at scale, especially hard-to-abate ones such as steel and cement production. This paper maps the role countries could play in future green hydrogen industrial markets based on three criteria: resource endowment, existing industrial production, and economic relatedness. Our analysis shows how the potential for green hydrogen production and leadership in industrial applications is distributed unequally around the globe. Countries like the United States and China could emerge as frontrunners in future green hydrogen markets and lead in industrial applications, such as ammonia, methanol, and steel production. Other resource-rich countries could upgrade along value chains and compete with import-dependent industrial powers for jobs and market shares. A transition in existing value chains will also give rise to new market and geopolitical dynamics and dependencies. This paper contributes empirical evidence to the debate on the geopolitics of hydrogen and guides in defining strategic industrial policies.

## 1. Introduction

Green hydrogen[1] could play a significant role in the decarbonization of hard-to-abate industrial sectors, such as steel and cement [1]. Global hydrogen demand is expected to grow by 700 % by 2050 [2], from today's 70 million tons per year [3]. The use of green 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 [4,5].

Previous studies on the geopolitics of hydrogen have analyzed the different roles that countries could adopt in future hydrogen markets and how the associated economic gains might affect international relations [6,7]. 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 [8]. 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 are supported by the sector's higher economies of scale and are lower risk than other potential applications [8].

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

* Corresponding author at: Institute for Advanced Sustainability Studies (IASS), Berliner Str. 130, 14467 Potsdam, Germany.
*E-mail addresses:* laima_eicke@hks.harvard.edu (L. Eicke), ndeblasio@hks.harvard.edu (N. De Blasio).

[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.

https://doi.org/10.1016/j.erss.2022.102847
Received 27 May 2022; Received in revised form 19 August 2022; Accepted 13 October 2022
Available online 25 October 2022
2214-6296/© 2022 Elsevier Ltd. All rights reserved.

that would give them a distinct advantage in future green hydrogen markets: resource endowment, current industrial production, and economic relatedness. We then apply this framework to identify countries' potential in using green hydrogen at scale for three industrial applications: ammonia, methanol, and steel production. Finally, we use three case studies to analyze the role of supportive political economy in driving a country's transition to specific roles in future green hydrogen value chains. These case studies help to elucidate the challenges and opportunities of different country groups in defining their strategic industrial positioning in future industrial value chains and outline 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 green hydrogen but integrates it based on insights from the global value chain literature. Our findings demonstrate that this integrated perspective offers new insights into the different roles countries could assume in a green hydrogen economy and the distribution of associated economic gains and losses. They further inform the debate on how the shift towards green hydrogen might create new geopolitical conflicts and affect international relations beyond the energy sector. They also provide guidance and recommendations for defining the needed strategic industrial policies to accelerate the transition to a low-carbon economy for hard to abate sectors.

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 green 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.

## 2. Literature review and framework

The debate on the geopolitics of the energy transition has significantly intensified over the past decade [9–17] focusing on three main questions: a) how does the increasing use of renewable energy affect international relations? b) Which countries might become the winners and losers in the energy transition? and c) how does the energy transition to a low-carbon change overall international relations? [10]. Although most analyses have focused on wind and solar energy, the debate on the geopolitical implications of green hydrogen adoption at scale has been rising. Scholars have argued that the projected rapid growth in green hydrogen demand might lead to new geopolitical opportunities and challenges [6–8,18]. Literature on peace and conflict has called hydrogen the 'new oil' [7] and warned that emerging hydrogen markets could lead to geo-economic competition and conflict [14]. New trade patterns might give rise to novel export champions, and resource-poor countries might face new geopolitical dependencies [6]. Some studies have analyzed the potential for green hydrogen production worldwide to identify potential winners [6,18,19], while others have addressed potential global trade patterns and governance [7].

Most of these studies have addressed the above questions based on a classic definition of geopolitics, thus analyzing the "influence of geography on the power of states and international affairs with [..] emphasis on […] the strategic importance of natural resources, their location, transportation routes, and chokepoints" [20]. Very few studies have focused on a critical geopolitics approach, which moves beyond geographical boundaries and includes economic, political, cultural, and technological aspects and constructions that are "changeable over time" [10,21]. Using an approach rooted in critical geopolitics, this paper argues that in the energy transition to a low-carbon economy it is important to look beyond natural resource endowments to identify changes in international relations and that the adoption of green hydrogen becomes at scale, countries will dynamically affect global value chains over time, based on economic and technological developments.

In current literature, few articles hint at the importance of value chains for international relations [7,14,22–24]. A notable exemption is a work of Lachapelle et al. on the division of labor in renewable energy technologies globally, highlighting the diverse strategies countries employ to gain leadership across value chain segments [24]; but only very few examine in detail the geopolitical implications of green hydrogen adoption at scale in industrial applications and the associated impact on value chains [8]. Some of these studies have explored the technological and cost improvements in hydrogen applications [23,25] or examined hydrogen value chains in country-specific case studies, for example, in Germany [26], Japan [27] and the United States [28]. 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 green 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. We argue that a detailed understanding of global value chains can help to overcome the dichotomy of winners and losers in the energy transition and provide a much more granular understanding of the diverse roles of countries in a green hydrogen economy. Furthermore, these insights can inform debates on how the shift towards green hydrogen might create new conflicts and affect international relations beyond the energy realm, in particular between countries of the Global North and the Global South.

The literature on global value chains encompasses various disciplines, including business and management studies, geography, development studies, and international political economy [29]. This paper draws on the concepts of industrial upgrading as well as integration and segmentation along value chains, as discussed in more detail in the following paragraphs.

Critical segments of future green hydrogen value chains include research and development, production, distribution, applications, and retail of products to end users (see Fig. 1). As discussed, our analysis focuses on green hydrogen production and its industrial applications using ammonia, methanol, and steel production as examples (highlighted in dark blue in Fig. 1).

Existing literature on global value chains highlights how a product's final value 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 [30,31]. In the case of green hydrogen, this implies that industrial applications, such as ammonia, methanol, or steel production, could yield more added value for stakeholders 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 [32,33], 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 energy sectors thanks to favorable and stable policies to grow global market shares and the required skilled labor force [34–36]. Pursuing green industrialization has been


**Fig. 1.** Green hydrogen value chain segments for industrial applications.

especially important for Global South countries, where policymakers have used strategic industrial policies to upgrade a country's value chain position [30,37]. Several studies have also highlighted the importance of technology transfer and knowledge spillovers from related industries to enable upgrading processes in renewable value chains [30,38–46].

Nascent green 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 is key in highlighting 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 [47].

Integration is usually associated with gains in higher value accumulation and a more substantial degree of control [32,47]. 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 [48], 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 [49] and the war in Ukraine [50]. Strategic industrial policies driving integration could support the relocation of carbon-intensive industries closer to low-cost green hydrogen production [8].

We argue that combining the two research streams on global value chains and the geopolitics of green 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 green hydrogen highlighted countries that could benefit from adopting 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 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.

#### 2.1.1. Resource endowment

Green hydrogen is hydrogen produced by splitting water into hydrogen and oxygen using renewable electricity. The availability of plentiful renewable energy sources, such as sun radiation and wind speeds, land availability and a countries own energy demand is decisive; additionally freshwater availability and enabling infrastructure are critical for producing green hydrogen at scale. Accordingly, these variables have been used by Pflugmann and De Blasio [6] to assess green hydrogen potentials globally.

#### 2.1.2. 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 [51]. 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 [8].

#### 2.1.3. 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 [8]. Future economic growth of products or industries at a national or subnational level has been successfully predicted based on economic relatedness [52,53], to evaluate the percentage of related activities in a particular location.[3] Related activities require comparable knowledge and enabling factors to build transferable skills that increase the potential for new markets and sectoral economic growth [53–56]. Economic activities highly related to ammonia, methanol, and steel production increase the potential for these applications to be developed in a given country based on existing transferable skills, business networks, raw material availability, and infrastructure.

These three criteria elucidate a country's potential to engage in future green hydrogen value chains. While high potentials indicate the expectation of future economic gains along value chains, countries may or may not live up to these expectations. The realization of this potential depends on various factors that shape a country's political economy, such as national and international policies, finance and market dynamics, stakeholder relations and path dependencies [19,57–59]. A detailed analysis of these factors at a global scale is beyond the scope of this paper and, we believe, would thwart the goal of a transparent and objective overview. At the same time, we recognize these factors' importance and address them in the country case studies, where more in-depth analysis is warranted (see Section 5).

Using the three criteria, resource endowment, industrial production, and economic relatedness, we cluster countries into five groups (see Table 1): Resource-rich countries with industrial hydrogen-based productions 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

[3] 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 Mcp refers to a matrix indicating the presence of activity p in location c; ϕpp′ is a measure of similarity between activities p and p′; For further details on the methodology, see [70].

**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 |

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 green 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 [8]. 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 ([64]:56). Ammonia could also be used as a hydrogen carrier for the long-distance transport of green hydrogen ([3]). Most methanol (accounting for 11 % of global hydrogen demand) is used in the chemical industry [3]. Like ammonia, methanol could further enable global hydrogen markets as it can be used as a fuel or as a carrier for the transport of hydrogen [3]. 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 [15].

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 [61]. From a long-term perspective, IRENA predicts a decline in green hydrogen costs by up to 85 % by 2050 [48], making it the dominant hydrogen source [8].

## 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 green 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 [6]: '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 green 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[8] [66]. Otherwise countries were coded with 'one.'

### 3.1. 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 [67] and steel [68] is above 1 %, or in the case of methanol,[9] a country's share of global net exports is above 1 %.[10] Otherwise, it is coded as 'zero.'

### 3.2. 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; otherwise, it is coded as 'zero' [70]. The economic relatedness global averages are 0,152 for ammonia, 0,134 for methanol, and 0,248 for steel [70].

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.

To ensure the consistency of available databases across several value chains and at a global scale, we opted for a binary coding scheme at the

[4] Refining would be another prominent hydrogen application, accounting for 33 % of the current demand [60] (excluded from the analysis).

[5] The combined potential for renewable electricity production per country is calculated based on the wind power potential, which is based on NREL [62], and the solar power potential, which is based on Pietzecker et al. [63].

[6] Primary energy consumption is based on the year 2019 [64].

[7] Countries with freshwater resources below this threshold predominantly use these for current drinking, household consumption, industrial use, and/or irrigation demand and have no additional capacities for increased water demand for hydrogen production [6]. Freshwater resource data are based on AQUASTAT [65].

[8] The infrastructure score indirectly also accounts for economic development, financial variables such as access to capital markets and cost of capital, and political stability which are enabling factors for a country's ability to develop infrastructure at scale which is key to produce and trade hydrogen at scale [6].

[9] 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 [69].

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

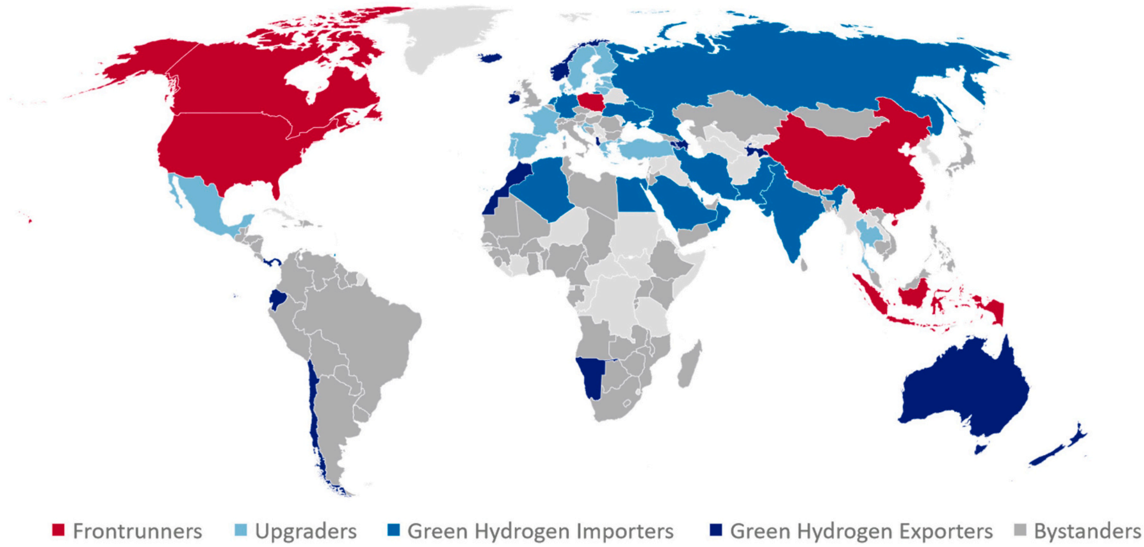


**Fig. 2.** Geopolitical map of green ammonia production potential.

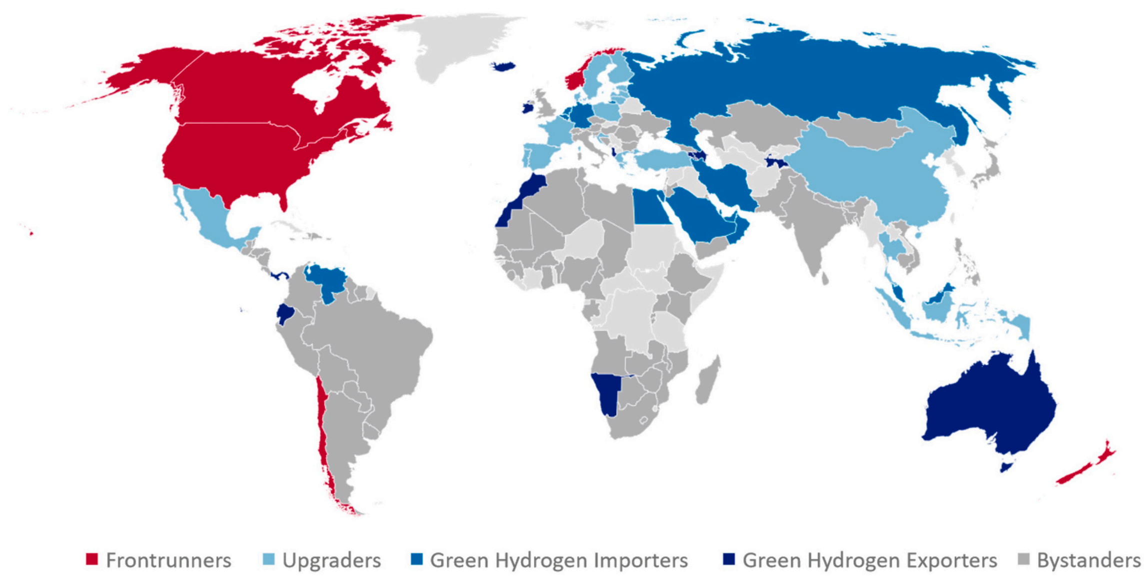


**Fig. 3.** Country potential for methanol production based on green hydrogen.

expense of a reduced granularity. At the same time, our analysis is based on conservative assumptions on which we have conducted extensive sensitivities analyses in previous studies [6,71].

Overall, frontrunners, upgraders, green hydrogen exporters, and importers will shape future green hydrogen geopolitics and markets more than bystanders. From an industrial value chain perspective, frontrunners, upgraders, and green hydrogen importers will be critical as exporters will focus only on commodity trading. For this reason, we focused our case studies on the United States (frontrunner), Thailand (upgrader), and Germany (importer). These case studies also help to elucidate how a country's political and economic context influences its ability to attain a specific role in green hydrogen industrial value chains.

Case studies were selected based on three criteria. First, we targeted countries representative of an entire country group that also provided consistency on the underlying fundamentals across the three selected industrial applications. The United States and Thailand fall in the same country group for all applications, and Germany in two out of three. Second, we chose countries with clear political support (political willingness) to drive the transition to frontrunners, upgraders, or green hydrogen importers in future green hydrogen value chains. These policies are discussed in the respective case studies (see Section 5). Third, we prioritized a geographically diverse distribution to include critical future global markets. It should be noted that the current dominance in industrial hydrogen applications and markets was not the driving selection parameter. 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 [13].

## 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.

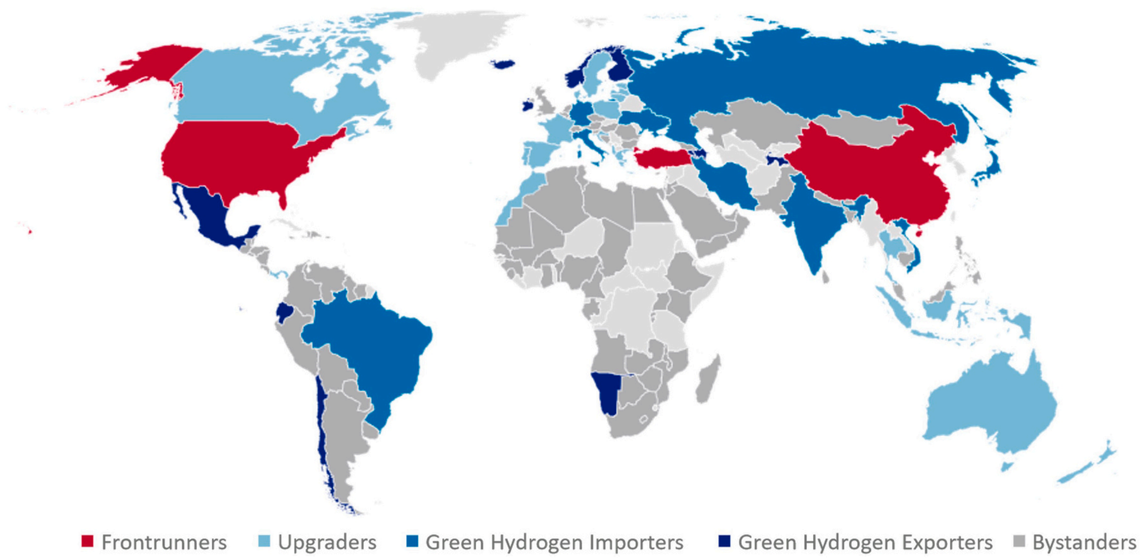


**Fig. 4.** Country potential for steel production based on green hydrogen.

### 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 (3.5 %), and Egypt (3.1 %). 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 (2.7 % market share) or Poland (1.5 %), 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, or Thailand, could evolve into green ammonia upgraders. Finally, countries with high green hydrogen production potentials but low transferrable skills could also benefit by exporting green hydrogen to import-dependent ammonia producers such as Egypt or Germany (see Fig. 2).

### 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 green hydrogen exporters to countries with extensive green methanol-based industries but low production potentials (see Fig. 3).

### 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 % respectively). While China and the United States are well positioned to become frontrunners in future green steel markets, India, Japan, 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 Fig. 4).

### 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 green 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 Fig. 5).

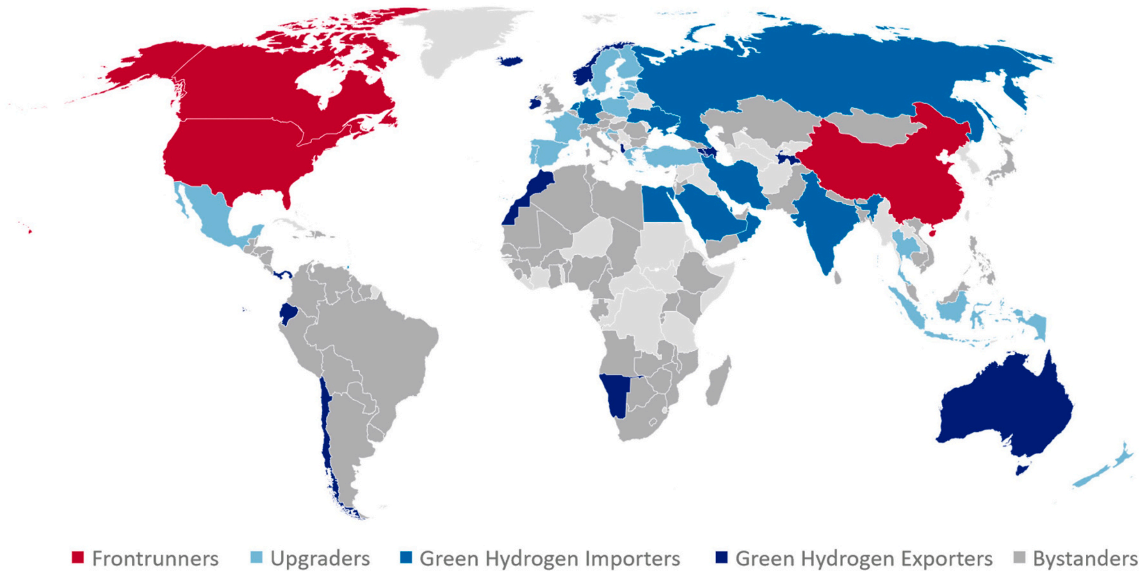


**Fig. 5.** Country potential for at least two industrial green hydrogen applications.

## 5. Case studies—opportunities and challenges

### 5.1. *The United States—a frontrunner*

The United States has a high potential to become a frontrunner in industrial green hydrogen value chains, due to a large resource endowment, existing industrial production of ammonia, methanol and steel and highly related economic activities that support sectoral growth. 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 [3]. At the same time, the country's vast solar, wind and freshwater endowments [6,65] could turn the United States into a green hydrogen export champion; furthermore they have the potential to become 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.

The US development into a frontrunner in industrial green hydrogen value chains is enabled by a supportive political economy context. Energy has been seen as center piece for national security and geopolitical influence in the US for decades [10,72]. These concerns have been key drivers for renewable energy production, especially after the oil crisis. Based on booming shale gas extraction, the US has turned from an energy importer to an energy exporter – with the ambition to "lead on all forms of energy", which implies strengthening its position not only in LNG gas markets but also in emerging green hydrogen markets [72]. Accordingly, 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 [73]. One central instrument is the 'Energy Earth shot Initiative,' which aims to reduce the cost of green hydrogen by 80 % to $1 per kg by 2030 [74]. With investments of about 400 million in 2022 alone, the program provides grants to green 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, [75]]. Accordingly, industrial stakeholders such as USS Steel Corp. are exploring decarbonization options [76], while the largest U.S. ammonia producer, CF Industries, is building its first green ammonia plant in Louisiana, which should be operational by 2023 [77]. These strategic industrial policies go in the direction of establishing the United States as a frontrunner in future global green hydrogen value chains [74].

### 5.2. *Thailand—a potential upgrader driving green industrialization*

Thailand has the potential to upgrade its role in industrial value chains based on vast renewable resource endowments for green hydrogen generation, related skills and a supportive business network based on high economic relatedness. Thailand already leads in the ASEAN[11] region with more than 60 % of the regional installed solar capacity [78]. While biofuels still account for the majority of renewable electricity supply, government policies support the increase of wind and solar energy production [78,79]. Based on improvements in water management in the past decades, Thailand's water plan foresees no resource scarcity that would restrict green hydrogen production [80]. The first plants for green hydrogen production are already being built by the largest state-owned energy utility, EGAT [81], and by the Chinese company Wison Engineering, which plans to start production in 2023 [82]. Additionally, Thailand could 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 [83]. 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 [82]. These related economic activities 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.

This development is generally supported by Thailand's political economy context. 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

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

innovation, especially for the chemical sector, which is seen as the country's 'growth engine' [84]. Upgrading Thailand's positioning along green hydrogen value chains would highly resonate with these economic development goals. However, 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 [85]. At a cross-border level, ASEAN countries hold meetings to coordinate policies among member states and foster regional initiatives for the deployment of new green hydrogen plants and enabling infrastructure [86]. 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 [71,87]. Although several plants for green hydrogen production are being developed [88], recent estimates forecast that Germany could, at most, produce only a third of the needed green hydrogen demand by 2045 [87].

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 [89,90]. These industries are well established and often operate in captive markets with highly integrated infrastructure networks, including 400 km of hydrogen pipelines [3,91].

As these sectors decarbonize, a key challenge facing Germany will be how to remain competitive despite its import dependency. This challenge for the countries' political economy is already seen in the chemical sector, which is under pressure due to the increasing offshoring of production facilities [87]. On the other hand, highly specialized transferable skills, especially in the plastics sector, innovation clusters, and customer proximity, could become key assets [87].

The German government strongly supports the 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 [3]. 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 [3]. 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 [92].

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 [94], mainly Middle Eastern and Northern African countries [93,94]. At the national level, Germany supports public partnerships and private sector collaborations with Morocco, Saudi Arabia, UAE, and Australia [95–98]. In addition, resource potentials for green hydrogen exports have been assessed in cooperation with West and sub-Saharan African states, including Namibia [99].

## 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 [6–8]. 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 green 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, have the potential to 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. Given a supportive political economy context, like in the US, 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 [17,100].

Our analysis highlights that countries with highly developed ammonia, methanol, or steel industries, such as Saudi Arabia, Japan, or Germany, are also resource-constrained and would depend on green hydrogen imports to meet demand. Hence, their role in future green hydrogen markets will be limited unless these constraints are addressed at scale through appropriate policy instruments and innovation investments. It is important to note that limited resource availability does not always imply that a country will entirely depend on imports. As the case study on Germany highlights, Berlin could still satisfy one-third of its green hydrogen demand with domestic production but will need to do so cost competitively [87]. Gulf countries like Saudi Arabia, the United Arab Emirates, and Oman are also announcing new green hydrogen plants [101]. Still, regardless of their vast renewable energy potential, they are classified as importers due to the significant freshwater constraints they face, which would not allow them to compete at scale. At the same time, addressing these constraints will come at a cost. Deploying desalination capabilities at scale would require "billions in investments and considerably increase the capital required for developing hydrogen supply" [101] and might regardless intensify internal conflicts [102].

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 [6,103,104]. These new geopolitical dependencies will also be a function of future market structures. Like natural gas, green hydrogen markets will emerge as regional ones, but only global supply diversification might "reduce the risk of politically driven supply disruptions and increase a country's energy security" [6]. Furthermore, green ammonia or methanol could further enable global hydrogen markets thanks to their higher hydrogen density by volume, hence reducing long-distance transport costs [8]. Initial studies have mainly modeled potential trade streams between countries but Nuñez-Jimenez and De Blasio [71] highlight that trade will also depend on a country's political choices regarding energy security, independence, and cost optimization [71]. Finally, shared international hydrogen regulations and standards will be essential in shaping future markets and might be a further source of conflict.

Further 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 green hydrogen exports. Countries with high resource potentials and highly skilled labor forces, like Thailand or Spain, could instead aim to upgrade their value chain position and expand industrial hydrogen applications. These competing interests might result in trade barriers or conflicts; green hydrogen importers might protect internal markets with import tariffs on industrial products. At the same time, upgraders might support local industries with subsidies and local content requirements. Various studies on the dynamics of wind and solar value chains illustrate how diverse economies, including the United States, China, India, Spain or South Africa, have used trade and investment barriers to strengthen the buildup of domestic industries [35,37,46,105–112].

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. Hence the promise of 'sustainable development' and green industrialization, often associated with the energy transition [114], 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 [13,115,116]. This result might intensify previous debates in the UNFCCC on the need for technology transfer and financial support to enable sustainable development and green industrialization for all [42,117–121].

Finally, we have identified several adjacent research topics that need further academic focus on the geopolitics of green hydrogen value chains. Potential areas include but are not limited to:

- Analyze how the shift to green hydrogen changes countries roles and creates gains and losses by applying the proposed framework to further value chain segments and other sectors using green hydrogen as an input. While our analysis focuses on a country's potential for green hydrogen-based ammonia, methanol, and steel production, further could examine the interplay between the remaining value chain segments, expand to other green hydrogen applications, or compare value chain structures across sectors, such as oil and gas.
- Further investigate how the evolution of green hydrogen value chains shapes international relations. Our analysis pointed towards competing dynamics between current industrial powers and countries that might upgrade their position in industrial value chains. Further research on the specific dynamics in the chemical and steel sectors could help clarify the relative importance of further political and economic factors, in concrete country contexts. Previous research on relocations in wind and solar value chains might offer interesting entry points for a comparative analysis [46,106].
- Expand research on how the shift towards green hydrogen might affect international relations beyond the energy realm. Our analysis indicates that the gains from green hydrogen value chains might be unequally distributed. Further research might potentially asymmetric power relations in green hydrogen value chains and integrate concepts from political ecology and post-colonial studies [5,122].

[12] A country's income level classification is based on the World Bank [113]. Low-income countries have a gross national income (GNI) per capita below $1045; lower middle-income countries have a GNI per capita between $1046 and $4095; upper middle-income countries between $4096 and $12,695; high-income countries above $12,695.

## 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 [6], 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 and elucidate the role of the political economy for countries' success in these roles through three case studies. Our findings offer more granular insights into the different roles countries could assume in future green hydrogen markets, focusing on industrial applications. Thus, they contribute empirical evidence to the ongoing debate on the geopolitics of green hydrogen and elucidate the distribution of potential economic gains and losses and the associated geopolitical and market implications. This analysis also elucidates how adopting green hydrogen at scale might create competition among frontrunners in a green race and tensions between green hydrogen importers and industrial upgraders. This nascent dynamics will also affect international relations beyond the energy realm, fostering the debate on sustainable development and a just transitions between countries of the Global North and the Global South.

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:

### 7.1. *Frontrunners*

Countries with vast resource endowments and considerable market shares in today's hydrogen industrial applications, like the United States, 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 upscaling of green hydrogen production and industrial applications.

### 7.2. *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, such as Thailand, 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 [123–125].

### 7.3. *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.

### 7.4. Green hydrogen importers

Resource-constrained countries with industrial hydrogen-based production, such as Germany, 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.

### 7.5. 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.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

Data will be made available on request.

## Acknowledgements

The authors thank Andreas Goldthau, Silvia Weko, Henry Lee, John Holdren, Venky Narayanamurti, and Abishek Malhotra for feedback and comments on earlier versions of this paper.

## References

[1] S. Griffiths, et al., Industrial decarbonization via hydrogen: a critical and systematic review of developments, socio-technical systems and policy options, Energy Res. Soc. Sci. 80 (2021), 102208.
[2] BP, Statistical Review of World Energy, 2019.
[3] IEA, The Future of Hydrogen, International Energy Agency, Paris, 2019.
[4] IEA, Hydrogen, Available from: https://www.iea.org/reports/hydrogen, 2021.
[5] P. Devine-Wright, Decarbonisation of industrial clusters: a place-based research agenda, Energy Res. Soc. Sci. 91 (2022), 102725.
[6] F. Pflugmann, N. De Blasio, The geopolitics of renewable hydrogen in low-carbon energy markets, Geopolitics Hist. Int. Rel. 12 (1) (2020) 9–44.
[7] T. Van de Graaf, et al., The new oil? The geopolitics and international governance of hydrogen, Energy Res. Soc. Sci. 70 (2020), 101667.
[8] IRENA, Geopolitics of the Energy Transformation: The Hydrogen Factor, 2022. Abu Dhabi.
[9] I. Overland, et al., The GeGaLo index: geopolitical gains and losses after energy transition, Energy Strateg. Rev. 26 (2019), 100406.
[10] R. Vakulchuk, I. Overland, D. Scholten, Renewable energy and geopolitics: a review, Renew. Sust. Energ. Rev. 122 (2020), 109547.
[11] D. Criekemans, Geopolitics of the renewable energy game and its potential impact upon global power relations, in: D. Scholten (Ed.), The Geopolitics of Renewables, Springer, London, 2018, pp. 37–74.
[12] D. Scholten, The Geopolitics of Renewables, Springer, 2018.
[13] A. Goldthau, L. Eicke, S. Weko, The global energy transition and the global south, in: The Geopolitics of the Global Energy Transition, Springer, 2020, pp. 319–339.
[14] M. Blondeel, et al., The geopolitics of energy system transformation: a review, Geography Compass 15 (7) (2021).
[15] IRENA, A New World. The Geopolitics of the Energy Transformation, Global Commission on the Geopolitics of Energy Transformation, Abu Dhabi, 2019.
[16] M. O'Sullivan, I. Overland, D. Sandalow, The Geopolitics of Renewable Energy. HKS Working Paper No. RWP17-027, 2017.
[17] A. Goldthau, et al., Model and manage the changing geopolitics of energy, Nature 569 (7754) (2019) 29–31.
[18] T. Van de Graaf, Clean hydrogen: building block of a new geopolitical landscape, in: Energy and Geostrategy 2021, Spanish Institute for Strategic Studies, 2021, pp. 185–230.
[19] M. Pfennig, M. Bonin, N. Gerhardt, Ptx-Atlas: Weltweite Potenziale für Die Erzeugung von Grünem Wasserstoff und Klimaneutralen Synthetischen Kraft—Und Brennstoffen, Fraunhofer IEEE Institute für Energiewirtschaft und Energietechnik, Kassel, Germany, 2021.
[20] I. Overland, The geopolitics of renewable energy: debunking four emerging myths, Energy Res. Soc. Sci. 49 (2019) 36–40.
[21] P.M. Amineh, Globalisation, Geopolitics and Energy Security in Central Eurasia and the Caspian Region, 2003.
[22] M. Noussan, et al., The role of green and blue hydrogen in the energy transition—a technological and geopolitical perspective, Sustainability 13 (1) (2021) 298.
[23] B. Lebrouhi, et al., Global hydrogen development-a technological and geopolitical overview, Int. J. Hydrog. Energy 47 (11) (2022) 7016–7048, https://doi.org/10.1016/j.ijhydene.2021.12.076.
[24] E. Lachapelle, R. MacNeil, M. Paterson, The political economy of decarbonisation: from green energy 'race'to green 'division of labour', New Polit. Econ. 22 (3) (2017) 311–327.
[25] S. Chen, et al., Hydrogen value chain and fuel cells within hybrid renewable energy systems: advanced operation and control strategies, Appl. Energy 233 (2019) 321–337.
[26] D. Coleman, et al., The value chain of green hydrogen for fuel cell buses–a case study for the Rhine-main area in Germany, Int. J. Hydrog. Energy 45 (8) (2020) 5122–5133.
[27] M. Nagashima, Japan's Hydrogen Strategy and Its Economic and Geopolitical Implications, Ifri, 2018.
[28] M.F. Ruth, et al., The Technical and Economic Potential of the H2@ Scale Hydrogen Concept Within the United States, Available from:, National Renewable Energy Lab.(NREL), Golden, CO (United States), 2020.
[29] L. Kano, E.W. Tsang, H.W.-c. Yeung, Global value chains: a review of the multi-disciplinary literature, J. Int. Bus. Studies 51 (4) (2020) 577–622.
[30] S. Pipkin, A. Fuentes, Spurred to upgrade: a review of triggers and consequences of industrial upgrading in the global value chain literature, World Dev. 98 (2017) 536–554.
[31] G. Gereffi, J. Lee, Why the world suddenly cares about global supply chains, J. Supply Chain Manag. 48 (3) (2012) 24–32.
[32] G. Gereffi, The global economy: organization, governance and development, in: N.J.S.a.R. Swedberg (Ed.), The Handbook of Economic Sociology, Princeton University Press and Russell Sage Foundation, Princeton, NJ, 2005.
[33] J. Humphrey, H. Schmitz, How does insertion in global value chains affect upgrading in industrial clusters? Reg. Stud. 36 (9) (2002) 1017–1027.
[34] C. Binz, B. Truffer, Global innovation systems—a conceptual framework for innovation dynamics in transnational contexts, Res. Policy 46 (7) (2017) 1284–1298.
[35] G.C. Chen, C. Lees, Growing China's renewables sector: a developmental state approach, New Polit. Econ. 21 (6) (2016) 574–586.
[36] C. Gandenberger, et al., The international transfer of wind power technology to Brazil and China, in: Working Paper Sustainability and Innovation, Fraunhofer ISI, Karlsruhe, 2015.
[37] M. Bazilian, V. Cuming, T. Kenyon, Local-content rules for renewables projects don't always work, Energy Strateg. Rev. 32 (2020), 100569.
[38] L. Tajoli, G. Felice, Global value chains participation and knowledge spillovers in developed and developing countries: an empirical investigation, Eur. J. Dev. Res. 30 (3) (2018) 505–532.
[39] L. Eicke, S. Weko, Does green growth foster green policies? Value chain upgrading and feedback mechanisms on renewable energy policies, Energy Policy 165 (2022), 112948.
[40] L. Eicke, S. Weko, 'Winning' the energy transition: looking beyond resources, in: D. Tentori (Ed.), Energy & Geopolitics: The Green Transition in Times of War, Italian Institute for International Political Studies (ISPI), 2022.
[41] A. Öhman, E. Karakaya, F. Urban, Enabling the transition to a fossil-free steel sector: the conditions for technology transfer for hydrogen-based steelmaking in Europe, Energy Res. Soc. Sci. 84 (2022), 102384.
[42] R. Lema, A. Lema, Technology transfer? The rise of China and India in green technology sectors, Innov. Dev. 2 (1) (2012) 23–44.
[43] H. Liu, D. Liang, A review of clean energy innovation and technology transfer in China, Renew. Sust. Energ. Rev. 18 (2013) 486–498.
[44] D. Ockwell, R. Byrne, Improving technology transfer through national systems of innovation: climate relevant innovation-system builders (CRIBs), Clim. Pol. 16 (7) (2016) 836–854.
[45] A. Pueyo, et al., The role of technology transfer for the development of a local wind component industry in Chile, Energy Policy 39 (7) (2011) 4274–4283.
[46] F. Zhang, K.S. Gallagher, Innovation and technology transfer through global value chains: evidence from China's PV industry, Energy Policy 94 (2016) 191–203.
[47] G. Gereffi, J. Humphrey, T. Sturgeon, The governance of global value chains, Rev. Int. Polit. Econ. 12 (1) (2005) 78–104.
[48] IRENA, Green Hydrogen Cost Reduction. Scaling up Electrolysers to Meet the 1.5°C Climate Goal, 2020. Abu Dhabi.
[49] I. Øverland, et al., Covid-19 and the Politics of Sustainable Energy Transitions, 2020.
[50] D. Simchi-Levi, P. Haren, How the War in Ukraine Is Further Disrupting Global Supply Chains, Available from: https://hbr.org/2022/03/how-the-war-in-ukraine-is-further-disrupting-global-supply-chains, 2022.
[51] M. Lambkin, Order of entry and performance in new markets, Strateg. Manag. J. 9 (S1) (1988) 127–140.
[52] F. Neffke, M. Henning, R. Boschma, How do regions diversify over time? Industry relatedness and the development of new growth paths in regions, Econ. Geogr. 87 (3) (2011) 237–265.
[53] R. Hausmann, et al., The Atlas of Economic Complexity: Mapping Paths to Prosperity, Mit Press, 2014.

[54] R. Hausmann, C.A. Hidalgo, The network structure of economic output, J. Econ. Growth 16 (4) (2011) 309–342.
[55] C.A. Hidalgo, et al., The product space conditions the development of nations, Science 317 (5837) (2007) 482–487.
[56] C.A. Hidalgo, et al., The principle of relatedness, in: International Conference on Complex Systems, Springer, 2018.
[57] L. Baker, P. Newell, J. Phillips, The political economy of energy transitions: the case of South Africa, New Polit. Econ. 19 (6) (2014) 791–818.
[58] H. Brauers, P.-Y. Oei, The political economy of coal in Poland: drivers and barriers for a shift away from fossil fuels, Energy Policy 144 (2020), 111621.
[59] P. Newell, D. Mulvaney, The political economy of the 'just transition', Geogr. J. 179 (2) (2013) 132–140.
[60] IRENA, Hydrogen: A Renewable Energy Perspective, International Renewable Energery Agency, Abu Dhabi, 2019.
[61] B. Radowitz, Russia's war pushes blue and grey hydrogen costs way above those of green H2: Rystad, Available from: https://www.rechargenews.com/energy-transition/russias-war-pushes-blue-and-grey-hydrogen-costs-way-above-those-of-green-h2-rystad/2-1-1189003, 2022.
[62] NREL, in: Global CFDDA-based Onshore and Offshore Wind Potential Supply Curves by Country, Class, and Depth (Quantities in GW and PWh), 2014.
[63] R.C. Pietzcker, et al., Using the sun to decarbonize the power sector: the economic potential of photovoltaics and concentrating solar power, Appl. Energy 135 (2014) 704–720.
[64] EIA, in: U.S.E.I. Administration (Ed.), Total Primary Energy Consumption, 2019.
[65] AQUASTAT, in: F.s.G.I.S.o.W.a. Agriculture (Ed.), Conventional Water Resources: Surface Water and Groundwater, 2020.
[66] WEF, The Global Competitiveness Report, 2019.
[67] USGS, Mineral Commodity Summaries 2021, 2021.
[68] Worldsteel, 2021 World Steel in Figures, 2021.
[69] OEC, Methyl alcohol, Available from: https://oec.world/en/profile/hs92/methyl-alcohol, 2021.
[70] OEC, Economic Relatedness Data, Available from:, 2021 https://oec.world/.
[71] A. Nuñez-Jimenez, N.De Blasio, The Future of Renewable Hydrogen in the European Union: Market and Geopolitical Implications, 2022.
[72] M. O'Sullivan, J. Bordoff, By not acting on climate, congress endangers U.S. National Security, Foreign Policy (2022). https://foreignpolicy.com/2022/07/21/climate-change-action-us-congress-biden-bill-national-security/. (Accessed 21 July 2022).
[73] US Department of Energy, Department of Energy Hydrogen Program Plan, 2020.
[74] Office of Energy Efficiency and Renewable Energy, Hydrogen Shot, Available from: https://www.energy.gov/eere/fuelcells/hydrogen-shot, 2021.
[75] The University of Texas at Austin (UT), H2@Scale Project Launched in Texas, 2020.
[76] Reuters, U.S. Steel, Norway's Equinor eye clean hydrogen production, Available from: https://www.reuters.com/business/energy/us-steel-norways-equinor-eye-clean-hydrogen-production-2021-06-29/, 2021.
[77] Renews, US ammonia producer unveils green hydrogen project, Available from: https://renews.biz/68065/us-ammonia-player-unveils-green-hydrogen-project/, 2021.
[78] C.-S. Hong, Thailand's Renewable Energy Transitions: A Pathway to Realize Thailand 4.0, The Diplomat, 2019.
[79] IEA, Thailand, Available from: https://www.iea.org/countries/thailand, 2021.
[80] S. Sethaputra, et al., Thailand's Water Vision: a Case Study, Available from: https://www.fao.org/3/AB776E/ab776e04.htm, 2000.
[81] EGAT, EGAT to Advance Hydrogen Production in Thailand, 2019.
[82] M.P. Bailey, Wison Engineering awarded EPCC contract for new hydrogen plant in Thailand, Available from: https://www.chemengonline.com/wison-engineering-awarded-epcc-contract-for-new-hydrogen-plant-in-thailand/?printmode=1, 2021.
[83] D. Yoshimoto, Thailand sees strong interest in advanced ammonia systems, Available from: https://ammonia21.com/articles/7856/thailand_sees_strong_interest_in_advanced_ammonia_systems, 2017.
[84] Royal Thai Embassy, Thailand 4.0, Available from: https://thaiembdc.org/thailand-4-0-2/, 2021.
[85] PTT, PTT Teams up With Leading and Public and Private Sector to Drive 'Hydrogen' to Be Alternative Energy of the Future of Thailand, 2020.
[86] ASEAN, Hydrogen in ASEAN: Economic Prospect, Development & Applications, Available from: https://aseanenergy.org/event/hydrogen-in-asean-economic-prospect-development-and-applications/, 2021.
[87] Prognos, Öko-Institut, Wuppertal-Institut, Klimaneutrales Deutschland 2045. Wie Deutschland seine Klimaziele schon vor 2050 erreichen kann, 2021.
[88] BmWi, "<book-title>Wir wollen bei Wasserstofftechnologien Nummer 1 in der Welt werden": BMWi und BMVI bringen 62 Wasserstoff-Großprojekte auf den Weg</book-title>, 2021.
[89] BmWi, Stahl und Metall, Available from: https://www.bmwi.de/Redaktion/DE/Textsammlungen/Branchenfokus/Industrie/branchenfokus-stahl-und-metall.html, 2021.
[90] Statista, Ammonia production worldwide in 2020, by country, Available from: https://www.statista.com/statistics/1266244/global-ammonia-production-by-country/, 2022.
[91] Shell, The Future of Hydrogen, Shell Deutschland Oil GmbH, 2017.
[92] EC, Supporting clean hydrogen, Available from: https://ec.europa.eu/growth/industry/strategy/hydrogen_en, 2022.
[93] IRENA, IRENA-European Union Workshop. A Dialogue Between EU and North African States on a Regulatory Framework to Develop Green Hydrogen Supply, Demand and Trade, Available from: https://www.irena.org/-/media/Files/IRENA/Agency/Events/2021/Oct/IRENA-Event-North-Africa_-20211011_V2.pdf?la=en&hash=00148D00000BAB268B58E36D37844FE7F187F887, 2021.
[94] EC, A Hydrogen Strategy for a Climate-neutral Europe, 2020.
[95] Ghorfa, Bundesregierung unterzeichnet Wasserstoff-Abkommen mit Marokko, Available from: https://ghorfa.de/de/bundesregierung-unterzeichnet-wasserstoff-abkommen-mit-marokko/, 2020.
[96] BmWi, Deutschland und die Vereinigten Arabischen Emirate verstärken Energiepartnerschaft mit neuer Wasserstoff-Taskforce, 2021.
[97] BmWi, Altmaier unterzeichnet gemeinsame Absichtserklärung zur Deutsch-Saudischen Wasserstoffzusammenarbeit, 2021.
[98] BmWi, Unterzeichnung einer Absichtserklärung zur Gründung eines deutsch-australischen Wasserstoffakkords, 2021.
[99] BmBF, Potenzialatlas Wasserstoff: Afrika könnte Energieversorger der Welt werden, Available from: https://www.bmbf.de/bmbf/de/home/_documents/potenzialatlas-wasserstoff-afr-ergieversorger-der-welt-werden.html, 2021.
[100] S. Fankhauser, et al., Who will win the green race? In search of environmental competitiveness and innovation, Glob. Environ. Chang. 23 (5) (2013) 902–913.
[101] D. Ansari, The Hydrogen Ambitions of the Gulf States. Achieving Economic Diversification while Maintaining Power in SWP Comment, 2022.
[102] A. du Plessis, Water as a source of conflict and global risk, in: Water as an Inescapable Risk, Springer, 2019, pp. 115–143.
[103] P. Toft, Intrastate conflict in oil producing states: a threat to global oil supply? Energy Policy 39 (11) (2011) 7265–7274.
[104] M.J. Bradshaw, The geopolitics of global energy security, Geogr. Compass 3 (5) (2009) 1920–1937.
[105] A. Hipp, C. Binz, Firm survival in complex value chains and global innovation systems: evidence from solar photovoltaics, Res. Policy 49 (1) (2020), 103876.
[106] J. Meckling, L. Hughes, Globalizing solar: global supply chains and trade preferences, Int. Stud. Q. 61 (2) (2017) 225–235.
[107] Y. Dai, L. Xue, China's policy initiatives for the development of wind energy technology, Clim. Pol. 15 (1) (2014) 30–57.
[108] R. Quitzow, J. Huenteler, H. Asmussen, Development trajectories in China's wind and solar energy industries: how technology-related differences shape the dynamics of industry localization and catching up, J. Clean. Prod. 158 (2017) 122–133.
[109] D. Prud'homme, et al., "Forced technology transfer" policies: workings in China and strategic implications, Technol. Forecast. Soc. Chang. 134 (2018) 150–168.
[110] J.-C. Kuntze, T. Moerenhout, Local Content Requirements and the Renewable Energy Industry - A Good Match? International Centre for Trade and Sustainable Development (ICTSD), 2013.
[111] O. Johnson, Promoting green industrial development through local content requirements: India's National Solar Mission, Clim. Pol. 16 (2) (2015) 178–195.
[112] D.L. Hill, Trade and investment barriers in solar and wind global production networks, in: Megaregionalism 2.0: Trade And Innovation Within Global Networks 67, 2018, p. 105.
[113] World Bank, World Bank Country and Lending Groups, 2021.
[114] S. Helgenberger, et al., Mobilizing the co-benefits of climate change mitigation: building new alliances – seizing opportunities – raising climate ambitions in the new energy world of renewables, in: COBENEFITS IMPULSE (Policy Paper), 2017.
[115] L. Eicke, A. Goldthau, Are we at risk of an uneven low-carbon transition? Assessing evidence from a mixed-method elite study, Environ. Sci. Pol. 124 (2021) 370–379.
[116] R. Quitzow, et al., The COVID-19 crisis deepens the gulf between leaders and laggards in the global energy transition, Energy Res. Soc. Sci. 74 (2021), 101981.
[117] J. Kirchherr, F. Urban, Technology transfer and cooperation for low carbon energy technology: analysing 30 years of scholarship and proposing a research agenda, Energy Policy 119 (2018) 600–609.
[118] A. Lema, R. Lema, Technology transfer in the clean development mechanism: insights from wind power, Glob. Environ. Chang. 23 (1) (2013) 301–313.
[119] J. McGee, J. Wenta, Technology transfer institutions in global climate governance: the tension between equity principles and market allocation, Rev. Eur. Comp. Int. Environ. Law 23 (3) (2014) 367–381.
[120] B.M. Hoekman, K.E. Maskus, K. Saggi, Transfer of technology to developing countries: unilateral and multilateral policy options, World Dev. 33 (10) (2005) 1587–1602.
[121] M. Glachant, A. Dechezleprêtre, What role for climate negotiations on technology transfer? Clim. Pol. 17 (8) (2016) 962–981.
[122] T. Kalt, J. Tunn, Shipping the sunshine? A critical research agenda on the global hydrogen transition, GAIAEcol. Perspect. Sci. Soc. 31 (2) (2022) 72–76.
[123] E. Asiedu, Foreign direct Investment in Africa: the role of natural resources, market size, government policy, institutions and political instability, World Econ. 29 (1) (2006) 63–77.
[124] M.J. Bürer, R. Wüstenhagen, Which renewable energy policy is a venture capitalist's best friend? Empirical evidence from a survey of international cleantech investors, Energy Policy 37 (12) (2009) 4997–5006.
[125] M. Busse, C. Hefeker, Political risk, institutions and foreign direct investment, Eur. J. Polit. Econ. 23 (2) (2007) 397–415.