Studies in Energy, Resource and Environmental Economics

Rainer Quitzow
Yana Zabanova *Editors*

The Geopolitics of Hydrogen

Volume 2: Major Economies and Their Strategies

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Editors

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ISSN 2731-3409 ISSN 2731-3417 (electronic)
Studies in Energy, Resource and Environmental Economics
ISBN 978-3-031-84021-0 ISBN 978-3-031-84022-7 (eBook)
https://doi.org/10.1007/978-3-031-84022-7

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

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Introduction

Rainer Quitzow and Hannah Lentschig

Abstract This introductory chapter provides an overview of the emerging geopolitics of hydrogen. The geopolitics of hydrogen describe the interplay of political, economic, technological as well as resource-related considerations as countries and economic blocs navigate the development, production, distribution, and use of hydrogen in the transition to a net-zero economy. It encompasses the influence of geographical factors essential for hydrogen generation, transport and use, technological choices and their implications for national competitiveness as well as questions of political and economic power—both domestic and international—that shape hydrogen strategies. In the following, we review how these factors are beginning to play out in the development of an international hydrogen economy. We sketch out seven critical dimensions, in which the geopolitics of hydrogen are taking shape: the politics of hydrogen production pathways; competition in clean hydrogen technologies; security of hydrogen supply and shifting energy geographies; hydrogen trade and infrastructure; industrial decarbonization and green industrialization; the uncertainty of hydrogen demand and the politics of risk; and sustainability and global equity. We conclude by presenting how the remainder of this book contributes to our understanding of the geopolitics of hydrogen.

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R. Quitzow and Y. Zabanova (eds.), *The Geopolitics of Hydrogen*, Studies in Energy, Resource and Environmental Economics, https://doi.org/10.1007/978-3-031-84022-7_1

1 Understanding the Geopolitics of Hydrogen—Why It Matters

As the world grapples with the imperative of transitioning toward a climate-friendly energy and industrial system, hydrogen has emerged as a key protagonist in the unfolding narrative of a future net-zero economy (Kovac et al., 2021). Beyond being a mere energy carrier and potential fuel of the future, hydrogen's role in the transition to net-zero touches on central facets of the international political economy of energy. With nations around the world aiming to strategically position themselves in the pursuit of cleaner and more efficient energy systems, energy transition narratives are being reshaped by the promise and potential of hydrogen as a climate-friendly technology that can help decarbonize global supply chains, enhance energy resilience and security, and foster economic growth and industrial upgrading (Noussan et al., 2021; Quitzow & Zabanova, 2024a; van de Graaf et al., 2020).

The COVID-19 pandemic and its repercussions across the global economy have helped in accelerating the international 'hydrogen race,' presenting it as an important entry point for addressing the 'twin challenge' of decarbonization and economic recovery in some of the leading countries (IRENA, 2022). Similarly, the invasion of Ukraine and the ensuing energy crisis have functioned as an additional driver of European hydrogen ambition, reframing it as a substitute for Russian gas imports (Zabanova, 2024).

Indeed, hydrogen and its derivatives, like ammonia or methanol, can function as versatile energy carriers within a future net-zero economy. They allow for the long-term storage and transport of renewable energy and have the potential to replace hydrocarbons as feedstocks for the production of chemicals and basic materials. These properties allow this molecule to assume similar functions to those performed by hydrocarbons in today's high-carbon economy. In this vein, hydrogen raises similar energy security questions as traditional energy commodities, pertaining to its supply and exchange within a global trading system. The development of infrastructure for the production and transport of hydrogen comes with important implications for the control over future energy flows. That said, increased electrification of end-uses coupled with the challenges of producing renewable hydrogen at scale as well as storing and transporting hydrogen makes it unlikely to occupy the dominant position of today's hydrocarbons (Riemer et al., 2022).

Moreover, with every country having access to some form of renewable energy resources such as wind, hydro, and solar power, the geopolitics of hydrogen will be different in nature than the geopolitics of oil and gas (Scholten & Bosman, 2016). While the relative abundance of renewable energy resources will play a role in the development of future hydrogen production hubs, geographical factors will not constrain its production in the same way as for oil and gas. Hydrogen production will also hinge on other factors, like access to technologies, the industrial capacities underpinning production and innovation, the economic and political conditions for enabling investment in a hydrogen economy, and, last but not least, geopolitical alliances and strategic partnerships. Moreover, large-scale production centers may be supplemented by decentralized local production sites (IRENA, 2022; Quitzow & Zabanova, 2024b).

Nevertheless, hydrogen has assumed an important role in debates on the interplay of nations' long-term energy security and their efforts in meeting climate objectives. Hydrogen's requirements for its efficient production and transport have significant implications for the way in which countries seek to (re)position themselves within a future carbon-neutral economy, in which areas they will likely compete and collaborate, and how they balance strategic decision-making to secure both a sustainable and reliable energy future (IRENA, 2022; Quitzow & Zabanova, 2024b). The emerging hydrogen economy will also likely be closely intertwined with the (re)location of energy-intensive industries (Eicke & De Blasio, 2022).

Against this background, the geopolitics of hydrogen provides important insights into how countries around the world are likely to shape—and be shaped—by the evolving dynamics of the global energy transformation. The transition away from trading traditional fossil resources such as oil and gas to trading hydrogen alongside clean technologies and critical raw materials can alter geopolitical dynamics associated with the control and exchange of energy resources in the international system (Blondeel et al., 2021). Countries' pursuit of green industrialization and emerging trade relations between future importers and exporters of hydrogen come with geopolitical and economic implications (Pflugmann & De Blasio, 2020). The resulting geography of international hydrogen value chains is likely to co-evolve with the reconfiguration of broader geopolitical and geoeconomic fault lines within the world economy. Hydrogen as a future energy carrier and important arena for clean energy innovation is likely to influence the geopolitical map of the global energy economy, with both 'old' and 'new' economic powers including China, the European Union (EU), Brazil, Japan, and the United States (US) striving to place themselves at the forefront of this transformation (IRENA, 2022).

2 Key Dimensions of the Geopolitics of Hydrogen

The geopolitics of hydrogen describe the interplay of political, economic, technological as well as resource-related considerations as countries and economic blocs navigate the development, production, distribution, and use of hydrogen in the transition to a net-zero economy (Pflugmann & De Blasio, 2020; Van de Graaf et al., 2020). It encompasses the influence of geographical factors essential for hydrogen generation, transport and use, technological choices, and their implications for national competitiveness as well as questions of political and economic power—both domestic and international—that shape hydrogen strategies (Blondeel et al., 2021; Scholten, 2023). In the following, we review how these factors are beginning to play out in the development of an international hydrogen economy. We sketch out seven critical dimensions, in which the geopolitics of hydrogen are taking shape: the politics of hydrogen production pathways; competition in clean hydrogen technologies; security of hydrogen supply and shifting energy geographies; hydrogen trade and infrastructure; industrial decarbonization and green industrialization; the uncertainty of hydrogen demand and the politics of risk; and sustainability and global equity.

2.1 The Politics of Hydrogen Production Pathways

The different methods with which hydrogen can be produced present a central point of contention in the emerging hydrogen economy. Today, hydrogen is predominantly derived from natural gas through emissions-intensive steam methane reforming (SMR), referred to as 'gray hydrogen,' or, in some cases, via coal gasification, which still plays an important role in countries like China and South Africa. The combination of SMR with carbon capture and storage (CCS) technologies produces so-called blue hydrogen, while renewable or 'green' hydrogen, produced through water electrolysis using renewable electricity, is the least CO_2-intensive production pathway (Hermesmann & Müller, 2022).

With current hydrogen value chains mainly relying on fossil fuels, the path toward less emissions-intensive hydrogen will depend not only on overcoming technical challenges but also on establishing standards and benchmarks for the classification of production pathways and the measurement of their emission-intensities (Noussan et al., 2021). Standards and regulations will determine the competitiveness of these different production methods and hence the strategic position of different countries or firms. While countries with abundant renewable energy resources may favor the prioritization of renewable hydrogen and strict emission standards, those with access to low-cost fossil fuels may prefer an approach that relies on multiple production pathways, accepting the residual emissions of blue hydrogen production. Not only fossil fuel-producing countries strongly support blue hydrogen, including countries in the Middle East and Norway, but also the US and Japan are pursuing pragmatic approaches with support for fossil-based production pathways.

Additionally, the debate on hydrogen production technologies extends to the contested role of nuclear energy in the power system. A number of European countries reject the risks of the technology and hence oppose the use of hydrogen produced via electrolysis using nuclear power. For other countries, nuclear power is not only a viable low-carbon energy option, but a source of prestige and strategic importance, given its close links to nuclear defense technologies. While the European Commission and prominent EU member states, like Germany or Spain, have championed hydrogen production using renewable electricity, this has faced resistance from other member states, most notably from France who wants to see the inclusion of nuclear energy as a power source for electrolysis (Quitzow & Zabanova, 2024a). Further afield, biofuel champion Brazil is keen to include hydrogen production from biomass as an additional variation of low-carbon hydrogen (Lira, Kramer, Quitzow, this volume). Each pathway has differing political, economic, and environmental implications, creating relative winners and losers (Quitzow & Zabanova, 2024a, 2024b, 2024c).

2.2 Competition in Clean Hydrogen Technologies

Competition over technological leadership in a future hydrogen economy adds an additional layer to the geoeconomics of the sector. The hydrogen sector represents an important sphere of technological competition, both between rival technologies and between the major economic blocs vying for technological leadership. Europe has long held a leading position in the field of hydrogen technologies, and firms and politicians are determined to retain their competitive advantage in the face of Chinese competition. Similar to cleantech sectors like wind and solar energy and electric vehicles, China has rapidly emerged as a low-cost competitor, most notably in traditional alkaline electrolyzers (Gong and Quitzow, 2023; van de Graaf et al, 2020).

Moreover, technological competition is also linked to questions of raw material supply. Critical minerals, like nickel and platinum, are important inputs for the production of hydrogen-related technologies. Concerns over asymmetric dependencies are driving efforts to secure technological sovereignty and to diversify the emerging supply chain relationships. Uncertainty regarding future supplies may also influence technological pathways. Due to their flexibility, proton-exchange membrane (PEM) electrolyzers offer important benefits for use in a power system dominated by variable renewable energy supplies. However, they rely heavily on so-called platinum group metals (PGM), a scarce mineral resource, adding a risk and hence cost to their development (Pepe et al., 2023).

Finally, technological competition also extends to the sphere of hydrogen trade, with different players experimenting with different options for the transport of hydrogen over longer distances. The options are manifold, ranging from pipelines to different options for ship-based transport. Each technology option comes with distinct challenges and implications. While ammonia has emerged as one of the favored options for transporting hydrogen by ship, it is not only a highly toxic substance but also raises the challenge of reconversion for applications that require hydrogen in its pure form. Alternatively, it could shift part of the value creation process upstream as ammonia production and relocate to exporting countries (Eicke & De Blasio, 2022).

2.3 Security of Hydrogen Supply and Shifting Energy Geographies

As countries transition from fossil fuels to an energy geography dominated by renewables and hydrogen, this also raises important new energy security questions. On the one hand, renewable hydrogen is viewed as an option for breaking fossil fuel dependencies, offering both options for domestic production and a new and expanded set of potential partners for sourcing hydrogen. It provides countries with an opportunity to diversify their energy sources and trading partners, thereby reducing vulnerabilities and asymmetrical dependencies associated with the fossil fuel-based energy economy. On the other, these new supply partnerships may lead to a new set of dependencies, along with tensions over who has access and on what terms. It raises questions regarding the rules and practices that will shape international hydrogen trade and which actors will influence or even dominate a future hydrogen market. Clearly, this will also be influenced by the choice of production technologies outlined above (Quitzow et al., 2023; Scholten et al., 2020; van de Graaf et al., 2020).

Hydrogen also provides the possibility of enhanced energy independence in 'prosumer' countries, including China and the US, who possess sufficient production capacities to meet their domestic hydrogen consumption needs and possibly even export to international markets. In particular, China could become significantly less dependent on energy imports, with significant implications for energy geopolitics (Quitzow & Gong, 2024). How these actors engage in the global hydrogen market depends on their national hydrogen strategies and industrial policies and to what extent they will choose to promote exchanges within an international market place. Developments in large future import markets, such as Japan and the EU, will shape the recalibration of global interdependencies, arising from the quest for energy diversification and independence and the need for globally integrated infrastructure development. This includes geopolitical competition over trade partners and control of supply chains (Pepe et al., 2023; Quitzow & Zabanova, 2024a, 2024b, 2024c).

Countries in Latin America, Sub-Saharan Africa, and Oceania could emerge as central hubs for hydrogen production. For example, renewable resource-rich countries like Spain, Chile, or Morocco hope to transition from their roles as net energy importers to major exporters of green hydrogen. The prospect of such energy 'newcomers' to become central hydrogen export markets underscores the potential for increased influence in the new geography of trade underpinning the changing global energy landscape. Similarly, coastal areas and ports play a crucial role in the scale-up of clean hydrogen production, pointing to the potential for countries like Brazil to evolve from historically 'minor' energy powers into future hydrogen hotspots. At the same time, historic fossil producers like Australia or Saudi Arabia are well-positioned to leverage their existing know-how and trade relations to position themselves as important exporters of hydrogen (IRENA, 2022).

2.4 Hydrogen Trade and Infrastructure

As hydrogen emerges as an important dimension of energy security, hydrogen trade and the infrastructure needed for this will also emerge as an important geostrategic dimension of the energy system. Changing energy import and export relationships can influence the balance of trade, economic dependencies, and diplomatic relationships between countries. Global power competition over major value chains and central export markets could lead to the regionalization of trade relations and a fragmented global hydrogen market that capitalizes on unequal terms of trade and rivalry over supply (Pepe et al., 2023).

In this context, control over infrastructure, including physical infrastructure for storing and transporting hydrogen as well as institutional infrastructure shaping market exchanges, assumes strategic importance. This is particularly important for importing countries, dependent on foreign suppliers of hydrogen to fuel their net-zero economies. Developing diversified transport routes has emerged as a key consideration as countries like Japan or Germany begin developing plans for the development of transport infrastructure. It has also become a point of contention between countries dependent on imports and those strategically positioned en route between potential export and import hubs. France, a potential transit country between Germany and the Iberian Peninsula, for instance, has expressed important reservations regarding the development of pipeline connections across its territory (Bouacida, 2024). Shipping routes provide a more costly alternative to the politically cumbersome development of pipeline transport, with ports like Rotterdam, Kobe, or Port of Pecém in Brazil seeking to position themselves as major hydrogen trading hubs (Lira, Kramer, Quitzow, this volume).

This build-up of physical infrastructure is complemented by the development of international standards and rules governing international hydrogen value chains. These rules of the game will determine the trajectory of hydrogen trade and the formation of markets, constituting another central dimension in which nations seek leadership and influence. As an international hydrogen market takes shape, pricing and market access will assume geoeconomics importance, with countries likely striving to control these aspects to gain a strategic advantage (Flath et al., 2023).

2.5 Industrial Decarbonization and Green Industrialization

Ultimately, the geopolitics of hydrogen cannot be separated from its ultimate purpose—the decarbonization of end-use sectors. Here, its role in the decarbonization of energy-intensive industries, most notably steel and chemicals, stands out as a critical arena of geopolitical competition. Nations with access to abundant and low-cost renewable energy resources suitable for green hydrogen production may become attractive destinations for industries seeking to decarbonize. This has the potential to redirect investment from traditional locations in industrialized countries to new production hubs in emerging and developing countries (Quitzow et al., 2025). Such shifts in investment patterns could reshape global economic power dynamics and impact geopolitical relationships as nations seek to secure their positions in emerging green industries (Eicke & De Blasio, 2022).

However, renewable energy resources alone will not suffice to catalyze investment. It will require the needed industrial capacities to translate low-cost energy resources into competitive industrial production, and it will rely on the financial and political backing from future offtakers to secure such investments. Given the strategic role of steel and chemicals, supplying basic inputs to a wide range of industries, major economies are also keen on retaining their domestic production capacities, despite potential disadvantages in terms of low-cost hydrogen supply. Industrialized countries have begun to provide subsidies and incentives for the decarbonization of domestic production facilities as well as investments in hydrogen production and transport. It remains to be seen how the interplay between cost differentials, pre-existing industrial capacities, and strategic industrial policy will shape the future geography of industrial production.

2.6 The Uncertainty of Hydrogen Demand and the Politics of Risk

Despite the rising global momentum of the hydrogen market ramp-up, the scale and scope of a future hydrogen economy remains highly uncertain. While hydrogen is primarily used in oil refining and chemical production today, the range of possible hydrogen applications in a net-zero economy is both large and highly contested (IEA, 2019). Climate mitigation scenarios suggest a potential role for hydrogen in end-use sectors ranging from industrial production, different parts of the transport sector, domestic heating, and for balancing renewable power generation. Indeed, hydrogen represents a versatile energy carrier that could replace fossil fuels in a diversity of applications (Weißenburger et al, 2024). It is precisely this versatility that has fueled substantial disagreement and uncertainty with regard to the specific applications where hydrogen could and should play a role. This has triggered discussions about cost and environmental efficiency as well as technical feasibility, not only of hydrogen but of competing technologies. It is widely accepted in the scientific community that the electrification of end-uses is the most efficient pathway for decarbonization, so many argue that scarce hydrogen resources should be limited to those applications where electrification is not a viable option (Schreyer et al., 2024). Nevertheless, many hydrogen strategies continue to emphasize applications across various end-use sectors, including transport and heating (Weko; Gong & Quitzow, both in this volume).

As a result, questions persist about where and to what extent hydrogen will be needed, making current estimates regarding future demand highly uncertain (Noussan et al., 2021; Riemer et al., 2022). Contention regarding hydrogen production technologies and rules governing the CO_2 footprint and other dimensions of hydrogen production and trade add to this uncertainty. This also means that investment in the hydrogen sector remains a highly risky endeavor.

This in turn points to questions of who will bear the risks and associated costs of early investments and who will reap the benefits in the case of success. This is a classic question of market vs. state, as firms seek guarantees from their governments to secure their bets on hydrogen as a promising decarbonization option. It raises questions regarding the efficient and effective use of public spending and how to avoid excessive rents by private actors, as they pursue strategies to maximize the benefit for their shareholders.

But these questions also extend beyond the domestic sphere, as as resource-rich countries position themselves to supply industrial demand centers. This is giving rise to high-stakes negotiations between importers and exporters as they consider large-scale investments, not only in hydrogen production but also in trade-related infrastructure, like pipelines, ports, and ships. It remains to be seen how partners from the private and public sectors and from exporting and importing countries find ways to unlock the needed investments, thereby allocating risks and rewards across stakeholders and regions.

2.7 Sustainability and Global Equity

The distribution of the costs and benefits of hydrogen development and its socio-economic and environmental impacts across countries is also at the heart of global discussions of equity and a just transition. From a global equity perspective, it is critical to ensure that the transition to a hydrogen-based economy aligns with broader global goals, including environmental sustainability, social justice, and inclusive economic development. Large-scale deployment of renewable energy infrastructure for hydrogen production may raise concerns about local resource use and the role of local communities and their livelihood (Cremonese et al., 2023). Hydrogen investments may affect local land use and biodiversity and increased demand for water from hydrogen production—not only from electrolysis but also SMR (IRENA, 2023)—may exacerbate challenges in regions facing water scarcity, affecting local livelihoods and food production. Moreover, many regions with high renewable energy potential in the Global South are also characterized by low levels of electricity access, raising questions related to the allocation of costs and benefits across stakeholder groups (Cremonese et al. 2023; Müller et al., 2022).

These challenges represent important points of contention in the development of hydrogen partnerships between industrialized countries keen to secure hydrogen supply to power future net-zero industries and resource-rich countries seeking to industrialize. Governments and local communities in potential exporting countries are raising questions regarding the distribution of benefits both locally and internationally. Concerns regarding the (re)establishment of neocolonial trade relationships and patterns of extractivist economic development have been raised by governments and civil society actors. They are articulating ambitions to increase downstream value creation in net-zero industries like steel making or fertilizers. At the same time, workers and populations in the industrialized world fear loss of jobs and incomes if energy-intensive industries relocate to resource-rich locations. The emerging hydrogen economy is also likely to be closely intertwined with the (re)location of energy-intensive industries (Kalt & Tunn, 2022).

In sum, these sustainability and equity concerns not only play an important role in shaping the willingness of potential exporting countries to pursue ambitious hydrogen strategies, but they also raise fears of deindustrialization and deteriorating quality of life in existing industrial centers, with important political implications. This highlights the indispensable role of international cooperation and dialogue to confront the challenges of hydrogen development. It requires collaboration among governments from different countries, industrial stakeholders across the value chain, local communities, and civil society. Despite increasing geopolitical rivalry, the geoeconomics of hydrogen and decarbonization of industrial value chains is inherently cooperative in nature (Lentschig et al., 2025). It is not only a matter of reducing dependencies and managing supply chain risks. Rather it requires approaches and narratives that can persuade partners to join the global effort of building a sustainable hydrogen economy (Quitzow & Zabanova, 2024c; Quitzow et al., 2023).

3 Objective and Contribution of This Book

In the preceding discussion, we have pointed to the multidimensional nature of the geopolitics of hydrogen, highlighting seven, partly overlapping dimensions affecting cooperation and competition in the sector: the politics of hydrogen production pathways; competition in clean hydrogen technologies; security of hydrogen supply and shifting energy geographies; hydrogen trade and infrastructure; industrial decarbonization and green industrialization; uncertainty of hydrogen demand and the politics of risk; and sustainability and global equity. Each of these dimensions plays a role in how actors in an emerging hydrogen economy position themselves, shaping strategies and engagement with partners.

In this book, we take this as the starting point for an analysis of hydrogen policy-making in a group of major economic powers and hydrogen frontrunners. The book explores how each of these countries is choosing to engage with the different dimensions of geopolitical competition and discusses possible drivers behind these developments. By focusing on the policies in these major economies, the book also acknowledges the important role of governments in shaping an emerging hydrogen economy. Like in other cleantech sectors, the early phases of market and technology development are strongly shaped, if not determined, by government policy-making. Compared to renewable energy technologies—the most important success story to date (Hoppmann et al., 2013)—this is even more pronounced in the hydrogen sector, given the multiple uncertainties across supply and demand outlined above.

The book does not claim to provide a comprehensive review of country strategies. Rather, it constitutes a starting point for understanding how the geopolitics of hydrogen is unfolding. The book examines both domestic and international hydrogen policies in eight countries. It begins with a review of hydrogen policies in the US, China, and the European Union as the three major economies shaping geopolitical rivalry. The latter is informed by analysis conducted in the first volume of this series on hydrogen strategies in the European Union and key member states

(Quitzow & Zabanova, 2024a, 2024b, 2024c). It explicitly accounts not only for EU-level policy-making but also the role of important EU member states. This is followed by an analysis of Japan and the UK, both G7 countries with distinct priorities and approaches that diverge significantly from those in the US and the EU. Finally, we cover Australia and Brazil, two G20 countries with rich renewable resource endowments but distinct energy and industrial legacies and geostrategic positions. Each actor's unique approach to hydrogen reflects its strategic priorities, technological and industrial capabilities, and long-term energy security objectives amidst the complex global challenges posed by climate change.

In the *US*, the hydrogen sector is being shaped by a confluence of energy security and decarbonization objectives. The government has promoted hydrogen as a way to further enhance its goal of achieving energy independence, while reducing carbon emissions and stimulating the development of a future-oriented manufacturing sector. The US has been striving for leadership in hydrogen innovation and production by fostering a robust green industry that not only meets domestic demand but also positions it as a potential player in global exports. Given the polarized political landscsape in the country, the US stance is also characterized by a high degree of uncertainty. It remains to be seen how hydrogen development will play out under the second Trump administration.

China, currently the world's largest hydrogen producer and consumer, has not made hydrogen a major policy priority so far. Nevertheless, a number of provincial governments are competing for investments in hydrogen production, while the national government supports a number of pilot cities for the development and deployment of fuel-cell electric vehicles. Oversees, it has started to weave hydrogen into its external energy strategy built around global value chain expansion and technological cooperation. By investing in technological collaboration and strategic partnerships around the globe, China seeks to enhance its global reach and role as an economic power in a future net-zero economy.

The *European Union* and its member states are spearheading the majority of transcontinental hydrogen endeavors. Dependent on future hydrogen imports to decarbonize its industry, the EU is promoting international partnerships and cross-border pipeline infrastructure and is seeking to foster a common approach to clean hydrogen production and use, albeit hampered by diverging interests in leading member states. Notwithstanding these internal challenges, the EU is aiming to leverage its single market and regulatory capabilities to establish itself as a leader in the global hydrogen economy.

In *Japan*, we witness an ambitious drive to establish a 'hydrogen society,' emphasizing technological innovation and green hydrogen production as cornerstones of its energy strategy. The nation envisions a future where hydrogen plays a central role in various sectors, ranging from transport to industrial applications. Notably, it also plans not only to use but also to export controversial ammonia co-firing technology to reduce local emissions from existing coal power plants. It seeks to create a self-sustaining hydrogen 'ecosystem' that fosters energy security and decarbonization, with the former taking precedence over the latter for the time being.

The *United Kingdom* stands at the forefront of European 'hydrogen-in-industry' initiatives, aiming to blend domestic strategies with regional and international collaboration to advance a hydrogen application in important domestic industry sectors such as chemicals, glass, and steel. Historically a signficant European fossil producer, the country seeks to become a key player in local and European hydrogen markets in order to decarbonize its industry while ensuring economic competitiveness and growth.

Australia, endowed with vast renewable energy resources, strives to position itself as a global hydrogen powerhouse, aiming to leverage its natural advantages to become a major exporter of green hydrogen. The focus is to capitalize on its abundant renewable potential to produce low-cost and environmentally friendly hydrogen, although important regional players have insisted on retaining a parallel focus on fossil-based hydrogen production. Despite its skilled workforce and innovative capacities, efforts to promote technological leadership and attract investments in downstream industries have been slow to emerge, though there are signs of increasing ambitions.

In *Brazil*, renowned for its bioenergy capabilities and role as the world's third-biggest producer of renewable electricity, clean hydrogen has been identified as a strategic asset in the nation's commitment to energy independence, economic growth, and sustainable development. High shares of renewable energy and a well-developed domestic wind energy industry make it an attractive location for investment in export-oriented hydrogen, especially in the Northeast of the country. Its steel and chemical industries also offer important opportunities for downstream hydrogen use.

Each chapter delves into the unique dimensions of these players' hydrogen ambitions and their implications in shaping the geopolitics of the emerging global hydrogen economy. The analysis of each actor's national hydrogen policies and plans offers the backdrop for a discussion of its international engagement in the hydrogen sector within the context of broader climate and energy foreign policies. Each chapter provides an overview of bilateral and multilateral hydrogen cooperation and concludes with a reflection on the countries position in the emerging geopolitics of hydrogen. Given the variance in scope and ambition of actors' hydrogen strategies, each chapter's structure and specific focus are tailored to the individual contours of the respective case.

The volume concludes with a chapter that reflects on and contextualizes key findings and themes of each case study against the broader backdrop of international hydrogen politics. It discusses how each country's hydrogen ambition coupled with its external hydrogen action is shaping the future trajectory of a global hydrogen economy. It reflects on how they relate to the emerging geopolitics of hydrogen and the countries' potential position and role within it. Through the lens of these cases, this book aims to provide readers with a nuanced understanding of how the 'hydrogen revolution' is not only shaping global decarbonization efforts but also influencing geopolitical contours of the twenty-first century.

Acknowledgements Research for this chapter was financially supported by the German Federal Foreign Office within the framework of the project "Geopolitics of the Energy Transformation – Implications of an International Hydrogen Economy" (GET Hydrogen), funding reference number AA4521G125.

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Hydrogen Policy in the EU: Navigating the Union's Internal Dynamics and Geopolitical Challenges

Yana Zabanova and Rainer Quitzow

Abstract This chapter discusses the evolution of hydrogen policy in the European Union (EU) and related developments in key Member States. It examines the role of the EU as a global policy frontrunner and zooms in on the key measures used by the bloc to promote a hydrogen economy, with a focus on hard-to-abate sectors. It also analyses how the EU's institutional nature as a supranational union of 27 Member States affects its emerging hydrogen sector as compared to other major economies. EU policy-making on hydrogen has been challenged by the bloc's heterogeneity and structural disparities, with Member States having starkly diverging starting points, priorities, and competitive advantages when it comes to the energy transition and green industrial policy. Wealthier and more industrialised Member States have been able to offer generous domestic subsidies for hydrogen, in addition to benefiting from larger amounts of EU-level funding. As a future hydrogen importer, the EU has also put a growing emphasis on hydrogen in its foreign energy and climate policy, even though its hydrogen-related investments in third countries have been relatively limited to date. More recently, the EU, like other major economies, has grappled with the realisation that the green hydrogen economy will take longer to develop than originally anticipated. The persistently high costs of green hydrogen and the difficulties in mobilising demand in key sectors increase the uncertainty about hydrogen's future role in the EU's economy and in international trade.

1 Introduction

Driven by its ambitious climate goals and the need to decarbonise hard-to-abate sectors, the European Union (EU) has prioritised the development of a strong domestic hydrogen economy and an international hydrogen market. The EU's

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R. Quitzow and Y. Zabanova (eds.), *The Geopolitics of Hydrogen*, Studies in Energy, Resource and Environmental Economics, https://doi.org/10.1007/978-3-031-84022-7_2

Hydrogen Strategy, adopted in July 2020, presents a hydrogen vision as an essential component of the EU's path to net zero and for retaining leadership in clean technologies. Developed in the midst of the global Covid-19 pandemic, the EU Hydrogen Strategy was strongly informed by ideas of green recovery. Further geopolitical shocks, such as Russia's invasion of Ukraine in 2022 and the gas supply crisis, cemented the EU's resolve to decrease its reliance on fossil fuels and to speed up the green transition as a means to boosting energy security. The EU subsequently increased its targets for the production and import of hydrogen, launched domestic production subsidies, and adopted mandatory quotas for industry and transport. Against the background of intensifying international cleantech competition and an emerging global subsidy race, the EU has attempted to invigorate its green industrial policy, adopting the Net-Zero Industry Act in May 2024 (European Commission, n.d.-e).

However, the EU's nature as a supranational actor, with 27 Member States and a division of competencies in key policy areas, sets it apart from other global frontrunners like the USA, Japan, or China. On the one hand, it generates a number of benefits. With a combined population of 448 million people, the EU has a large and attractive single market with unified rules and skilled labour resources—one that can be used to generate demand for green products. The EU's continually developing and expanding Emissions Trading System (EU ETS) is an important pillar with the potential to help incentivise the use of low-emission hydrogen in industry and the maritime sector. ETS revenues are channelled to support innovation and the commercialisation of climate-friendly technologies across Member States, including hydrogen-related applications. With the launch of the European Hydrogen Bank in 2023, this now also includes subsidies for hydrogen production. The bloc also has a developed cross-border gas infrastructure that can be repurposed to carry hydrogen, as well as seaports striving to position themselves as transit hubs for clean fuels.

However, the EU's supranational character also comes with a number of limitations. Its Member States are very diverse in their size, fiscal power, and competitive advantages. Important decisions on the future course of EU policy depend on the EU's ability to reach compromise among the Member States. While the bloc's ambitious climate policy is set at the EU level, energy policy remains largely in the remit of Member States. Reflecting this governance challenge, there are discrepancies between the climate and energy policy defined by the European Commission and the pathways outlined by the Member States. Importantly, the EU's fiscal powers are limited, as it lacks the powers to autonomously raise taxes. The bulk of the EU's seven-year budget, known as the Multi-Annual Financial Framework, comes from Member States' contributions. Absent a major emergency, the bloc is also not allowed to finance its budget by issuing EU-level debt.

In this vein, the EU's hydrogen policy co-exists with the policies developed by proactive Member States, each with a particular starting point and motivation for their engagement. There are those countries that plan to import large amounts of hydrogen, such as Germany, as well as those that aim at becoming exporters, like Spain or Norway (as a member of the European Economic Area), or trading hubs, like the Netherlands or Italy. At the same time, France—a key transit country between the

Iberian Peninsula and Central European countries—is clearly prioritising domestic hydrogen development.

While many of these strategies may be complementary, they also involve major conflicts of interest, raising tensions in EU-level negotiations. Understanding the evolving place of the EU in the global hydrogen economy thus requires an understanding of policies and strategies at the EU level and in important Member States as well as the interplay between these two levels. In the following chapter, we thus frame European hydrogen policy as the confluence of relevant policies and regulations at both levels of governance. We explore how the EU-level policies and processes interact with developments in important Member States and discuss implications for the evolving role of the EU in the broader geopolitics of hydrogen.

This chapter is structured in the following way. First, it describes the EU's strategic vision of a hydrogen economy, its interplay with the priorities and strategies at the Member State level, and the obstacles this vision is facing. Then, it presents key domestic policies in the EU to promote a hydrogen economy, also highlighting policies developed by leading Member States. As the next step, the chapter discusses the external dimension of the EU's hydrogen vision, exploring the bloc's engagement in multilateral governance as well as its efforts to make hydrogen a more prominent component in its bilateral relations as part of the EU's overall external energy and climate policy. The conclusion will summarise the key findings of the chapter.

2 The EU's Strategic Vision for Hydrogen in a Changing Geopolitical Environment

The European Union's hydrogen vision is firmly rooted in the bloc's increasingly stringent climate policy. With the announcement of the landmark European Green Deal in December 2019, the EU officially put itself on the path to becoming the world's first "climate-neutral" continent by 2050. The net-zero goal has since been enshrined in the European Climate Law (2021) and is legally binding. Since then, the EU has adopted an interim target of reducing GHG emissions by 55% by 2030, and a 90% reduction target by 2040 was proposed by the Commission in February 2024 (European Commission, 2024a).

When the EU adopted its "Hydrogen Strategy for a Climate-Neutral Europe" in July 2020, this took place amidst a global wave of interest in clean hydrogen. The bloc followed in the footsteps of key Asia–Pacific economies such as Japan, South Korea, and Australia, which had adopted their strategies in 2017–2019. In Europe, France kicked off the new trend with its 2018 Hydrogen Plan, followed by the Netherlands (April 2020), Norway (May 2020), and Germany (June 2020) (Albrecht et al., 2020, p. 5). By the end of 2024, 20 out of 27 Member States had adopted hydrogen strategies.

The EU Strategy presents hydrogen as essential to reaching Europe's climate goals by helping decarbonise hard-to-abate sectors. It also emphasises the EU's technological edge in the hydrogen sector and stresses that investment in hydrogen would bring sustainable growth and jobs, especially important in the context of pandemic recovery efforts. In the strategy, the EU made it clear that renewable hydrogen would be prioritised as most compatible with EU goals, yet other types of low-carbon hydrogen would likely be needed as a transitional solution. Finally, the strategy put forward ambitious "strategic objectives": installing "at least" 6 GW of renewable electrolysis capacity domestically by 2024 to produce up to 1 million tonnes of green hydrogen, and as much as 40 GW by 2030 (European Commission, 2020).

Russia's invasion of Ukraine in February 2022 provided an additional impetus to the EU's hydrogen plans. In the REPowerEU package of proposals presented in May 2022, the European Commission laid out a vision of phasing out the EU's dependence on Russian fossil fuels through diversifying suppliers, reducing energy demand, and accelerating the energy transition, including by developing a hydrogen economy. REPowerEU also introduced much more ambitious (albeit non-binding) targets for hydrogen: 10 million tonnes in domestic production by 2030, with an equal amount in imports (European Commission, 2022a).

Since the publication of the EU's hydrogen strategy in 2020, the EU has emerged as the global region with the largest number of announced hydrogen projects. It has adopted important regulatory acts, including a definition of renewable hydrogen, mandates for green hydrogen use in industry and transport, and a set of rules for the future hydrogen infrastructure. The EU and its Member States have allocated tens of billions of euros to support projects along the hydrogen value chain. Finally, hydrogen has become an important focal area in the international outreach by the European Commission and selected Member States.

Despite this increasing momentum, the EU's strategic vision on hydrogen has also encountered a set of challenges. Some of them are rooted in the EU's nature as a supranational entity uniting 27 separate nation states. Others result from the shifting geopolitical realities in Europe and the intensifying global cleantech competition. Internally, charting a common European course on hydrogen has proven complicated. Member States have very different starting points, comparative advantages, and priorities in the hydrogen economy. This has led to disagreements across a number of policy dimensions, resulting in significant delays in adopting key pieces of legislation. There are differences, for instance, on what role low-carbon hydrogen—such as blue hydrogen from natural gas with carbon capture and storage (CCS) or electrolytic hydrogen with nuclear as a power source—should play and how important hydrogen imports should be. There are also clear differences—and oftentimes a mismatch—between the Member States' renewable energy potential and their industrial and innovation capacity. As a result, most hydrogen projects in Europe are clustered in the more industrialised Member States with greater fiscal resources, while lower-income Member States with better renewable energy endowments oftentimes lag behind (Quitzow et al., 2023, pp. 13–14).

The mounting green backlash in many Member States is another prominent challenge. The European energy transition is entering a more difficult and costlier phase, with a growing impact on businesses and households. The farmers' protests that rolled through several Member States in 2023–2024 featured resistance against the European Green Deal's stricter environmental and climate requirements. In the Netherlands, the outcome of the 2023 parliamentary elections, where the far-right Party of Freedom emerged victorious, has added uncertainty to the country's traditionally robust energy transition policy and its hydrogen development plans. Earlier in Poland and Hungary, persistent democratic deficits led to a row with the European Commission, blocking these countries' access to billions of EUR in pandemic recovery funding, a key source of financing for planned hydrogen-related projects. While the election of former President of the European Council, Donald Tusk, in Poland has put this to rest, the situation persists in Victor Orban's Hungary (Hodgson, 2024).

In addition, hard security challenges for the EU are beginning to compete for attention and resources with the green transition (Eyl-Mazzega and Gherassim, 2024, p. 6). Faced with the prospect of US disengagement from European security under the Trump Administration, the EU is under pressure to substantially increase its defence spending. In early March 2025, the Commission proposed the ReArm Europe Plan, aiming to mobilise up to 800 billion EUR to strengthen Europe's military capabilities.

There is also a growing realisation that a hydrogen economy in Europe will develop more slowly and cost much more than originally hoped for. The EU's original assumptions about "costs, availability, and technical feasibility" of green hydrogen (Graf & Buck, 2024, p. 30) have proven overly optimistic due to the rising costs of inputs such as labour, capital, and technology (Liebreich, 2023). In fact, in 2023–2024, clean hydrogen became more, rather than less, expensive (Martin, 2024b). High costs have negatively affected future customers' willingness to pay, resulting in far fewer offtake contracts than needed to achieve the EU targets. In its comprehensive report published in July 2024, the European Court of Auditors called for a "reality check" for the EU's hydrogen policy (European Court of Auditors, 2024).

As a result of these challenges, progress on the ground has been limited. Of the 7.2 million tonnes of hydrogen consumed in the EU in 2023, 99.7% was produced from fossil fuels (ACER, 2024, p. 4). Electrolyser capacity in operation remains negligible: as of September 2024, it stood at merely 385 MW—a far cry from the EU's now missed 6 GW target for 2024. Existing capacity was spread over 214 plants, meaning that most facilities in question were small-sized (Hydrogen Europe, 2024, p. 20). A lion's share of this electrolyser capacity is located in leading industrialised economies, such as Germany, Spain, Sweden, France, Denmark, and Austria (ACER, 2024, p. 37). Europe still leads the world in the number of announced projects (617 vs. 280 in North America) but is falling behind North America and China in project maturity and committed capacity (Hydrogen Council and McKinsey & Company, 2024, p. 8). In addition, a spate of project cancellations occurred throughout 2024, including several projects that had successfully secured EU or national funding. On the other hand, a number of large green hydrogen projects are moving forward. In July 2024, three projects with a combined capacity of 730 MW—to be implemented by TotalEnergies in the Netherlands and by Shell and EWE AG in Germany—all adopted FIDs, sparking hopes that the ramp-up of the green hydrogen sector was finally picking up speed in Europe (Collins, 2024b).

Geoeconomically, too, the EU is currently facing a changed situation compared to the years 2019–2020 when its optimistic hydrogen vision was originally formulated. The competitiveness of European industry has suffered under high energy prices. The EU also fears falling behind in the global cleantech race, where heavyweights like China and the USA are increasingly resorting to market-distorting measures. There is a concern that generous subsidy schemes abroad, such as in the US, might lure investment away from Europe, thereby undermining the EU's edge on hydrogen technologies. This begs the question of how adequate the EU's economic governance, premised on the idea of fiscal discipline and public debt and deficit thresholds,[1] is to the challenges of the green transition, which requires large amounts of public investment (Huertas Ruiz & Dura Ferrandis, 2023).

At the same time, following Russia's invasion of Ukraine, the EU is placing a much higher strategic emphasis on diversifying international partnerships and decreasing excessive dependencies on single suppliers. The EU's plans to import hydrogen and derivatives make it attractive as a long-term strategic partner for many prospective hydrogen exporters. The latter include, prominently, countries in the Global South, where the EU and its leading Member States have built a strong reputation as providers of climate finance. The challenge here is to reconcile the EU's hydrogen import aspirations with the growing interest of partner countries to use hydrogen to produce higher value-added industrial goods domestically (UNIDO, IRENA, and IDOS, 2023, p. 23; Cassidy & Quitzow, 2023; Weko et al., 2023). Furthermore, many potential hydrogen suppliers to the EU have fossil-reliant grids and low electricity access rates domestically. Thus, there is a tension between using their renewable energy for hydrogen production for export, and decarbonising their own economies, and expanding access to clean energy.

3 Domestic Hydrogen Policies and Politics

3.1 The Struggle to Define the European Hydrogen Market

Consistent with its strict climate goals, the EU has prioritised renewable hydrogen, produced via electrolysis with renewable power. However, it took the bloc several years to agree on a detailed definition of what qualifies as renewable hydrogen. The prolonged process reflects the divergent positions of key hydrogen stakeholders. Most prominently, France pushed for rules that would confer benefits to its electricity system dominated by nuclear energy—something that was opposed by Germany and Spain. While the German government opposes nuclear energy as a matter of principle, Spain is keen to reap benefits from its abundant renewable resources.

In July 2023, the EU finally adopted delegated acts to the Renewable Energy Directive (RED II), which contain the definition of *renewable gaseous and liquid*

[1] The Maastricht Treaty (1992) introduced debt and deficit thresholds for Member States: gross public debt may not exceed 60% of GDP, while the fiscal deficit is limited at 3%.

fuels of non-biological origin (RNFBOs) as well as a methodology to calculate greenhouse gas emissions savings. RFNBO is the term used in EU legislation to refer to green hydrogen and its derivatives, like green ammonia and green methanol, as well as e-fuels. This stringent definition underpins the EU's binding targets for hydrogen use in the industry and transport sectors in the RED (see following section for details) as well as eligibility for EU support schemes.

To have their hydrogen recognised as a RFNBO, grid-connected renewable hydrogen production facilities will have to comply with three key requirements: *additionality* (making sure that hydrogen is generated with new renewable power facilities, so as not to divert existing renewable energy from other important decarbonisation uses), *temporal correlation* (making sure hydrogen is produced at times where there is renewable energy available in the grid), and *geographic correlation* (referring to the location of the electrolyser vis-à-vis the renewable energy installation). Although there are important exemptions catering to countries with large shares of nuclear power, like France, as well as phase-in periods, these strict rules present a major challenge for investments in renewable hydrogen in the Union. Indeed, in September 2024, Robert Habeck, Germany's then-Minister of Economy and Climate Protection and a major advocate of ambitious climate and energy policies, petitioned the Commission to extend phase-in periods to unlock direly needed investments (Collins, 2024c).

These EU rules are not only critical for the ramp-up of renewable hydrogen in Europe but will also apply to future hydrogen exporters who want to benefit from policy-driven demand in the EU. For this, certification schemes are needed that will take into account the specificities of local power systems. Nevertheless, given the EU's prominent position in the emerging global hydrogen economy, its approach has begun to shape market rules in other countries, signalling the continued relevance of the so-called Brussels effect (Bradford, 2019). In the USA, for instance, companies wishing to benefit from tax credits for hydrogen investments will need to comply with the EU-inspired requirements of additionality, temporal matching, and deliverability (akin to geographic correlation) (Webster & Ruiz Guix, 2024).

Other types of low-carbon hydrogen (e.g. blue hydrogen made from natural gas with CCS or nuclear-based hydrogen) are still awaiting a legal definition. There is a general guideline they must provide at least a 70% reduction in GHG emissions relative to the fossil fuel comparator.[2] In September 2024, the Commission published a draft delegated act to the Hydrogen and Gas Market Directive containing a detailed methodology for calculating GHG emissions savings (European Commission, 2024f). It is expected to be finalised and adopted in 2025. While the EU's existing demand-side mandates clearly prioritise RFNBOs, the slower than expected scale-up of green hydrogen is beginning to raise interest in low-carbon hydrogen as a solution for the transitional period (Holl et al., 2024). The launch of Norway's large-scale CO_2 storage facility in the Barents Sea in September 2024 may improve the prospects of blue hydrogen production in northern Europe (Parkes, 2024b). In addition, the draft delegated act allows the use of grid electricity to produce

[2] This translates into the GHG intensity threshold of 3.38 $kgCO_2eq/kgH_2$.

low-carbon hydrogen, provided the emissions threshold is not exceeded. Currently, grid electricity in Sweden, Norway, and France can already be used to meet these requirements, and Austria and Finland are close as well (Holl et al., 2024, p. 22).

As for Member States, their positions have reflected a far wider range of preferences for hydrogen production pathways from the outset. Some, like Spain with its developed renewable energy potential, clearly prioritise green hydrogen. Others, like Germany, have put an emphasis on green hydrogen but are gradually opening to blue as well (in its July 2024 import strategy Germany stated its readiness to import blue hydrogen in a transitional phase) (BMWK, 2024a). Germany's strong relationship with Norway and the latter's initial interest in supplying Germany with blue hydrogen, along with its readiness to contribute to developing an infrastructure link for such exports, played a role in this regard (however, the planned Norway-Germany hydrogen pipeline project was eventually scrapped in 2024). Many Member States with a large share of fossil fuels in the economy have considered a combination of green and blue hydrogen from the very beginning—these include Italy, Hungary, and Poland. Finally, France, with its large domestic nuclear fleet, occupies a special place in consistently pushing to have nuclear-based hydrogen granted a special status at the European level. In addition, France is the leading European country promoting the exploration of geological (also called native, or white) hydrogen following discoveries of deposits in its Lorraine region.

3.2 Creating Hydrogen Demand: The Limits of EU Regulatory Power

The EU has been ahead of other global competitors in mandating the use of renewable hydrogen and derivatives in industry and transport, including in aviation and maritime shipping (see Table 1). The revised Renewable Energy Directive (RED III) targets a 42% share of renewable hydrogen in industry by 2030 and 60% by 2035[3] as well as 1% in the transport sector by 2030. The EU mandates are addressed to Member States, rather than individual companies, meaning that each Member State is responsible for designing policies and support measures to ensure the targets are met at the national level. Given the persistently high costs of green hydrogen and the production capacity constraints, this will be a steep challenge, and many Member States have failed to take the needed steps towards realising this goal. In addition, for green hydrogen mandates to be successful, they need to be accompanied by measures to stimulate demand for related downstream products, such as green steel or green fertilisers, to allow them to benefit from the green premium (Marcu et al, 2024).

[3] It is possible for Member States to discount the contribution of RFNBOs in industry use by 20% under two conditions: (a) the Member State has contributed to the EU's overall renewable energy target of 42.5% by 2030; and (b) if the share of hydrogen from fossil fuels consumed in the Member State does not exceed 23% in 2030 and 20% in 2035. This caveat has been introduced to give nuclear-based hydrogen a role in industrial decarbonisation.

Table 1 Sectoral green hydrogen demand mandates in the EU

Sector	Legal basis	Targets	Notes
Industry	RED III	RFNBO share: 42% (2030) 60% (2035)	Refers to hydrogen use as a fuel and feedstock Targets can be discounted by 20% in Member States using large volumes of low-emission non-fossil (e.g. nuclear-based) hydrogen
Transport—all modes	RED III	1% RFNBO subtarget (2030) (*within the aggregate 5.5% target for advanced biofuels from waste and residues and RFNBOs*)	Additional incentive: in the aviation and maritime sectors, the energy content from RFNBOs counts 1.5 times twice for achieving mandated emissions reductions targets
Aviation	ReFuel Aviation Regulation	Synthetic fuels share: 1.2% (2030–2031) 2% (2032–2034) 5% (2035) 10% (2040) 15% (2045) 35% (2050)	These are sub-targets within broader SAF blend mandates which apply to fuel suppliers at EU airports Electrolytic hydrogen produced with nuclear power is eligible
Maritime shipping	FuelEU Maritime regulation	*1% (2031)—non-binding* 2% (2034)—binding, if the indicative target for 2031 is not met	Additional incentive for use of RFNBOs: until 2033, GHG savings from the use of e-fuels will be counted twice towards meeting the broader sectoral GHG intensity reduction targets

Source Authors' own compilation based on EU legal acts (RED III, ReFuelEU Aviation, FuelEU Maritime)

The EU is also promoting demand for renewable hydrogen-based fuels in the aviation and maritime sectors with the ReFuelEU and FuelEU Maritime Regulations. Unlike directives (such as RED III), which need to be transposed into national legislation, EU regulations are immediately applicable in all Member States. The ReFuelEU Aviation regulation chooses a decarbonisation pathway with sustainable aviation fuels (SAFs). Today mostly represented by biofuels, SAFs also include synthetic fuels, such as e-kerosene made by combining renewable hydrogen with CO_2. The regulation mandates aviation fuel suppliers in the EU to supply a 2% SAF blend by 2025 and a 6% blend by 2030, which includes 1.2% in hydrogen-based synthetic fuels (see Table 1). The scale of the challenge is enormous: by the end of 2024, the share of SAF in aviation fuel consumption in Europe is expected to be just over 0.6% (Luman et al, 2024). SAFs remain marginal and very expensive, and there are no sufficient production capacities in the EU to meet expected demand (Alexe & Briggs, 2024). Hence, there are growing fears that ReFuelEU will not be able to deliver. While Germany, France, Norway, and Sweden have announced plans to develop SAF (Transport & Environment, 2024), no final investment decisions had been adopted as of November 2024, and the implementation timeline remains uncertain. As for large-scale e-fuel imports into Europe, they are complicated by investor uncertainty due to the EU's changing regulatory framework, as well as strict European regulations on what counts as a sustainable CO_2 source, making it difficult to produce RFNBO-compliant e-fuels in locations outside of the EU (Marcu et al, 2024).

Additionally, quotas have been formulated for the maritime sector in the FuelEU Maritime Regulation (see Table 1), while the Alternative Fuels Infrastructure Regulation (AFIR) mandates the deployment of hydrogen refuelling infrastructure in urban centres and along major European highways. Similar to RFNBOs and SAF, it is questionable if these targets will be met. The complexity of EU rules coupled with limited EU funding is likely to hamper the needed investments, laying bare the limits of EU regulatory action.

3.3 Financing Investments in Hydrogen Supply and Demand

The EU is only beginning to introduce direct support instruments for hydrogen production and demand that could underpin the ambitious targets and mandates outlined in the previous section. Production subsidies are provided by a specially designed facility called the European Hydrogen Bank (EHB), set up in 2023 and endowed with a budget of 3 billion EUR coming from the Innovation Fund. The EHB is understood as part of the EU's response to the US Inflation Reduction Act, which introduced hydrogen tax credits in the US. However, there are important differences in the scope of funding and eligibility. The EHB has a predetermined budget, while support in the US is theoretically uncapped. Furthermore, in the EU, only successful bidders will receive the subsidy, and in the US, any entity complying with the requirements can benefit from the hydrogen tax credit. Finally, the US scheme is technology-neutral, with the amount of subsidy based on the carbon intensity of hydrogen, whereas the EHB expressly supports renewable hydrogen and its derivatives. (At the same time, Trump's re-election in the US has introduced significant policy uncertainty regarding the future of the IRA hydrogen tax credits).

The Bank's first pilot auction (also referred to as the Innovation Fund hydrogen auction), with a budget of 800 million EUR, was held between November 2023 and February 2024, offering a fixed premium of up to 4.5 EUR/kg to successful bidders. It proved highly popular, attracting 132 bids from hydrogen producers in 17 European countries, led by Spain with 46 bids, Germany with 20, and Norway with 14. Seven green hydrogen projects were selected, poised to receive a total subsidy of 720 million EUR. There were three projects from Spain, two from Portugal, and one each from Finland and Norway, submitting bids for subsidies as low as 0.37 to 0.48 EUR/kg H2 (European Commission, 2024c). Successful projects are required to begin producing renewable hydrogen within five years of signing the grant agreement, i.e. latest in 2029.

The low level of the subsidy requested by successful bidders in the first auction compared to the persistently high costs of green hydrogen production means that offtakers will be expected to shoulder the lion's share of the green premium for renewable hydrogen. While all projects were required to show that they had taken "pre-contractual steps" towards securing offtake with one or more partners for at least 60% of the projected produced volumes, these are not finalised offtake agreements (Directorate-General Climate Action, 2024a). As such, there is still the risk that offtakers might not pay the high costs for the green hydrogen produced. A second round of auctions was launched in December 2024, with a budget of 1.2 billion EUR, including 200 million EUR in dedicated funding for maritime fuels. Following intensive lobbying by the EU electrolyser industry, the auction introduced a special "resilience" criterion, prohibiting applicants from sourcing more than 25% of electrolyser technologies from China (Directorate-General Climate Action, 2024b). (However, India is likely to emerge as a serious contender in electrolyser manufacturing as well). The second auction attracted 61 bids from 11 countries (European Commission, 2025b). A third auction, with a budget of up to 1 billion EUR, is planned for the second half of 2025.

The EHB is also offering a voluntary model called "auctions-as-a-service". It allows Member States to contribute additional national funding to EHB auctions to support bids on their territory that did not make the final cut in the EU-wide selection. The option is meant to promote streamlined, Europe-wide rules for auctions, preventing an excessive national fragmentation of support schemes and cutting costs for individual governments. For the second round of auctions launched in December 2024, Austria, Spain, and Lithuania have earmarked up to 836 million EUR combined in national funding, complementing the auction's budget of 1.2 billion EUR (Martin, 2024c). There is some discussion of Member States using their unspent RRF funds or cohesion funds for this purpose.

In parallel, several Member States are also introducing separate hydrogen support schemes outside of the Innovation Fund auctions (see Table 2). Most Member States focus on promoting domestic hydrogen production, with the notable exception of H2Global, Germany's 4 billion EUR support scheme, which subsidises imports from non-EU countries (but is planning to include European producers in the future auctions). H2Global offers ten-year guaranteed offtake contracts for green hydrogen and derivatives, helping to derisk investments in hydrogen production and supply to the European market. It features double-sided auctions—for international producers on the one end and for European hydrogen offtakers on the other. The price difference is then compensated with funding from the German government.

H2Global's first three auctions—for green ammonia, methanol, and synthetic sustainable aviation fuels (e-SAF)—were held in November 2022 (Parkes, 2023). Fertiglobe, a strategic partnership between Saudi Arabia's ADNOC and the Dutch fertiliser producer OCI, emerged as the winner in the renewable ammonia auction. The company has plans to produce green ammonia in Egypt and has signed a contract with Hintco, the intermediary created for implementing the H2 Global scheme. It aims at supplying up to 19,500 tonnes of green ammonia in 2027, with plans to ramp up this volume to a cumulative 397,000 tonnes by 2033 (Hintco, 2024). By contrast, the

Table 2 Hydrogen production subsidies (operational and planned) in EU Member States

Country	Scheme	Support amount	Details
Contributions to the European Hydrogen Bank auctions ("auctions-as-a-service" model)			
Austria	Direct grants in the framework of the *Hydrogen Support Act (Wasserstoff-Förderungsgesetz)*	820 million EUR	National contribution including 400 million for the second auction beginning in December 2024 plus up to 420 million for the years 2025–2026
Lithuania	Direct grants	36 million	National contribution to the second round of EHB auctions (launched in December 2024), funded out of the Modernisation Fund budget
Spain	Direct grants	400 million EUR	For the second round of EHB auctions (launched in December 2024), to be funded from the national Recovery and Resilience Plan
Other national support schemes			
Denmark	*Power-to-X tender* auction-based fixed-price subsidy	DKK 1.25 billion (ca. 170 million EUR) in 2023	Six projects with 280 MW combined electrolysis capacity were selected, obtaining up to 2 EUR/kg H2 in subsidies
Finland	Direct grants	200 million EUR	Supports investments in production of RFNBOs and the deployment of energy storage with up to 45% of investment costs. Partially funded by the RRF
France	Direct grants for investment costs	900 million EUR	Supports the production of liquid fuels from biomass and renewable hydrogen for use in industrial processes and transport. State aid approved by the Commission in March 2024

(continued)

Table 2 (continued)

Country	Scheme	Support amount	Details
Germany	H2 Global, a double-sided auction scheme for hydrogen producers and offtakers	900 million EUR for the pilot tender and 2.2 billion EUR for the second tender (launched in February 2025)	The German government subsidises the difference between the purchase price and the sales price of hydrogen and derivatives
Italy	Auction-based direct grants	590 million EUR (up to 20 million per project)	Supports renewable hydrogen production in hydrogen valleys throughout Italy
Netherlands	H2 Global double-sided auctions for hydrogen producers and offtakers	300 million EUR	Extension of Germany's H2Global mechanism to cover cooperation with the Netherlands
Netherlands	OWE ("Subsidy scheme for scaling-up fully renewable hydrogen via electrolysis"), an auction-based scheme	2023 selection round: 250 million awarded 2024 selection round: 998 million EUR earmarked	Combines investment grants and operational support
Poland	Auction-based grants	640 million EUR	Programme announced in November 2024; support for RFNBOs and low-carbon hydrogen, as well as for refuelling infrastructure
Portugal	Auction-based contracts for difference	70 million EUR	Supports production of renewable hydrogen and biomethane (70 million EUR each) with ten-year contracts

(continued)

Table 2 (continued)

Country	Scheme	Support amount	Details
Spain	Direct grants	800 million EUR	Supports seven projects that produce hydrogen production projects close to its consumers. Approved by the EU Under the Hy2Use IPCEI scheme
Spain	Direct grants for investment costs	1.2 billion Euros	Investment support for the production of renewable hydrogen in hydrogen clusters, or valleys, with a minimum electrolysis capacity of 100 MW. Fully funded by RRF. State aid approved by the Commission in July 2024

Source Authors' own compilation based on publicly available sources and the European Commission's state aid approval announcements

e-SAF auction has failed to attract any bids, reflecting the lack of production capacity development globally. H2Global's second auction round, with a budget of 2.5 billion EUR (including 300 million EUR in funding contributed by the Netherlands), was launched in February 2025. It features four regional lots (for Africa, Asia, North America, and South America & Oceania), as well as one global lot (Hintco, 2025).

3.4 Developing and Regulating a Hydrogen Infrastructure

To create a functioning hydrogen market in Europe, the EU also needs to develop a cross-border hydrogen transport infrastructure connecting hydrogen producers, industrial consumers, and transit hubs. Such infrastructure would include pipelines, green seaports, and hydrogen storage sites. This would allow, for example, green hydrogen produced in Spain to reach industrial sites in northwest Germany, or the Ports of Rotterdam and Hamburg to become hubs for long-distance imports of green liquid fuels, which can be redistributed to other Member States. In addition, a cross-border CO_2 network would be important as a source of sustainable CO_2 for the production of hydrogen-derived e-fuels. At the moment, there is still no comprehensive plan for a 2050 European net-zero infrastructure, however (Graf & Buck, 2024, p. 23). Instead, there are only Ten-Year Network Development Plans (TYNDPs) issued every two years separately by the electricity and gas network operators, ENTSO-E and ENTSO-G.

An integrated hydrogen infrastructure in Europe would require large-scale investments on the order of tens of billions of euros that public funding alone could not provide. One estimate developed by the Commission puts the costs in the range of 28–38 billion EUR for EU pipelines and 6–11 billion for storage (European Commission, 2022a, p. 7). Another estimate produced by European gas transmission system operators (TSOs) originally put the investment needs for a 53,000 km hydrogen backbone by 2040 at 80 to 143 billion EUR. An update released in November 2023 revised these estimates upwards, citing the rising costs of all components (Martin, 2023). The EU can support the development of a European hydrogen infrastructure in three main ways: by financing selected projects, granting a preferential status to other projects to help them attract other sources of investment, and by creating a clear regulatory framework facilitating investment into the future hydrogen infrastructure.

The EU's strategic investment instrument, the Connecting Europe Facility-Energy (CEF-E), supports intra-European cross-border infrastructure, including hydrogen pipelines and electrolysers. To receive funding from CEF-E, the projects need to be recognised as Projects of Common Interest (PCI).[4] Since 2023, there is also an additional category called Projects of Mutual Interest (PMI), referring to infrastructure links between the EU and neighbouring countries. However, CEF-E has a small budget of only 5.84 billion EUR for the years 2021–2027 for all types of energy infrastructure. In addition to funding, the EU can grant a special status to promising cross-border hydrogen infrastructure projects. This brings the benefits of greater political visibility, preferential treatment (e.g. faster permitting and licensing), and the possibility to receive national subsidies from Member States. The PCI/PMI status confers precisely such advantages. The PCI/PMI list finalised in 2024 is the first to include hydrogen projects: out of 166 projects selected, 65 are hydrogen and electrolyser projects (European Commission, 2023e).

So-called Important Projects of Common European Interest (IPCEI) are another case in point. IPCEI can be proposed by groups of Member States to promote cross-border cooperation and to capitalise on European synergies. They typically bundle tens of individual projects united by a common theme. If accepted by the European Commission, they are exempted from state aid rules and can receive funding support from national governments, which also has the potential to unlock a significant amount of additional private funding. The infrastructure-focused "Hy2Infra" IPCEI approved by the Commission in February 2024 has a record budget of 6.9 billion EUR and bundles 33 projects in seven Member States (France, Germany, Italy, the Netherlands, Poland, Portugal, and Slovakia). These include electrolysers, hydrogen pipelines, H2 storage facilities, and port infrastructure (European Commission, 2024b).

Thirdly, the EU has the important task of developing rules and regulations for the future European network for renewable gases. Clarity on the rules is indispensable

[4] To be recognised as PCI, projects must fulfil the following requirements: have a significant impact on at least two Member States and contribute to promoting market and network integration, enhancing security of supply, promoting energy market competition, and/or contribute to the sustainability transition.

for attracting private investment. This is the focus of the Hydrogen and Decarbonised Gas Package, which entered into force in August 2024. The package introduces a new EU entity to be put in charge of the future network, called the European Network of Network Operators of Hydrogen (ENNOH), which will draw up ten-year hydrogen network development plans starting in 2026. It also increases coordination between hydrogen, electricity, and natural gas networks. The legislation regulates connections and access to the gas grid for renewable and low-carbon gases, establishes a certification system for such gases, and regulates tariff-setting for hydrogen transmission and distribution.

Several Member States are already taking action to develop their hydrogen infrastructure. In the Netherlands, which is positioning itself as a future hydrogen hub for Northwest Europe (Stam et al., 2024), the state-owned company Gasunie began construction of the national hydrogen backbone in October 2023. Germany is following suit with its vision of a 9040 km long core hydrogen grid (*Wasserstoff-Kernnetz*). The pipelines are expected to enter in operation between 2025 and 2032 (BMWK, 2024b). In November 2024, Germany's KfW development bank approved a 24 billion EUR loan for the network construction (KfW, 2024). Germany puts an emphasis on integrating its future network with the rest of Europe, requiring that projects within the *Wasserstoff-Kernnetz* have a PCI or IPCEI status. Spain, too, is planning a national hydrogen backbone, which would include pipelines and storage sites, with the total expected amount of investment estimated at 4.9 billion EUR (Martin, 2024a). Finally, in April 2024, the Danish government reached an agreement with opposition parties to finance a national hydrogen network on the Jutland peninsula, to be constructed by state-owned electricity and gas TSO, Energinet (Collins, 2024a). The planned network also envisions a 340 km pipeline link to Germany, which would enable Denmark to export green hydrogen to its neighbor (Laity, 2025).

There are other examples of cross-border cooperation taking place within the EU. Germany and Belgium have agreed to link their hydrogen networks (Kyllmann, 2023). Spanish, Portuguese, French, and German gas operators have joined efforts to implement the H2Med project, a planned pipeline connecting the Iberian Peninsula with Northwest Europe (H2Med, 2023). MosaHyc is an infrastructure project aiming at creating hydrogen pipelines linking France, Germany, and Luxembourg in the Moselle-Saar region. There is also the AquaDuctus pipeline that aims to bring green hydrogen from North Sea offshore wind farms to German industrial consumers (Buljan, 2023), as well as various electrolyser facilities, hydrogen storage projects, and cross-border hydrogen valleys in Denmark, France, Germany, the Netherlands, Spain, and other countries.

4 An Emerging EU Industrial Policy: Up to the Task?

As a global actor, the EU has traditionally prioritised free trade, competition, and a rules-based international order. Yet with the rise of protectionist policies globally, as well as with the EU's growing dependency on imports of critical raw materials and of many net-zero technologies, the bloc has started to rethink its approach to industrial policy. To date, this has consisted primarily in the promotion of research, development, and innovation. Active support for investments in manufacturing has been slow to emerge. However, the war in Ukraine and increasing geoeconomic rivalry are increasing the willingness to consider a more activist green industrial policy, revealing important challenges for its effective design and implementation.

4.1 Supporting Innovative Technologies in the Hydrogen Sector: An Uneven Landscape

One of the strengths of the EU in the hydrogen economy is its strong track record of funding research, development, innovation, and demonstration. The EU and key European Member States have devoted large volumes of funding to this end. At the European level, the leading actor is the EU's Clean Hydrogen Partnership (CHP). It is a prominent public–private partnership uniting three partners: the European Commission, the industrial grouping called Hydrogen Europe, and the research community Hydrogen Europe Research.[5] CHP promotes the development, commercialisation, and scaling of hydrogen technologies and also engages strongly in pre-normative research, i.e. research that aims to inform future standards (Clean Hydrogen Joint Undertaking, 2022). The CHP has been allocated a 1 billion EUR budget for 2021–2027 from the EU's flagship Horizon research funding framework as well as a matching amount from private partners. It has also received an additional 200 million EUR for its work on hydrogen valleys out of the 2022 REPowerEU package.

R&D funding for hydrogen by Member States, especially those with a strong interest in hydrogen, often exceeds the volumes at the EU level. For instance, in 2023 alone, France spent 586 million EUR and Germany 330 million EUR (see Fig. 1). However, for Member States with limited resources of their own, gaining access to EU funding for research and innovation has been a major motivation behind an increased interest in hydrogen.

Demonstration and first commercialisation represent another key area in which the EU is providing support. The EU Innovation Fund, launched in 2020, is one of the world's largest funding programmes for innovative low-carbon technologies, including hydrogen. The fund supports innovative clean technologies that are past the research stage but are not yet bankable. Its budget is made up of revenues from the auctioning of 530 million EU ETS allowances between 2020 and 2030. At a CO_2 price of 75 EUR, this would put it at approximately 40 billion EUR until 2030 (European Commission, n.d.-a). The Fund's focus on new technologies, rather than on large-scale deployment and scaling-up of commercially available technologies, sets it apart from the US's landmark Inflation Reduction Act (2022). Another difference is that in

[5] The CHP is a successor of the Fuel Cells and Hydrogen Joint Undertaking (FCH JU) established in 2002.

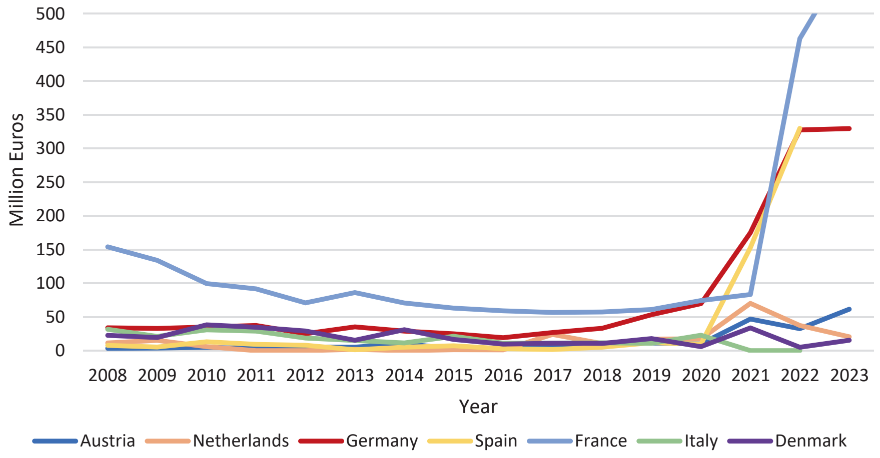

Fig. 1 Public funding for R&D in hydrogen and fuel cells in selected EU Member States, 2008–2023, in million EUR. *Source* Authors, based on IEA (2024)

the US, companies can benefit from support in the form of tax credits for a period of ten years without having to undergo a time-consuming competitive selection process.

Since its inception, the Innovation Fund has issued four large-scale calls, each explicitly targeting hydrogen projects. While the fund is open to all Member States, in practice, the geography of the supported projects reflects existing imbalances in the innovation capacity (see Fig. 2). Lower-income Member States are generally underrepresented (Quitzow et al, 2023). Distribution of funding for hydrogen and electrolyser projects confirms this disparity: of the 2.2 billion EUR in grants that the Innovation Fund awarded in 2020–2023, 74% went to only three countries: Sweden, the Netherlands, and Spain, while Eastern European countries received less than 1% of the total (European Court of Auditors, 2024, pp. 94–95).

Aware of such disparities, the EU set up the *Modernisation Fund* in 2020 with the express goal of supporting the transition to carbon neutrality in lower-income Member States.[6] The Fund's budget relies on the revenues from the auctioning of 2% of EU ETS allowances between 2021 and 2030 as well as additional allowances transferred by beneficiary states. Between 2021 and 2023, the fund disbursed 9.68 billion EUR to eligible Member States to support their green transition (European Commission, 2023g). While hydrogen is listed as a priority area, in practice very few hydrogen projects have been financed so far. One of them is a small green hydrogen production project in Lithuania funded with 2.5 million EUR (Modernisation Fund, n.d.). However, Lithuania is also planning to use its Modernisation Fund budget to contribute national funding to the European Hydrogen Bank's auctions.

[6] Modernisation Fund original members include Bulgaria, Croatia, Czechia, Estonia, Hungary, Latvia, Lithuania, Poland, Romania, and Slovakia, which were joined in 2024 by Portugal, Greece, and Slovenia.

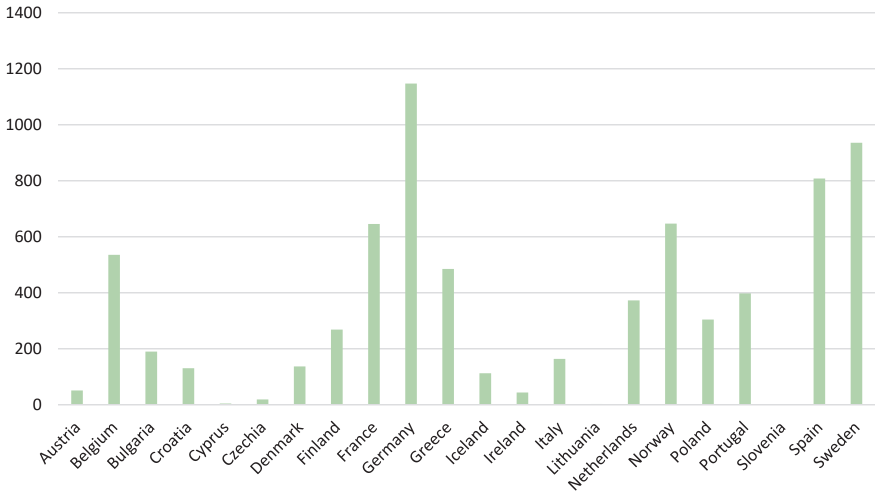

Fig. 2 Innovation Fund grants to member states as of September 2024, million EUR. *Source* Authors, based on the data taken from: Innovation Fund—Portfolio of signed projects. https://dashboard.tech.ec.europa.eu/qs_digit_dashboard_mt/public/sense/app/6e4815c8-1f4c-4664-b9ca-8454f77d758d/sheet/bac47ac8-b5c7-4cd1-87ad-9f8d6d238eae/state/analysis

In addition to these EU-level funds, IPCEI, as already mentioned above, are a prominent funding instrument. They are required to involve at least four Member States. Since 2022, there have been four hydrogen IPCEI "waves",[7] with a combined amount of 18.9 billion EUR in public funding and supporting projects along the entire hydrogen value chain (European Commission, n.d.-b). Given that IPCEI are funded through national subsidies, it is unsurprising that companies from the wealthier and more industrialised Member States tend to be overrepresented.

4.2 *An Emerging European Agenda in Support of Domestic Manufacturing*

The EU has lagged behind other global heavyweights in the manufacturing of clean energy technologies. The European industrial strategy, published in March 2020 and updated in March 2021, identifies the green transition (along with the digital transition) as a priority area. It emphasises the importance of engaging with industry and pursuing "open strategic autonomy", which is to be achieved by diversifying international partnerships, using industrial alliances, and monitoring strategic dependencies (European Commission, n.d.-c).

[7] The four IPCEI include Hy2Tech and Hy2Use approved in 2022, as well as Hy2Infra and Hy2Move approved in 2024.

To engage industry, the EU has set up a Europe-wide Clean Hydrogen Alliance. The alliance has outlined a pipeline of over 750 viable projects for the deployment of low-carbon and renewable hydrogen in Europe. In 2022, it organised a prominent Electrolyser Summit, where the leading European electrolyser companies pledged to increase the manufacturing of electrolysers tenfold to 17.5 GW by 2025 (European Clean Hydrogen Alliance, 2022). The Innovation Fund, too, is increasingly focusing on cleantech manufacturing: in the third and fourth calls, it earmarked 2.1 billion EUR combined for the manufacturing of electrolysers, fuel cells, heat pumps, and energy storage technologies (European Commission, 2022c; 2023d). In particular, the fourth call issued in November 2023 with a record budget of 4 billion EUR aims to "strengthen industrial manufacturing capacity, technology leadership, and supply chain resilience in Europe" (European Commission, 2023d).

Despite these developments, a robust EU-level industrial policy focusing on cleantech manufacturing remains elusive. For one, there is no consensus among Member States on the best approach to green industrial policy in general. While some wealthy Member States like Germany and France actively support national subsidies, others (e.g. the Netherlands or Ireland) would prefer to use such subsidies only sparingly, fearing their potential to distort the level playing field in the EU. Still others, like cost-conscious Austria, Portugal, or Greece, believe in the importance of cheap green technology imports. Finally, the governments in a few Member States, including Hungary and the Czech Republic, simply do not prioritise climate policy to the same extent (Dennison & Engström, 2024).

In any case, funding remains the most basic challenge for developing EU-wide industrial policy. Unlike sovereign nation states, the EU does not levy taxes and cannot borrow on capital markets, absent an emergency of the sort of the Covid-19 pandemic. As alluded to above, EU ETS revenues have become an increasingly prominent source of funding for green industrial policy but are not sufficient in themselves. The Recovery and Resilience Facility (RRF), the main part of the EU's NextGenerationEU pandemic stimulus package, has emerged as another essential source of funding. Based on more than 800 billion EUR in EU-level debt, it is a temporary instrument, however, running out in 2026 (Pisani-Ferry et al, 2023). RRF funds are allocated to and administered by Member States on the basis of their national recovery and resilience plans. At least 37% of RRF funding is required to go to climate-related measures. For many Member States, access to RRF funding served as a strong incentive to consider supporting hydrogen development (some of them for the first time ever). The combined amount, as earmarked in updated Recovery and Resilience Plans, reached 13.6 billion EUR (European Court of Auditors, 2024, p. 93). A large chunk of RRF funds remains unspent, however: by the end of 2023, the Commission had transferred less than 40% of the funds allocated to Member States (Schuman Associates, 2024). The remaining money could help fund hydrogen subsidies and other green transition measures, but only as a short-term fix.

To better position the EU in the global cleantech race, the European Commission proposed the "Green Deal Industrial Plan for the Net-Zero Age" (GDIP) in February 2023, which aims to support the "scaling-up of the EU's manufacturing capacity for the net-zero technologies and products" (European Commission, 2023a). The

Net-Zero Industry Act (NZIA), adopted in May 2024, is the key piece of legislation to meet this goal. To make the EU less dependent on cleantech imports, NZIA sets a domestic manufacturing target of 40% by 2030 for selected "strategic" clean technologies, including electrolysers. If the EU imports more than 50% of a certain category of technologies from a single country, NZIA will require Member States governments to introduce non-price criteria in public procurements tenders, with a weight of 30% (European Commission, n.d.-e). This provision is meant to offer a way to support European manufacturers when they are outpriced by foreign competitors.

NZIA also envisions anti-relocation incentives—such as grants, loans, or tax breaks or, in "exceptional cases", subsidies fully matching those offered by third countries—to help Member States compete with subsidies outside the EU. The NZIA also allows the acceleration of permitting procedures for so-called net-zero strategic projects and envisions upskilling the European labour force by establishing net-zero "academies" (Nicolai & Munchmeier, 2024). Finally, NZIA proposes to establish "Net-Zero Europe Platforms" as a body to coordinate the activities of the Commission and Member States, seek inputs from stakeholders, and ease access to financing.

Despite the many improvements above, NZIA does not provide fresh sources of funding to European industrial policy. In 2022–2023, the Commission floated the idea of creating a European Sovereignty Fund as a Europe-wide industrial policy instrument, but it failed to gain the approval of the Member States. Even the much scaled-down version of the instrument, the Strategic Technology Platform (STEP), has failed to attract the proposed 10 billion EUR in funding. In addition, an ambitious European green industrial policy requires collecting and analysing large amounts of data on issues like technologies, market development, and the business environment. However, the Commission's capacities are already overstretched with current responsibilities in the area of climate and energy policy. There is an acute need for more active and better organised data collection, more analytical staff, and better data infrastructure systems (Jäger, 2024).

Nevertheless, green industrial policy has been identified as one of the central tasks for the new European Commission formed in 2024. In February 2025, the Commission presented its Clean Industrial Deal strategy, aimed at bolstering Europe's industrial competitiveness and resilience–most prominently by bringing down energy prices—while promoting decarbonisation and greater circularity. In line with these priorities, the Strategy focuses primarily on energy-intensive industry and the cleantech sector. The Clean Industrial Deal envisions an Industrial Decarbonisation Accelerator Act, which would speed-up permitting for projects enabling industrial access to energy and climate-friendly technologies, an Industrial Decarbonisation Bank with a budget of up to 100 billion EUR (to be largely funded by EU ETS revenues), and the creation of lead markets for "green" products (European Commission, 2025a). The Clean Industrial Deal draws strongly on the findings of the highly influential September 2024 report *The Future of European Competitiveness* authored by Mario Draghi, former President of the European Central Bank. The Draghi report identifies three main areas of action: closing the innovation gap with the US and China, developing a joint plan for decarbonisation and competitiveness for European industry (including the imperative to lower energy prices), and increasing security and lowering dependencies. The report estimates the needed amount of investment at up to 800 billion EUR annually and advocates developing a Capital Markets Union to mobilise private investment, as well as using common European debt for financing investment in high-priority sectors at the European level (Draghi, 2024).

4.3 A Shift Towards State Aids: Quick Fix or Erosion of the Single Market?

Given the difficulties of creating a truly European industrial policy, the EU has opted to increase the space for implementing industrial policy measures at the Member State level. According to EU rules, any subsidies (called "state aids") granted by Member States require prior approval by the Commission, due to their potential to distort the single market. IPCEI, discussed above, is a prominent instrument utilising state aids, yet it is also a very selective one. In the wake of the war in Ukraine, the EU has taken significant additional steps to relax its restrictions on state aids, in particular in the area of the green transition.

The most momentous step in this direction has been the European Commission's adoption, in March 2023, of a Temporary Crisis and Transition Framework (TCTF). The TCTF allows state aid for the production and use of renewable hydrogen and derivatives and for industrial decarbonisation more generally. A new focus area includes support for the manufacturing of a wide range of green technologies, including electrolysers. The aid must be granted by December 31, 2025 (European Commission, 2024d). In parallel, the Commission has also revised the General Block Exemption Regulation (GBER). Under GBER, Member States can implement certain aid measures without going through the time-consuming notification and approval procedure. GBER allows Member States to support key sectors for the net-zero transition, including hydrogen, and increases the limits for state aid for undertakings in less-developed regions in the EU (European Commission, n.d.-d). The Clean Industrial Deal unveiled in February 2025, too, has put a stronger focus on mobilising national subsidies. Its proposed Clean Industrial State Aid Framework (CISAF), which is set to replace the TCTF and is expected to run until the end of 2030, envisions a faster approval of state aid measures for renewable energy deployment, industrial decarbonisation, and cleantech manufacturing (European Commission, 2025a).

The loosening of state aid rules has been controversial. A number of Member States—including Central and Eastern European states, but also Belgium, Denmark, Finland, Ireland, the Netherlands, and Sweden—have been concerned about the negative impact on competition and the single market, calling on the Commission to prevent sparking a subsidy race across EU countries (Euractiv, 2023). Indeed, these measures bear additional risks of creating a multi-speed transition, where stronger and larger economies use their resources to support their industry and harness the benefits of decarbonisation, while poorer states fall behind (Quitzow et al., 2023). Available spending data confirms that just a few large Member States have provided most of the subsidies in the EU. Between March 2022 and June 2023, Member States provided a total of 140.8 billion EUR in state aids to their companies. A lion's share of this amount went to companies in only three Member States: Germany (72.8 billion EUR), Italy (39.2 billion EUR), and Spain (12.1 billion EUR) (Ferraro et al, 2024).

5 EU Hydrogen Policy: External Dimensions

Endowed with comparatively scarce renewable energy resources relative to its decarbonisation needs, the EU has a strategic interest in securing reliable access to renewable hydrogen from abroad. A central priority of the EU's external energy strategy is the development of hydrogen trade. In line with its traditional role as a regulatory power (Bradford, 2019), it aims to establish a "global rules-based and transparent hydrogen market based on EU's experience" (European Commission, 2022b). It also encompasses the development of bilateral hydrogen partnerships, with a particular focus on the European Neighbourhood and Africa, but also other regions like Latin America or Central Asia.

5.1 EU Leadership in Multilateral Hydrogen Governance

The EU has a strong history of multilateral engagement on the energy transition and climate change and has adopted a similar approach in the area of the nascent international hydrogen governance. Today, the EU is an active participant in all multilateral hydrogen governance fora and platforms, supporting the emergence of a functioning international hydrogen market.

One prominent international platform is Mission Innovation, a global intergovernmental forum promoting public–private partnerships for the energy transition. The EU is a co-lead in Mission Innovation's Clean Hydrogen Mission, which promotes R&D and seeks to bring the costs of clean hydrogen to 2 USD per 1 kg by 2030. Moreover, in January 2021, the EU launched the Hydrogen Valley Platform within Mission Innovation, targeting 100 hydrogen valleys globally by 2030. This initiative builds on the EU's efforts to develop hydrogen valleys domestically, also as part of the Clean Hydrogen Partnership (see above). The platform is on track to reaching this target: as of December 2024, there were 98 hydrogen valley projects in 36 countries announced on the platform, with the largest share located in Europe (Clean Hydrogen Partnership, n.d.).

Another forum is the G7, where the EU has signed the Hydrogen Action Pact to promote the use of hydrogen and cooperation on Power-to-X technologies. The EU has also participated in the G20's International Hydrogen Economy Initiative, which seeks to align and harmonise hydrogen standards and certification procedures promote WTO-aligned hydrogen trade and mobilises finance (G20 Energy Ministers, 2023, pp. 15–16). The European Commission is also contracting party to the

International Energy Agency's (IEA) influential Hydrogen Technology Collaboration Programme (Hydrogen TCP) and a member of the Clean Energy Ministerial Hydrogen Initiative (CEM H2I), a voluntary multi-government initiative launched in 2019, also coordinated by the IEA. CEM H2I aims at promoting international collaboration "on policies, programmes, and projects to accelerate the commercial deployment of hydrogen and fuel cell technologies across all sectors of the economy" (IEA, n.d.).

The Commission also participates in the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE), established in 2003, which works on accelerating market deployment of hydrogen and fuel cells as well as on policy and regulatory activities. IPHE's work on hydrogen includes analysis of hydrogen production and hydrogen trade rules development. In particular, IPHE has focused on developing a methodology for calculating greenhouse gas emissions associated with different technological pathways of hydrogen production (electrolysis, steam methane reforming with CCS, coal gasification or biomass with CCS, as an industrial byproduct, and others). Tudor Constantinescu of the European Commission was one of the three individuals designing and directing the study, which is expected to contribute to shaping international clean hydrogen standards (IPHE, 2023, p. 11). Different EU Member States have been involved in this work, driven by their own technology preferences. Germany, however, due to its long-held scepticism about CCS, has not been involved in developing a methodology for blue hydrogen.

5.2 Promoting International Trade in Hydrogen and Infrastructure Links

A well-functioning international hydrogen market is strategically important for the EU, offering the bloc a chance to diversify suppliers and procure hydrogen at a competitive cost. Within the EU, the most active Member States advocating for international hydrogen trade has been Germany, which is expected to become the largest hydrogen importer in the EU, with plans to import between 50 and 70% of its future hydrogen demand (BMWK, 2024a). Germany is also the only Member State with a dedicated hydrogen import strategy, although the Netherlands, with its energy-intensive industry, is also expecting a need for hydrogen imports. Moving forward, the Commission is planning to develop a Union strategy for imported and domestically produced hydrogen. Member States are now required to include information on expected imports and exports of RNFBOs in the updates of their National Climate and Energy Plans (NECPs) (European Commission, 2024e). These plans are a key governance tool used by the Commission to coordinate efforts at the Member State and EU level.

Currently, the EU as a bloc does not have a scheme for supporting hydrogen imports, as for now the European Hydrogen Bank can only fund projects in EU ETS countries. However, the Commission has announced an interest in linking Germany's

H2Global scheme (see above) to the European Hydrogen Bank. Other importers, such as Japan, as well as exporters, like Australia, have also signalled their interest in collaboration within H2Global (Parkes, 2024a; see also chapter on Japan in this volume), placing Germany at the forefront of developments in support of international hydrogen trade.

Many other Member States, however, do not plan to import hydrogen at all and do not have initiatives in place to support international trade. Germany's active engagement on promoting hydrogen trade stands in sharp contrast, for instance, to the French position. Concerned with preserving energy sovereignty and promoting domestically produced nuclear-based hydrogen, France has been sceptical about hydrogen imports. As a result, and despite its strong influence in Africa, it has been reluctant to include hydrogen cooperation in its external energy policy, and it initially opposed projects involving the construction of European hydrogen pipelines. Other European countries, most notably Spain and Norway, have their own export ambitions and have little to gain from the development of a global hydrogen market, while most Central and Eastern European countries remain at relatively early stages of hydrogen policy development. They have yet to formulate a clear stance on hydrogen imports. Finally, countries like Sweden plan to produce and use hydrogen domestically, for instance, to produce industrial goods like green steel (Ćetković & Stockburger, 2024; Kilpeläinen et al, 2023).

Consequently, there is still no clearly defined framework for the promotion of external hydrogen trade by the EU. While there are plans to add hydrogen to AggregateEU, the EU's voluntary joint purchasing mechanism for natural gas, the timeline for this remains uncertain. EU-level funding for infrastructure links with third countries is also limited. The main instrument for this purpose is the newly introduced scheme for supporting "Projects of Mutual Interest" (PMI) under CEF-Energy. However, the only hydrogen project in this category—a hydrogen pipeline from Norway to Germany planned by Equinor and RWE (European Commission, 2023f, p.10) was scrapped in September 2024 due to high costs and a lack of demand (Reuters, 2024). The prospects of pipeline infrastructure links to other potential partners, like Ukraine, the UK, or North African countries (Weko et al, 2023, p. 21), are uncertain as well. Nonetheless, some progress has been made on the proposed SoutH2 corridor, meant to bring green hydrogen from Algeria and Tunisia to demand centres in Italy, Austria, and Germany (GasConnect Austria, 2025).

5.3 Bilateral Hydrogen Partnerships: EU and Member State Level

Bilateral energy diplomacy is traditionally not within the mandate of the European Commission but this is beginning to change as the EU realises the need to establish global hydrogen value chains. The 2020 Hydrogen Strategy refers to the need to mainstream hydrogen in the EU's international, regional, and bilateral energy and diplomacy efforts (European Commission, 2020, Sect. 7), albeit with the primary goal of establishing a global, liquid, rules-based market for hydrogen. With the adoption of hydrogen import targets in REPowerEU in 2022, the EU's growing interest in integrating hydrogen into its international partnerships has become more evident. The EU's external energy engagement strategy adopted in May 2022 highlights the importance of hydrogen partnerships, with a particular emphasis on the EU's Southern and Eastern Neighbourhood as well as a number of countries in sub-Saharan Africa (European Commission, 2022b).

Despite increased engagement by the Commission (Jerzyniak, 2024), leading Member States have remained at the forefront of bilateral hydrogen diplomacy. Germany has been the most proactive in its bilateral outreach. Germany has signed as many as 32 agreements on hydrogen with countries around the globe (Quitzow et al., 2024). This engagement builds seamlessly on Germany's longstanding efforts to project its soft power as an energy transition leader via its growing network of energy partnerships and dialogues (Quitzow & Thielges, 2020). Aside from signing agreements and MoUs, Germany has launched dedicated hydrogen diplomacy offices internationally, focusing in particular on countries dependent on fossil fuels. Under its H2Diplo initiative, Germany has set up offices in Angola, Colombia, Kazakhstan, Kenya, Nigeria, Oman, Saudi Arabia, and Ukraine (Auswärtiges Amt & H2diplo, n.d.).

Another active country is the Netherlands, as it pursues its vision of becoming a hydrogen hub for Northwest Europe, building on its strong expertise as a natural gas hub. The government has initiated partnerships with Australia, South Africa, and the Gulf States, including Saudi Arabia and Oman. Moreover, its activities are frequently complemented by engagement from the Port of Rotterdam, which is positioning itself as a major actor in European trade with its international partners (Stam et al., 2024).

Italy is less active at the global scale, but has expanded its traditional engagement with Algeria to hydrogen-related questions, operating largely via its state-owned energy companies, ENI and SNAM. Other countries have been conspicuously absent from bilateral hydrogen diplomacy. Despite its proximity to Morocco, Spain, for instance, has refrained from launching any formalised dialogue with its neighbour, a clear reflection of its own export ambitions. Similarly, France has made the deliberate choice not to engage in an import-oriented hydrogen diplomacy, but has some engagement in support of local hydrogen projects. Instead, leading French energy corporations, like Engie and Total, as well as hydrogen infrastructure companies like HDF Energy, have launched their own outreach, exploring opportunities for hydrogen development in Africa and other regions.

The EU is in the process of finding its place in this emerging landscape of hydrogen diplomacy (see Table 3). It has launched partnership agreements with a number of potential exporters globally. In many cases though, these agreements are mere indicators of the EU's interest in cooperation and do not come equipped with a budget. To bridge this funding gap, the Commission is increasingly pursuing its so-called Team Europe approach, a prominent element within its Global Gateway Strategy. This aims at the coordination of European efforts under the leadership of the Commission. Team Europe pools the resources of the EU, interested Member

States, and European financial institutions such as the European Investment Bank, the EBRD, or KfW (European Commission, 2021). In addition, the Clean Industrial Deal proposed by the Commission in February 2025 includes plans for so-called "Clean Trade and Investment Partnerships" (CTIPs) which would align EU external action with its industrial policy and resilience objectives. CTIPs are expected to diversify the EU's supply chains and expand the bloc's access to critical raw materials, clean energy and clean technologies (European Commission, 2025a).

So far, Team Europe has launched hydrogen-related initiatives in Africa and Latin America. In Africa, the European Commission has announced support for a hydrogen power plant in Morocco and green hydrogen production in Namibia (Team Europe, 2024a). According to a joint declaration signed with the Namibian government, the European Investment Bank (EIB) will potentially provide a loan of up to €500 m to finance renewable hydrogen and renewable energy investments (European Investment Bank, 2022). Another partner is Mauritania: in October 2023, the EU launched a Team Europe Initiative in the country, with the goal of supporting its ambition to become a green hydrogen hub. The initiative is expected to fund capacity building and green energy infrastructure, as well as promote job creation and help put in place an appropriate "legal and fiscal framework" (Shumkov, 2023). However, the funding for Mauritania has not been determined yet. Finally, in September 2024, the EU announced it would provide two grants worth 34 million EUR to South Africa to support the development of green hydrogen industry and infrastructure (Laity, 2024; EEAS, 2024).

In Latin America and the Caribbean, the EU is planning to support the production of green hydrogen in Chile, Colombia, Uruguay, Argentina, Panama, and Barbados (Team Europe, 2024b). In Chile, Team Europe has announced a Renewable Hydrogen Funding Platform for with 200 million EUR in financing from the European Investment Bank (EIB) and the German development bank KfW. In Brazil, part of a 2 billion Euro Team Europe Initiative is supposed to support a large-scale green hydrogen project. This would involve the construction of a 10 GW green hydrogen and ammonia production facility in the Brazilian state of Piaui, to be shipped to industrial offtakers in southeastern Europe (European Commission, 2023c).

Overall, the Commission's financial commitments have been relatively slow to materialise, representing a mismatch with the EU's ambitious import targets. The EIB's expanding hydrogen-related funding activities represent one vehicle that might begin to fill this gap. The bank has recently launched a line of funding for hydrogen projects in third countries. The EIB manages the Green Hydrogen Fund set up by the EU in 2021 to provide technical assistance and strategic advice on hydrogen to third states, with a 25 million EUR budget. With the new German contribution of 434 million EUR (Collins, 2023), the fund will be able to provide investment grants to developing countries to implement hydrogen-related initiatives and projects. In cooperation with EIB and other European development banks, the EU also hopes to leverage large-scale private sector resources for hydrogen investment, as envisioned in its Global Gateway initiative. However, experience has shown that leveraging private sector investment with the help of EU funds in partner countries has had limited success (Prontera & Quitzow, 2023).

Table 3 EU and Team Europe agreements containing a focus on hydrogen

Date	Partner country or regional bloc	Agreement name or type
May 2021	Japan	EU-Japan Green Alliance
May 2022	Gulf Cooperation Council	Strategic Partnership with the Gulf
October 2022	Morocco	EU-Morocco Green Partnership
November 2022 (MoU) October 2023 (Roadmap to the MoU for 2023–2025)	Namibia	Memorandum of understanding and establishing a strategic partnership on sustainable raw materials value chains and renewable hydrogen under global gateway Team Europe: EU, EIB, Germany, Netherlands, France, and Finland
November 2022	Kazakhstan	Memorandum of understanding between the EU and Kazakhstan on a strategic partnership in the fields of raw materials, batteries, and renewable hydrogen
November 2022	Egypt	Memorandum of understanding on the EU-Egypt Renewable Hydrogen Partnership
December 2022	Japan	Memorandum of understanding on Hydrogen
February 2023	Ukraine	Memorandum of understanding between the European Union and Ukraine on a Strategic Partnership on Biomethane, Hydrogen, and other Synthetic Gases
April 2023	Norway	EU-Norway Green Alliance
May 2023	South Korea	European Union—Republic of Korea Green Partnership
June 2023	Chile	Team Europe Initiative for the Development of Renewable Hydrogen in Chile. Participants: Austria, Belgium, Denmark, Finland, France, Germany, Ireland, Netherlands, Portugal, Spain, Sweden + European Commission, EIB, KfW
July 2023	Tunisia	Memorandum of understanding on a strategic and global partnership between the European Union and Tunisia
July 2023	Argentina	Memorandum of understanding on cooperation related to energy between the European Union and the Argentine Republic
July 2023	Uruguay	Memorandum between the EU and Uruguay on cooperation on renewable energy, energy efficiency, and renewable hydrogen

(continued)

Table 3 (continued)

Date	Partner country or regional bloc	Agreement name or type
October 2023	Mauritania	Team Europe Initiative to develop green hydrogen in Mauritania and accelerate its energy transition Participants: European Commission, France, Germany, Spain, and the European Investment Bank
November 2023	Canada	EU-Canada Green Alliance

Source Authors' own elaboration based on the Commission's documents

Notably, the EU has not engaged very proactively with the Gulf monarchies of Saudi Arabia, Oman, and the UAE, which have exhibited keen interest in becoming early hydrogen suppliers. Despite the EU's 2022 "Strategic Partnership with the Gulf Cooperation Council" (GCC), which emphasised the region's role as a potential supplier of renewable hydrogen to Europe, the level of engagement on the EU level has remained largely declarative (Bianco, 2023). This may be due to the heterogeneity of interests and positions both within the EU and the GCC blocs, making bilateral partnerships at the national level easier to implement compared to bloc-level engagement (Dienstbier & Ertl, 2023). For now, GCC countries are predominantly looking at Asia, which is already the main market for their fossil fuel exports, as the destination for their future hydrogen exports as well (Dienstbier & Ertl, 2023, p. 47).

In parallel, the EU has also undertaken efforts to develop cooperation with international hydrogen frontrunners, both those with export ambitions and those expected to emerge as importers. In the aftermath of Russia's invasion of Ukraine in 2022, the EU has intensified its cooperation efforts with Canada, which is a potentially large hydrogen producer. The European Commission and the Canadian Government set up a special working group on the green transition and liquefied natural gas (LNG). This aims at "lay[ing] the foundation for the development of reliable hydrogen supply chain between Canada and the EU as well as to develop common approaches to standards and the certification of hydrogen" (European Commission, 2023b). Yet the current absence of an LNG or hydrogen gas export infrastructure between Canada and the EU pushes these plans into a remote future. As for the USA, despite the latter's ambitious hydrogen production plans supported by the Inflation Reduction Act, hydrogen has not been at the forefront of various bilateral cooperation initiatives between the EU and the US. The EU has also launched cooperation with fellow prospective hydrogen importers in Asia such as Japan and South Korea, yet there have been few activities on this front so far. In general, efforts at cooperation between prospective hydrogen importers have been very limited. A situation where they compete for a limited supply of clean hydrogen in the future is therefore not unlikely.

6 Conclusion

The European Union and selected Member States have played a pioneering role in promoting a clean hydrogen economy. The EU has been developing a detailed regulatory framework for hydrogen, which assigns a priority to renewable hydrogen and has a tangible impact on policy discussions in other parts of the world. Starting in 2030, the EU is mandating the use of renewable hydrogen and its derivatives in industry and transport. With the launch of the European Hydrogen Bank in November 2023, the EU is now also offering hydrogen production subsidies, which are complemented by national-level support schemes in many Member States.

Yet the EU's vision is coming to grips with the challenging internal dynamics and the new geopolitical realities, leading to adjusted expectations. Defining a common European course on hydrogen has proven complicated, given the very different starting positions, priorities, and fiscal resources of Member States. There are growing fears about the weakening competitiveness of European industry vis-à-vis other global players. Cost reductions for clean hydrogen have lagged far behind initial forecasts, with repercussions for demand-side developments. These factors help explain the low number of final investment decisions (FIDs) in the hydrogen sector in Europe. Other pressing priorities, such as defence spending, are beginning to compete for attention and resources with the green transition as well. More generally, there is a growing concern in the EU that its fiscally conservative system of economic governance is ill-suited to address the mounting geopolitical challenges the bloc is facing today, which require large amounts of public investments.

In the face of the accelerating global subsidy race, the EU, due to its fiscal limitations and institutional setup, has been unable to agree on a large EU-wide green industrial policy support scheme. Instead, it has relaxed its strict rules on granting subsidies at Member State level. Predictably, a few Member States with larger fiscal resources have accounted for a lion's share of all subsidies granted, which poses a risk to the integrity of the EU's prized single market. A "Clean Industrial Deal" to boost competitiveness has been identified as the chief priority of the new European Commission formed in December 2024 but achieving its goals will require massive amounts of private and public investment and likely institutional reform.

Internationally, the EU has been actively involved in various multilateral hydrogen governance mechanisms aimed at promoting an international hydrogen market, developing common standards, and popularising hydrogen valleys. In addition, the EU's explicit acknowledgement of its future need for hydrogen imports has sparked the interest of potential exporters worldwide. These include both established energy producers like the Gulf States but also low- and middle-income economies in Africa and Latin America with large but still underexploited renewable energy potentials. Following the examples of proactive Member States such as Germany or the Netherlands, the EU is beginning to intensify its international outreach on hydrogen as well. Its connectivity initiative, the Global Gateway, is putting a growing emphasis on hydrogen as an important element in EU partnerships, even though the financing of such measures often remains uncertain. Within this context, the EIB is also likely to play a more prominent role in hydrogen partnerships in the future. A key challenge will be how to develop a strategy for the effective coordination of EU and Member State initiatives. The EU's Team Europe approach provides such a framework in principle but remains at an early stage in terms of practical implementation. Rather, for the time being, Germany's very active engagement strategy remains the more visible and tangible in terms of its financial envelope.

That said, the EU's expected dependency on hydrogen imports makes it more attractive as a long-term strategic partner for future hydrogen exporters. As the EU works on shaping diversified and resilient green value chains for hydrogen, one of the key challenges is to promote inclusive partnerships with the Global South that contribute to local socioeconomic development and decarbonisation. Done right, such partnerships could bring benefits and local acceptance on both sides, with positive impact for the global climate efforts as well. Moreover, such partnerships might be stepping stones for broader economic partnerships within a net-zero economy. In this vein, the EU's need to collaborate might also prove an asset as the EU seeks to build broader networks and alliances.

Acknowledgements Research for this chapter was financially supported by the German Federal Foreign Office within the framework of the project "Geopolitics of the Energy Transformation – Implications of an International Hydrogen Economy" (GET Hydrogen), funding reference number AA4521G125.

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China and the Geopolitics of Hydrogen: An Awakening Giant?

Xiaohan Gong and Rainer Quitzow

Abstract Over the past decade, China has emerged as a pivotal player in the energy transition, leading the global deployment of renewable energy and assuming an increasingly dominant role in clean energy supply chains. In the hydrogen sector, it was not among the initial frontrunners and continues to take a cautious approach. While developments have started accelerating, these are still primarily driven by sub-national actors. Against this background, the chapter explores Chinese developments in the hydrogen sector from a geopolitical perspective. It begins with a brief overview of China's broader energy foreign policy. This is followed by a review of its domestic hydrogen strategy and key developments in the Chinese hydrogen sector. Building on this, the paper provides an overview of China's international hydrogen-related policy, including engagement in technology cooperation, supply chain development and international standard-setting and bilateral cooperation with key partners. It concludes with a synthesis of China's emerging role within the nascent hydrogen economy. It highlights the country's key assets and potentials as well as the main concerns and priorities of its evolving policy approach.

1 Introduction

China has emerged as a key player in the global energy market since the turn of the century. This has coincided with its rapid increase in energy demand, turning it into a net energy importer in the late 90s (Meidan, 2023). To confront its increasing dependence on fossil fuel imports, its energy companies, most of them state-owned

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R. Quitzow and Y. Zabanova (eds.), *The Geopolitics of Hydrogen*, Studies in Energy, Resource and Environmental Economics, https://doi.org/10.1007/978-3-031-84022-7_3

enterprises (SOEs), have actively invested in foreign oil and gas fields and initiated oil and gas trade to secure its external energy supply (Gong, 2022). This has resulted in a growing presence in the Middle East and Central Asia as well as a number of African oil-producing countries, increasing Chinese influence but also vulnerability to developments in these regions (Meidan, 2023). In more recent years, the electricity sector has become a second important dimension of China's outward-oriented energy engagement, covering investments in traditional power generation, power grids as well as renewable energy (Chen et al., 2020).

These foreign engagements are driven by a combination of commercial and political objectives. Energy companies have invested to exploit economic opportunities in foreign energy markets and to engage in technology-related cooperation to boost their competitiveness on international markets. At the same time, these investments can be viewed as tools for realizing strategic objectives, like securing access to energy resources, exerting influence on strategically important countries, and becoming a leader in strategic energy technologies (Kenderdine & Lan, 2018; Tolipov, 2018). Indeed, against the background of growing geoeconomic rivalry, China's increasing dominance of green energy supply chains, most notably in the sphere of lithium-ion batteries and solar photovoltaics, has become a central concern of Western governments (Bond et al., 2024). At the same time, Chinese policymakers are concerned that constraints on access to international technological know-how could pose as a new threat to its energy security within the context of a transition to net zero, replacing dependence on energy imports as its main vulnerability (State Council, 2020; NDRC & NEA, 2017).

It is against this background that hydrogen is emerging as an increasingly influential factor in the evolving geopolitics of China's energy transition. The development of an international hydrogen economy comes with a host of geopolitical implications as countries vie for leadership in a net-zero economy (IRENA, 2022). In this vein, China's hydrogen development and its international hydrogen cooperation add an important new dimension to the discussion on China's increasing role in the international political economy of energy (de Blasio & Pflugmann, 2021). Hydrogen development will influence its existing energy relations and may influence the global distribution of power. This includes questions related to international hydrogen production and trade as well as the geoeconomics of emerging hydrogen technologies and supply chains (Nakono, 2022).

To shed light on these ongoing developments, this chapter provides an overview of China's international hydrogen policy and its related initiatives abroad. The chapter begins with a brief overview of China's broader energy foreign policy. This is followed by a review of its domestic hydrogen strategy and key developments in the Chinese hydrogen sector. Building on this, the paper provides an overview of China's international hydrogen-related policy, including engagement in technology cooperation, supply chain development, and international standard-setting. Section 5 discusses bilateral cooperation with key partners, including leading industrialized countries and a number of strategic energy partners. Section 6 sums up and discusses implications.

2 China's Evolving External Energy Strategy

Diversifying energy supply, expanding China's role in global energy value chains to enhance its influence, and fostering international technology cooperation are key dimensions of China's external energy strategy. Diversifying its supply of oil and gas remains a major goal of China's energy strategy, given its heavy reliance on imports (NDRC & NEA, 2016b). Policymakers have stressed the importance of diversifying oil and gas suppliers and transportation routes through investments in hydrocarbon extraction and the construction of pipelines (NDRC & NEA, 2017; NEA, 2022). A series of policy documents have called for expanding pipeline capacity and for ensuring its safe operation by collaboratively working with countries within its Belt and Road Initiative (BRI) (NDRC, 2016; NDRC & NEA, 2017).

Furthermore, China is increasingly pursuing a strategy aimed at enhancing its influence on the global energy sector by expanding its role in global energy value chains (NEA, 2014). To achieve this, China is trying to go beyond securing energy imports to developing stakes further upstream in the oil and gas sector as well as power generation. In this vein, China's energy SOEs have established their presence in the oil and gas industry of the Middle East, from exploration, transport, and refining to engineering services and equipment sales (Kenderdine & Lan, 2018). Chinese companies have also pursued overseas investments in various types of power generation, including coal-based power generation (especially in South and Southeast Asia), hydropower (especially Africa and Southeast Asia) as well as wind and solar (especially in Europe and Latin America) (Chen & Springer, 2021; Liedtke, 2017). While hydropower and coal-fired power generation have dominated overall, China has recently bowed to international pressure, announcing in 2021 that it would no longer invest in overseas coal projects. While Chinese-backed investments in the sector have not been halted entirely, there are now clear signs that the government has substantially reduced its support, giving an important boost to projects in the renewable energy sector (Wang et al., 2024).

As Kenderdine and Lan (2018) have argued, China's outward-oriented investment policy is part of a broader geoeconomic strategy. In an effort to graduate to an innovation-centered model of industrial development, the government is seeking to wind down excess industrial capacity in sectors like steel and cement making and promote the relocation of manufacturing industries to countries within the BRI. This provides its firms with new investment opportunities, while exporting Chinese standards (Xu & Miao, 2019). It is also an entry-point for positioning low-cost Chinese technology in developing country markets, especially in those sectors where China has found it difficult to compete with higher-quality Western products (Oh, 2021).

In addition, technology cooperation plays a critical role in boosting the competitiveness of the domestic energy industry (Zhao & Wu, 2012). Since 2007, Chinese energy policymakers have attached increasing importance to this dimension of its international energy policy (NDRC & NEA, 2016a, 2017). By engaging in technology cooperation, energy companies can enhance their innovation capacity and acquire advanced know-how for domestic use. The government's Opinions on Promoting Green Development under the Belt and Road Initiative (2022) and the 14th Five-Year Plan of Renewable Energy Development (2022) promoted international technology cooperation in the areas of cost-effective power generation by renewable energy, smart grids, hydrogen energy, energy storage and carbon, capture, use, and storage (CCUS) (NDRC et al., 2022).

SOEs are leading players in carrying out China's external energy strategy (Gong, 2022). SOEs are expected to improve the capacity of securing energy supply and lead the development of new energy (State Council, 2016a). To this end, the State-owned Assets Supervision and Administration Commission of the State Council (SASAC) engages with SOEs to develop company-specific five-year plans in support of national five-year plans (SASAC, 2016). The evaluation of energy SOEs also explicitly includes the appraisal of the contribution of overseas energy investments to the security of oil supply (NDRC, 2016). In this vein, China's national oil companies (NOCs) have helped its government to achieve policy objectives of diversifying foreign oil and gas supply. They have pioneered oil exploration in countries like Sudan and have invested in import infrastructure, like LNG terminals and pipeline projects, connecting China to supplies of natural gas in Russia and Central Asia (NDRC, 2013). In the electricity sector, State Grid has actively pursued acquisitions in foreign electricity transmission and distribution grid infrastructure projects (Zhang, 2023), including the Philippines, Portugal, and Brazil. More broadly, the Chinese government has encouraged electricity SOEs to pursue international cooperation in energy R&D, export energy services, and participate in standard-setting (NDRC & NEA, 2016a). China's energy-related five-year plans highlighted that electricity companies should introduce technology standards to foreign electricity projects (NDRC & NEA, 2016b; NEA, 2016).

3 Hydrogen Development in China

Despite being the world's largest producer and consumer of hydrogen, China's clean hydrogen policy is still at an early stage compared to global frontrunners like Germany or Japan (Gong et al., 2023). A clear policy agenda is only beginning to emerge. Nevertheless, China's hydrogen economy can build on a significant policy legacy, most notably in the area of fuel cell electric vehicles (FCEVs), as well as an increasingly dynamic investment agenda driven by a number of provinces seeking to capitalize on global trends in the sector. Before turning to China's international hydrogen activities, this section provides an overview of key developments in China's domestic hydrogen sector.

3.1 The State of China's Hydrogen Economy

China is the largest hydrogen producer in the world, accounting for approximately one-third of global output. Its production volume reached 37.81 million tons in 2022 (NEA, 2023), of which currently only a small fraction (approximately 2%) is based on renewable energy-based electrolysis (see Fig. 1). Nevertheless, given its abundant solar and wind resources in the North of the country and major hydropower resources in the Southwest, China is expected to significantly increase production of renewable electricity-based hydrogen (Gong et al., 2023). By 2030, the China Hydrogen Alliance predicts a share of 15% of national production. Currently, the Beijing-Tianjin-Hebei Region, the Yangtze River Delta, the Pearl River Delta, and Ningdong Energy and Chemical Base (located in Ningxia Province) are the most important areas of hydrogen development in China (China Center for International Economic Exchanges, 2021).

China is emerging as a global frontrunner in electrolysis-based hydrogen production (Xu & Yu, 2021). It accounted for two-thirds of both operational and announced electrolysis capacity in 2024 (Hydrogen Council & McKinsey, 2024). According to the IEA Hydrogen Production and Infrastructure Database, China had over 10 GW of electrolysis capacity either in operation or under construction in October 2024, more than double that of the EU (see Fig. 2). Deployment in China has been dominated by investments in alkaline electrolyzers, where the country has emerged as a cost leader. The productivity of alkaline electrolyzers in China is estimated at 1000–1200 m^3 per hour (Wen et al., 2019), and they are estimated to cost as little as $200 per kW (Guotai Junan Securities Co., Ltd, 2024), significantly below estimated costs in Europe (approximately $1200 per kW) (PV Magazine, 2024). As for storage and transportation infrastructure, an increasing number of demonstration projects

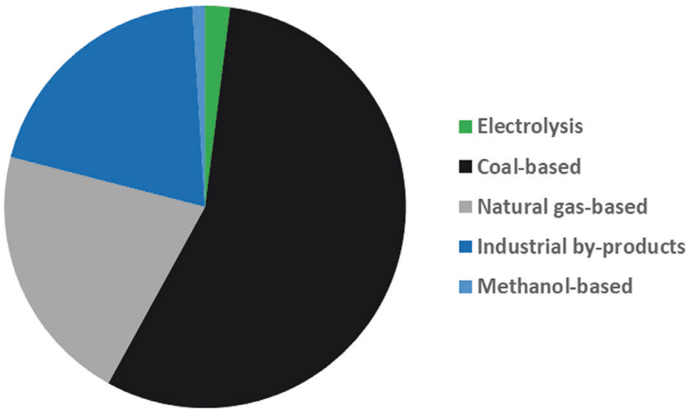

Fig. 1 China's hydrogen production in 2022. *Source* Authors, based on Securities Times China News (STCN) (2024)

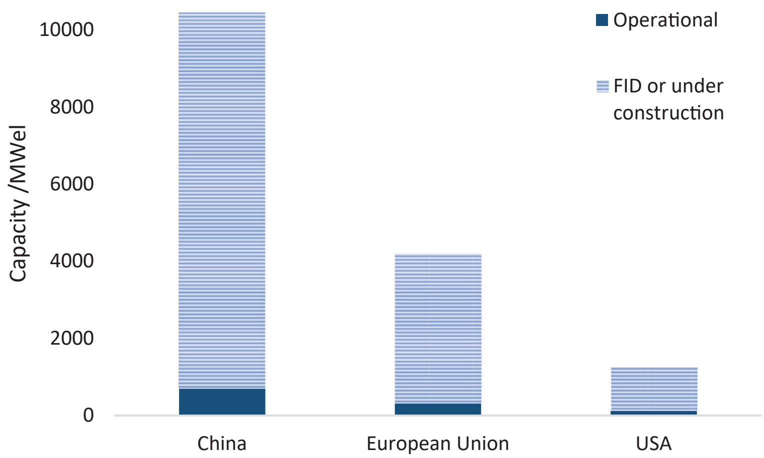

Fig. 2 Electrolyzer capacity in China, the European Union, and the US, operational and under construction, October 2023. *Source* Authors, based on the IEA Hydrogen Production and Infrastructure Database, October 2024

have emerged in the past years, including hydrogen refueling stations, short-distance hydrogen pipelines, and liquid hydrogen storage.

Outside the petrochemical sector, the most well-established application is the use of hydrogen in heavy-duty, commercial FCEVs. The development of fuel cells has been identified as a critical energy-related project in the state's high-technology development plan (Yi et al., 2018). China also promotes R&D and industrialization of polymer electrolyte membrane (PEM) fuel cells and solid oxide (SO) fuel cells (China Hydrogen Alliance, 2019). Since 2017, fuel cells have been gradually introduced in ships, buses, and commercial vehicles (Sun & Yang, 2021). FCEVs account for just 0.4% of new energy vehicles (NEVs) in China (Haitong Securities, 2021). Nevertheless, China accounted for over 50% of global FCEV sales in 2024 (up to end of October) (Collins, 2024a), and it is predicted that the number of FCEVs in China will reach around 2 million by 2035 and around 11 million by 2060 (S&P Global Commodity Insights, 2022), exceeding current policy objectives (see Sect. 3.3).

Chinese state-owned energy companies have played a major role in large-scale and capital-intensive hydrogen projects, including the construction of hydrogen refueling stations and pipelines. China National Petroleum Corporation (CNPC) and PipeChina are positioned to play a significant role in hydrogen transport (Tu, 2020), while China Petrochemical Corporation (Sinopec) has engaged broadly in the hydrogen business including launching renewable hydrogen production in Xinjiang and Inner Mongolia, building short-distance hydrogen pipelines, and repurposing petrol-/gas-refueling stations. The State Power Investment Corporation (SPIC), an important electricity SOE in China, is building on existing capacities in the power sector to explore opportunities in the field of electricity-based hydrogen production.

The development of China's hydrogen value chain still lags behind advanced economies and remains dependent on technology imports in a number of areas such as core elements of fuel cells (Tu, 2020; Xu & Yu, 2021). For instance, Chinese firms lack the capacity for large-scale manufacturing of platinum catalysts, needed for PEM fuel cell stacks (Haitong Securities, 2021). China also depends on imports of key parts of PEM electrolyzers (Wallstreet News, 2022a), which are more suitable for running on intermittent renewables than traditional alkaline systems. Similarly, China lacks capacities in important storage and transport technologies (Gong et al., 2023).

3.2 The Role of Hydrogen in China's Future Energy Supply System

China aims to increase the percentage of renewable hydrogen in its future energy system. According to the Working Guidance for Carbon Dioxide Peaking and Carbon Neutrality in Full and Faithful Implementation of the New Development Philosophy (2021), developing hydrogen value chains will help achieve the goal of accelerating the establishment of a clean, efficient, low-carbon, and safe energy system and will increase the supply of non-fossil fuels (The CPC Central Committee & State Council, 2021). The National Hydrogen Development Plan, launched in March 2022, identifies hydrogen's broader role in decarbonizing energy consumption and contributing to achieving carbon neutrality in hard-to-abate sectors, including the steel, transport, and chemical industries. By 2025, China seeks to establish a hydrogen supply system from industrial by-products and renewable hydrogen to reduce 1–2 million tons of CO_2 emissions annually (NDRC, 2022). In an effort to facilitate the sector's development, the government adopted the country's Energy Law in 2024, officially classifying hydrogen as an energy source rather than a hazardous chemical (PRC Energy Law, 2024). This will have important implications for the regulation and promotion of hydrogen within Chinese energy policy (Collins, 2024b).

The National Hydrogen Development Plan explicitly advances renewable hydrogen, although its initial goals have remained relatively modest. It aims to produce 100,000–200,000 tons of renewable hydrogen per year by 2025 (NDRC, 2022). The plan does not make any reference to CCUS technologies to reduce the carbon footprint of fossil-based hydrogen production. Before issuing the National Hydrogen Development Plan, the central government had already supported pilot city clusters for the promotion of FCEVs, especially those supported by renewable hydrogen (MOF et al., 2020a). The 14th Five-Year Plan of Renewable Energy Development (2022) further explains that renewable hydrogen production will be established in places where the cost of generating renewable electricity is low and where there have been pilot applications of hydrogen storage, transport, and use (NDRC et al., 2022). There are also strong signals that the Chinese government will continue supporting its hydrogen ambitions in the upcoming 15th Five Year Plan period from 2026 to 2030, building on the objectives and actions set-out in the National Hydrogen Development Plan. It has also clearly signalled that it wants to prioritize renewable hydrogen, but it has stopped short of announcing plans for a broader subidy scheme that goes beyond the scale of industrial pilot projects (Collins, 2025a). Instead, in its Guiding Opinions on Energy Work in 2025, the National Energy Administration has called on sub-national governments to "steadily develop renewable hydrogen production and sustainable fuel industries" (Collins, 2025b).

Hydrogen development plans adopted by sub-national governments include both plans to scale up conventional hydrogen production in the chemical sector and ambitious goals to expand renewable hydrogen, in some cases exceeding national goals. The role of different hydrogen production pathways varies from region to region. Coal-rich provinces and those with mature chemical industries, such as Shandong Province and Shanxi Province, still mainly pursue the production of hydrogen from coal or industrial by-products. Provinces rich in renewables are seeking to exploit these resources for electricity-based hydrogen production. Here Ningxia Province and the Autonomous Region of Inner Mongolia stand out, targeting 300,000 and 480,000 tons of renewable hydrogen by 2030, respectively. Given the lack of central-level guidance, renewable hydrogen production is not the main focus across the country. Rather, Chinese local and provincial governments are promoting a mix of hydrogen production pathways in an effort to boost overall supply (Gong et al., 2024).

3.3 Expanding Hydrogen Use

The National Hydrogen Development Plan also reconfirms China's longstanding aim to promote FCEVs and related technologies. The development of China's hydrogen-fueled vehicle industry dates back to 2012 (State Council, 2012). The 13th Specific Plan of Scientific and Technological Innovation in Transportation (2017) identified hydrogen FCEVs (MOST & MOT, 2017) as well as hydrogen storage and refueling as policy priorities (MOST & MOT, 2017). In 2020, the central government launched pilot applications of mid- to long-distance commercial FCEVs in hydrogen industrial clusters (e.g., Beijing and Shanghai) (MOF et al., 2020a). The National Hydrogen Development Plan (2022) highlights that in the transport sector, hydrogen will first be used to fuel hydrogen fuel cell commercial heavy vehicles and will then be gradually used to fuel hydrogen fuel cell passenger vehicles. By 2025, the number of hydrogen FCEVs should reach around 50,000 (NDRC, 2022). It is also a leader in the deployment of hydrogen refueling stations, accounting for approximately 40 percent of global installations at the end of 2024 (Collins, 2025c).

Stabilizing variable renewable power through hydrogen storage is another important area of projected hydrogen use. According to the 14th Five-Year Plan of a Modern Energy System (2022), hydrogen is envisioned to help increase the share of renewable energy in China's power system (NDRC & NEA, 2022a). Also, the National Hydrogen Development Plan states that China will explore and foster 'energy storage via hydrogen energy and wind or solar power.' (NDRC, 2022). NDRC and NEA further introduce that there will be demonstration projects for the use of hydrogen-based storage for balancing variable renewable power generation (NDRC & NEA, 2022a). Local governments such as Tianjin aim to use hydrogen as seasonal energy storage in the renewable power system (Tianjin Government, 2020).

Chinese policymakers have only recently addressed the role of hydrogen for the decarbonization of industry. Beginning in 2021, China has formulated goals to use hydrogen to decarbonize the steel industry and the chemical industry. According to the Notice by the State Council of the Action Plan for Carbon Dioxide Peaking Before 2030 (2021) and the National Hydrogen Development Plan, steel companies are expected to explore the use of renewable hydrogen to reduce carbon dioxide emissions. Since 2022, NDRC and NEA aim to support the coupling of the coal-chemical industry and renewable hydrogen development and to promote the use for renewable hydrogen as raw materials in chemical production (NDRC & NEA, 2022a). The Implementation Plan of Carbon Peaking of Industry (2022) recognizes hydrogen as low-carbon energy or a low-carbon raw material in decarbonizing the steel industry, the construction industry, and the transport industry (MIIT et al., 2022).

3.4 Promotion of Innovation and Industrial Development in the Hydrogen Sector

The 13th Industrial Development Plan of Strategic Emerging Industries (2016) identified hydrogen production and storage and hydrogen refueling stations as strategic emerging industries, demonstrating the central government's aim to pursue industrial leadership in the sector (State Council, 2016b). Overcoming technological bottlenecks of related core technology and key manufacturing equipment is considered important for its economic development (NDRC, 2022). While the government has emphasized fuel cells and FCEVs in the past, it has recently increased its attention to other segments of the hydrogen value chain including scaling-up the manufacturing of related production equipment and developing materials for hydrogen storage. Furthermore, the National Hydrogen Development Plan has identified the development of technical standards as an important priority.

The Chinese government first started to promote hydrogen-related technologies in its State Plan of High Technology Research and Development, issued in 1986 (The CPC Central Committee & State Council, 1986). An important priority at this stage was the promotion of R&D and manufacturing of hydrogen fuel cells, which was reiterated in 2021 (NDRC, 2021). The National Hydrogen Development Plan encourages the development of PEM fuel cells, specifically. More recently, China is also promoting R&D in the field of electricity-based hydrogen production. Initially, the National Mid-and-Long Term Development Plan of Science and Technology (2005) highlighted the importance of advancing the technology for producing hydrogen from both renewable energy and fossil fuels (including coal gasification) in an efficient and cost-effective manner. The Action Plans of Energy Technological Revolution and Innovation (2016–2030) promoted innovation in the field of hydrogen purification for its production from industrial by-products. With the State Council's strategy document, Energy in China's New Era (2020), the focus shifted to advancing technologies for producing hydrogen from electricity (State Council, 2020). The National

Hydrogen Development Plan aims to improve the efficiency of hydrogen production based on renewable energy and to increase the productivity of related production equipment (NDRC, 2022).

Over time, hydrogen storage and transport have been recognized as another important technological bottleneck for China's hydrogen development. Therefore, the National Hydrogen Development Plan stresses the importance of developing materials for hydrogen storage. The 13th Specific Plan of Scientific and Technological Innovation in Transportation (2020) promotes the manufacturing of equipment for high-pressure hydrogen storage and refueling (MOST & MOT, 2017). The 14th Five-Year Plan of Energy Technology Innovation seeks to advance the innovation and manufacturing of the equipment for hydrogen pipelines and hydrogen refueling stations with varying levels of compression.

A major development in the promotion of innovation in the hydrogen sector has come with the launch of the Central Enterprises Green Hydrogen Production, Storage, and Transportation Innovation Joint Venture. Initiated by SASAC and jointly led by CNPC and Sinopec, the initiative brings together major SOEs, technology providers, and academia in an effort to promote innovation and technology development in the fields of green hydrogen production and conversion, storage and distribution, hydrogen-based raw materials and power as well as safety and testing (China Hydrogen Alliance, 2024).

3.5 Advancing the Formulation of Hydrogen Standards

In 2020, the China Hydrogen Alliance issued the Standard and Evaluation of Low-carbon Hydrogen, Clean Hydrogen, and Renewable Hydrogen (2020). According to the document, low-carbon hydrogen should not exceed 14.51 kg of CO_2 emissions per kg of hydrogen, while clean and renewable hydrogen should not exceed 4.9 kg of CO_2 emissions per kg of hydrogen (see Table 1). The standard for clean hydrogen roughly equates to the benchmark of 36.4 g of CO_2 per MJ for low-carbon hydrogen set by the European CertifHy scheme (assuming an energy density of 120–140 MJ per kg of hydrogen). The Chinese benchmark for low-carbon hydrogen exceeds even the estimated emissions of hydrogen produced from natural gas via steam methane reforming (referred to as gray hydrogen). The emissions benchmarks should be quantified using a lifecycle approach, which takes into account the raw material acquisition phase, the transport phase of raw materials, the phase of production, on-site storage, and transport of hydrogen energy. For coal- and natural gas-based hydrogen, this includes the stage of coal and gas extraction and transport, respectively. For electricity-based hydrogen, the assessment begins with the production of electricity. Neither low-carbon nor clean hydrogen is subject to any restrictions in terms of the process of hydrogen production and may in principle include hydrogen production from any source. Renewable hydrogen is considered a sub-category of clean hydrogen with the added requirement that the hydrogen should be produced

Table 1 CO_2 emissions standards for low-carbon, clean, and renewable hydrogen issued by China's Hydrogen Alliance

	Low-carbon hydrogen	Clean hydrogen	Renewable hydrogen
Maximum CO_2 emissions per kilogram of hydrogen	14.51 kg	4.9 kg	4.9 kg
Hydrogen production from renewable energy	Not required	Not required	Not required

Source Gong et al. (2023)

via electrolysis with renewable energy. The latter may be produced on-site or may be purchased via an eligible certificate program.

In addition, the central government aims to gradually establish a system of hydrogen technology and safety standards. Dating back to 2005, the Standardization Administration of China (SAC) issued national standards for hydrogen production from electrolysis (SAC, 2005). The National Hydrogen Development Plan highlights the importance of establishing a system of hydrogen industrial standards for different segments of the hydrogen value chain from production to different areas of application (NDRC, 2022). Currently, the formulation of technological standards focuses on fuel cells and FCEVs (China National Institute of Standardization, 2022). The government has already initiated a series of standards for the use of hydrogen refueling equipment as well as the transport and production of liquid hydrogen (SAC, 2021a, 2021b, 2021c). It has announced that it intends to continue its promotion of hydrogen standards in the 15th Five Year Plan period (Collins, 2025a).

4 China's External Hydrogen Policy

As outlined in the previous section, China's emerging domestic hydrogen policy agenda remains at a relatively early stage. The government has begun to formulate modest supply-side targets, and, despite an emphasis on the importance of renewable hydrogen in a future, carbon–neutral energy system, it has not discouraged investment in fossil-based hydrogen. Instead, the policy remains centered on developing hydrogen-related industries and acquiring related technological know-how. Its external hydrogen engagement clearly reflects this nascent domestic hydrogen policy. It focuses on traditional industrial policy goals and follows patterns of its existing energy foreign policy rather than a distinctive hydrogen foreign policy.

This section provides an overview of China's emerging international hydrogen policy agenda. It begins with an overview of key policy goals. It then describes China's inward-oriented engagement with foreign partners as a vehicle for acquiring key technological know-how. This is followed by an overview of its multilateral hydrogen initiatives and activities in the field of international standard-setting. Bilateral cooperation with a number of strategic partners is covered in the subsequent section.

4.1 Policy Goals and Approaches to International Hydrogen Cooperation

The National Hydrogen Development Plan stated the objective of seeking technology cooperation on core hydrogen technology, equipment, and materials (NDRC, 2022) and actively engaging in international hydrogen standardization processes (NDRC, 2022). The Chinese government aims for both inward-oriented and outward-oriented hydrogen technology cooperation to boost domestic hydrogen technology innovation and participate in the development of global hydrogen value chains (State Council, 2021; NDRC, 2022; NDRC & NEA, 2022a). The National Hydrogen Development Plan stressed that China would work with states who own advanced hydrogen technologies to expand market shares in third states (NDRC, 2022). More specifically, NEA has indicated the intention to strengthen cooperation with Europe on hydrogen technology (NEA, 2021). The Mid-and-Long Term Development Plan of the Automobile Industry (2017) and Key Working Points of Standardizing New Energy Vehicles in 2020 (2020) have also highlighted China's intention of establishing cooperation on hydrogen technology and related standards.

Energy cooperation is also a dimension of China's efforts to 'green' the BRI (NDRC & NEA, 2017; NDRC et al., 2022). The government plans to initiate joint research and development of hydrogen energy, promote cooperation on green energy equipment, including hydrogen, and pursue training and communication activities with BRI states (NDRC et al., 2022). More specifically, BRI-related policy documents emphasize cooperation on hydrogen FCEVs. According to the Mid-and-Long Term Development Plan of Automobile Industry (2017), the government seeks to expand market shares in the fuel cell vehicle sector within the BRI and gradually integrate into global value chains (MOST et al., 2017). Additionally, the Key Working Dimensions of Standardizing New Energy Vehicles in 2020 (2020) stressed the importance of exporting the standards of China's new energy vehicles within the BRI, especially to ASEAN states and Central Asian states (MIIT, 2020).

The National Hydrogen Development Plan also stated that China would explore cooperation on hydrogen trade, the construction of hydrogen infrastructure, and the development of hydrogen-related products within the BRI (NDRC, 2022). Hydrogen trade might offer an opportunity for exports from Chinese provinces with rich solar, wind and hydro-resources in Northwest or Southwest China that are far from China's economic heartland. However, other hydrogen-related policies at the central level have so far rarely discussed hydrogen trade or plans for building international hydrogen infrastructure. It is likely that the Chinese government wants to prioritize the development of domestic production to avoid foreign dependencies. Given the large potential domestic demand, significant Chinese exports of hydrogen are also unlikely. Nevertheless, the hydrogen development plan of Shanghai, adopted in 2022, disclosed the aim to build a shipping terminal for hydrogen imports by 2035 to establish a center for hydrogen trade in East Asia (Shanghai DRC, 2022). Such a marketplace would give China a vehicle for participating in and influencing regional hydrogen markets.

4.2 China's Inward-Oriented Cooperation in Hydrogen Technology and Supply Chains

A key avenue for China's pursuit of hydrogen-related technological know-how is its inward-oriented international hydrogen cooperation. The Catalogue of Industries for Encouraging Foreign Investment 2022 highlights China's different focus areas of inward-oriented international hydrogen cooperation and encourages foreign hydrogen companies to build supply chains in China, including the manufacturing of equipment for hydrogen production and storage, hydrogen fuel cells, and FCEVs (NDRC & MOFCOM, 2022).

Renewable hydrogen production represents one important dimension of China's inward-oriented technology cooperation, including joint ventures and cooperation agreements with a number of European companies (Shell Global, 2022). There has also been some collaboration in the field of steam methane reforming in combination with CCUS, including with South Korea's green energy company SK E&S and state-owned Beijing Gas (Pekic, 2022). Foreign companies have also sought to expand shares in the sector of hydrogen storage and transport. French Air Liquide and Germany's Linde, for instance, have both engaged in the development of China's hydrogen refueling networks (Reuters, 2019). In line with China's traditional focus on fuel cells and FCEVs, technology cooperation in the field of hydrogen use also emphasizes this sector. Hyundai Motor is a central player in promoting the development of FCEV in China.

Finally, a number of foreign companies have also invested in research, development, and demonstration projects in the field of industrial hydrogen uses. BHP and China Baowu signed an MoU in 2020 to invest up to USD 35 million in hydrogen injection into blast furnaces and have set up the China Baowu-BHP Low-carbon Metallurgy Knowledge Sharing Center (BHP, 2020). Similarly, IHEC has promoted renewable hydrogen use in the metallurgical and chemical industries by working with the Shuimu Mingtuo Group and Hualu to establish the International Hydrogen Energy Metallurgy and Chemical Demonstration Zone (CSIRO, 2022).

4.3 Multilateral Engagement

According to Opinions on Improving the Regime and Implementation Measures of Energy Green Low-Carbon Transition (NDRC & NEA, 2022c), China also aims to integrate into global hydrogen value chains by engaging in multilateral organizations. The government targets cooperation via IRENA and IEA, the League of Arab States, the African Union, ASEAN, the Sustainable Energy Center of APEC and with Central and Eastern Europe (NDRC & NEA, 2022c) (see Table 2). China has worked closely with IEA and IRENA in the sphere of technology and to promote exchange on policy and best practices. In 2016, China joined the IEA Hydrogen Implementing Agreement to collaborate with other member states in hydrogen R&D and demonstration with the initial focus on hydrogen-based energy storage (IEA HIA, 2016).

More recently, the Administrative Center for China's Agenda 21 (ACCA21) collaborated with IEA in a study on the potential for hydrogen production with CCUS in China (IEA, 2022). Similarly, NEA and IRENA signed an MoU to deepen their cooperation on the production and use of renewable fuels such as hydrogen (IRENA, 2021). For the upcoming Five Year Plan period from 2026 to 2030, the government has articulated its intention to continue promoting international cooperation, in particular under the auspices of the BRI, BRICS and APEC (Collins, 2025a).

China is also a partner country in the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE) and is committed to collaborating to accelerate innovation in fuel cell and hydrogen technologies (IPHE, 2023). In particular, it has focused on fuel cell-related cooperation within IPHE in the past. By launching the International Hydrogen Fuel Cell Association (IHFCA), the China Society of Automotive Engineers sought cooperation on fuel cell-related R&D and the development of the hydrogen fuel cell value chain with international organizations and multinational corporations, including the United Nations Development Program (UNDP) and

Table 2 China's multilateral hydrogen cooperation

Multilateral organization or forum	Area of engagement
International Energy Agency (IEA)	Member of IEA Hydrogen Implementing Agreement since 2016 to collaborate with other member states in hydrogen R&D and demonstration with the initial focus on hydrogen-based energy storage
International Renewable Energy Agency (IRENA)	MoU in 2021 on collaboration in the spheres of production and use of renewable fuels, such as hydrogen
International Partnership for the Hydrogen Economy (IPHE)	Collaboration activities focused in particular on fuel cells so far
International Hydrogen Fuel Cell Association	Association initiated by China Society of Automotive Engineers aimed at promoting technology innovation for fuel cells and the development of hydrogen fuel cell value chains
United Nations Industrial Development Organization (UNIDO)	Launch of International Hydrogen Energy Center (IHEC) in 2021 within UNIDO's Global Programme for Green Hydrogen in Industry to attract international R&D funding to China and disseminate knowledge and advance research with international partners
Forum on China-Africa Cooperation	Declaration to promote hydrogen development within Declaration on China-Africa Cooperation on Combating Climate Change (2022)
Association of Southeast Asian Nations (ASEAN)	Commitment to promote R&D and technical exchange in Plan of Action to Implement the ASEAN-China Strategic Partnership for Peace and Prosperity (2021–2025)

Source Author, based on organization's websites and media reports a range of foreign companies (CSIRO, 2022). China has also supported the launch of the International Hydrogen Energy Center (IHEC) by the United Nations Industrial Development Organization (UNIDO). IHEC will promote China's hydrogen development and its international hydrogen cooperation by attracting international R&D funding and disseminating knowledge and advancing research involving China and other states (UNIDO, 2020).

According to the Declaration on China-Africa Cooperation on Combating Climate Change, both China and Africa will provide an investment-friendly environment and financial support for renewable hydrogen development projects. According to the Plan of Action to Implement the ASEAN-China Strategic Partnership for Peace and Prosperity (2021–2025), China and members of ASEAN should carry out joint R&D and technical exchange for hydrogen and fuel cells.

As highlighted above, China has actively promoted the formulation of hydrogen-related standards. In the National Hydrogen Development Plan, NDRC emphasized the importance of advancing international cooperation on standards for core hydrogen technology, equipment, and materials (NDRC, 2022). Moreover, the Notice on the Implementation Plan of Promoting the Development of New Energy in the New Ara (2022) states that increasing the global influence of China's hydrogen standards and participating in global standard-setting would help internationalize the domestic new energy industry (NDRC & NEA, 2022b). In this vein, the China-UK Hydrogen Energy Cooperation Forum as well as the Sino-German Energy Partnership have announced plans to advance international cooperation on hydrogen-related standard-setting (MFA, 2022; Sino-German Energy Partnership, 2022).

Given China's important emphasis on the promotion of fuel cells and FCEVs, it has pursued a particular focus on joint standard-setting in this area. Since 2020, the Ministry of Industry and Information Technology (MIIT) has promoted cooperation with the EU, Germany, France, Japan, and APEC on formulating standards for fuel cell vehicles (MIIT, 2020). As early as 2017, the Vice Chairman of SA attended the 2nd International Conference of the Industrial Development of Hydrogen Energy and Fuel Cells (SAC, 2017) and called for collaboration with foreign companies and scholars to help China to develop its fuel cell industry (SAC, 2017). In its 2022 working plan, SA plans to work with ISO, IEC, and ITU to develop standards relevant for carbon peaking and carbon neutrality, including hydrogen standards (SAC, 2022a, 2022b).

5 Bilateral Hydrogen Cooperation

Complementing China's inward-oriented foreign engagement and its multilateral cooperation on hydrogen, it is beginning to engage actively in bilateral cooperation with a number of leading industrialized countries. In the sphere of fuel cell vehicles, cooperation is taking place as part of its broader industrial policy strategy, aimed at internationalizing its automotive sector. Although there is no official policy on the promotion of overseas investment in hydrogen production, a number of SOEs have also started to engage with strategic energy partners in different world regions for the development of green hydrogen projects. For now, these are based in countries where China has strong, pre-existing engagement in the energy sector, notably in Brazil, Pakistan, Egypt, and Saudi Arabia (Quitzow & Gong, 2023). Additionally, there is nascent cooperation with Russian partners on fossil-based hydrogen production with CCUS. This section provides an overview of the main activities that have emerged along these various bilateral avenues for cooperation.

5.1 Technology Cooperation with Major Industrialized Countries

Complementing its inward-oriented technology cooperation, the Chinese government has promoted bilateral cooperation with a host of advanced industrialized countries, including Germany, the UK, the US, and Australia. With Germany, it engages via the Sino-German Energy Partnership and has launched funding lines for joint R&D in the area of FCEVs (NOW, 2022). According to the China-UK Hydrogen Energy Cooperation Forum, both states will jointly promote research and development of hydrogen technology to facilitate the development of their hydrogen value chains (MFA, 2022). The Australia–China Science and Research Fund Joint Research Center has provided funds for hydrogen-related research (ACSRF, 2023). In the 2022 Sino-American Forum on Cooperation in the Hydrogen Energy Industry, Chinese and American public and private bodies had dialogues on the prospects for potential hydrogen cooperation between important hydrogen regions in China, such as the Beijing-Tianjin-Hebei Region, the Yangtze River Delta and the Pearl River Delta, and Californian counterparts (CSIRO, 2022). In the 15th Five Year Plan, the government aims to expand technology cooperation with Europe (Collins, 2025b).

5.2 Industrial Policy for the Automotive Sector: Internationalization of FCEV Supply Chains

Government policies have also stressed the export of equipment and products of fuel cells and FCEVs, as part of a broader policy to promote the internationalization of its automotive industry. Since 2017, China has aimed to initiate bilateral and multilateral framework agreements of automobile industrial cooperation including hydrogen FCEVs. The Mid-and-Long Term Development Plan of Automobile Industry (MOST, MIIT & NDRC, 2017) promoted producers of hydrogen FCEVs to export products, services, technologies, and standards by investing in foreign markets rather than focusing on export sales alone. It targets overseas investments where Chinese firms retain management control and that enable technology cooperation (MOST, MIIT & NDRC, 2017). The Mid-and-Long Term Development

Plan of the Automobile Industry (2017) further explains that the central government will support companies in the automotive sector in their efforts to contribute to the development of overseas industrial parks (MOST, MIIT & NDRC, 2017). Overseas automobile industrial parks have been promoted by the Chinese government in cooperation with host country governments (EY, 2020), for instance in Kazakhstan. Typically, SOEs act as lead investors in cooperation with other state-owned or private firms. These industrial parks may benefit from infrastructure along the 'Maritime Silk Road' to explore the opportunities of incorporating hydrogen logistics in shipping, automobiles, and buses (Yue & Wang, 2022).

5.3 Green Hydrogen Cooperation with Strategic Energy Partners

Although China's hydrogen-related policies do not explicitly promote the export of electrolyzers, China's companies, such as PERIC Hydrogen Technologies, Cockerill Jingli Hydrogen, and Shandong Saikesaisi, have already exported electrolyzers to overseas markets (Brown & Grünberg, 2022), reflecting China's increasing capacity of manufacturing standard alkaline electrolyzers. Also, the hydrogen subsidiary of LONGi has the ambition of exporting alkaline electrolyzers to foreign markets (The Japan Times, 2023). These export ambitions align with China's policy of increasing its influence within the global energy sector by expanding its role in global energy value chains. A number of SOEs are beginning to spearhead cooperation with a number of strategic energy partners across different world regions, including Brazil, Pakistan, Egypt, Saudi Arabia, and Russia (Quitzow & Gong, 2023).

5.3.1 R&D Cooperation as a Precursor to Green Hydrogen Investment in Brazil

China's electricity companies have taken a strong position in the power sector of Brazil since 2010 and now hold over 10% of Brazil's generation, transmission, and distribution infrastructure (Global Development Center, 2021). Building on this, Chinese power sector SOEs are currently establishing R&D on green hydrogen and seeking the possibilities of building hydrogen value chains in Brazil. State Power Investment Corporation (SPIC) has been an active player in the financing of renewable energy projects and started technology cooperation on renewable hydrogen with Brazil prior to the publication of the National Hydrogen Development Plan (SPIC, 2020). In 2021, SPIC and its Brazilian subsidiary signed an MOU for the investment of US$3.5 million in the research and development of renewable hydrogen and smart energy with the Center for Energy Research of Brazil. The renewable hydrogen is expected to be used in energy storage and the production of ammonia and fertilizers in Brazil. Similarly, in 2020, China Three Gorges International Corporation

(CTGIC) was operating 17 hydropower and 11 wind power projects in Brazil. By leveraging its strong position in Brazil, CTGIC launched research and development activities in the field of renewable hydrogen and is collaborating with Brazil's Serviço Nacional de Aprendizagem Industrial (SENAI), a provider of industry-focused technical education and innovation services, to explore opportunities for cooperation in renewable hydrogen. With US$3.2 million, CTGIC and SENAI decided to establish a transaction platform for renewable hydrogen that can guarantee its origin (CTGIC, 2022).

5.3.2 Green Hydrogen Investment Within the China–Pakistan Economic Corridor (CPEC)

In October 2021, PowerChina International Group, a subsidiary of Power Construction Corporation of China (PowerChina), signed a cooperation agreement with international natural resources project developer Oracle Power to jointly develop a renewable hydrogen production facility in Pakistan's Sindh province. Building on the region's abundant solar and wind energy resources, it is expected to produce 150,000 kg of hydrogen per day (Whitlock, 2021). PowerChina would provide construction services and act as a joint developer, while Jiangsu Guofu, a privately owned Chinese firm, would provide the equipment. The companies have been assessing the commercial viability of the project and are looking for hydrogen offtakers from Pakistan, China, or third states, indicating the possibility of renewable hydrogen trade between the two countries (Oracle Power PLC, 2021). The investment is in line with the objectives of the longstanding China–Pakistan Economic Corridor (CPEC) initiative and Pakistan's role as a key partner in the BRI. The CPEC includes a series of investments in logistics and energy infrastructure, which provide the enabling environment for investments in hydrogen (Mardell, 2020).

5.3.3 Cooperation in the Middle East: Egypt and Saudi Arabia

After COP27 in Egypt, China Energy Engineering Corporation Limited (CEEC) signed an MoU on jointly developing a renewable hydrogen project with the Egyptian New Energy Authority, the Suez Canal Economic Zone Authority, sovereign wealth funds, and power transmission companies, signaling the start of China's hydrogen cooperation with Egypt. The project is expected to produce 210,000 tons of renewable hydrogen per year upon completion, which would be further converted to approximately 1.2 million tons of green ammonia (Hydrogen Insight, 2023a). CEEC will export the equipment, services, and technologies relevant for the combined development of solar, wind, and renewable hydrogen in this project. The project aligns with China's external energy strategy of exporting energy equipment, services, and technologies, in particular in BRI countries. Egypt serves as a gateway to the African Continent, and its Suez Canal connects the Mediterranean Sea to the Red Sea and the Indian Ocean.

Similarly, China has started to explore hydrogen cooperation with Saudi Arabia, building on its well-established and expanding relationship in the fossil fuel sector. At the Arab States-China Summit held in December 2022, Saudi Arabia and China signed an MoU on hydrogen energy and the encouragement of direct investment between the two states (Reuters, 2022). In 2023, Saudi Arabia's Aramco announced plans to collaborate with Chinese Since Gas to build a plant for the conversion of ammonia to hydrogen (SCMP, 2023). Moreover, Chinese wind-turbine producer Envision will be supplying turbines for the large-scale renewable hydrogen project being developed in Saudi Arabia under its Neom Project (Hydrogen Insight, 2023b).

5.3.4 Cooperation in Fossil-Based Hydrogen and CCUS with Russia

Against the background of the well-established Chinese-Russian gas cooperation, China has also begun cooperation on fossil-based hydrogen production with CCUS technology. In September 2022, Gezhouba Rus, a subsidiary of China Energy Engineering Group in Russia, announced the intention to cooperate with Rusatom for the construction of a plant for the production of hydrogen from natural gas with CCUS. The project includes plans to export low-carbon hydrogen from Sakhalin to China by sea in the form of liquid hydrogen as early as 2025 (Biogradlija, 2022). Given China's abundant potential to produce domestic hydrogen, cooperation with Russia is unlikely to be driven by concerns to secure future hydrogen supply. Rather, it would appear to represent an approach for maintaining active energy cooperation outside the oil and gas sector and good diplomatic relations with Russia.

6 Conclusion

China's hydrogen strategy—both internal and external—is still at an emergent stage (Quitzow & Gong, 2023). With the formulation of the National Hydrogen Development Plan, the government took a major step toward formalizing its policy approach. Nevertheless, the national targets remain modest, and policy remains ambiguous regarding the preferred production pathway. China's long-term vision clearly emphasizes the role of renewable hydrogen to help balance an energy system dominated by wind and solar energy. However, current policy provides ample space for the promotion of other forms of hydrogen production. Rather than a strong, centralized policy approach, local and provincial governments along with SOEs have been driving investment and policy experimentation in the sector, which includes efforts to boost fossil-based hydrogen production (Gong et al., 2024). While the government has reiterated its commitment to the hydrogen economy, in particular renewable hydrogen, in the 15th Five Year period from 2026 to 2030, its announcements have so far stopped short of proclaiming a marked acceleration of its ambitions (Collins, 2025a).

A major priority for the central government is the development and acquisition of technological know-how across the hydrogen value chain as part of a broader industrial policy agenda in emerging, green industries. Building on an important legacy in the promotion of FCEVs, China still places substantial emphasis on promoting this segment of its domestic hydrogen industry. However, in recent years, technology bottlenecks in hydrogen storage, transport as well as PEM fuel cells and electrolyzers have assumed increasing prominence in China's efforts to promote technological leadership in the field. These are pursued actively through inward- and outward-oriented technology cooperation with partners in other leading countries as well as active engagement in the development of hydrogen-related standards. Hydrogen FCEVs are also being promoted as part of a broader policy to support the internationalization of China's automotive industry. This has included the development of industrial parks focused on the automotive sectors in BRI countries.

Hydrogen is also emerging as an element of China's external energy policy, albeit not with a distinctive geopolitical strategy (Quitzow & Gong, 2023). Chinese SOEs are pursuing investments in renewable hydrogen projects in countries with pre-existing energy-related cooperation, including Brazil, Pakistan, Egypt, Saudi Arabia as well as Russia. In this vein, hydrogen-related cooperation can be seen as an extension of China's broader external energy policy, which combines commercial interests with the goal of expanding its influence along international energy value chains. With the exception of Russia, projects are predominantly focused on renewable hydrogen and extend cooperation into this new area of the energy sector. Although cooperation with Pakistan and Russia may involve the export of hydrogen to China, securing hydrogen supply does not appear to be an important driver of China's international involvement in the sector. The development of hydrogen imports as an energy security imperative does not feature as a theme in the National Hydrogen Development Plan, and China is likely to have sufficient renewable resources to supply its domestic economy with renewable hydrogen. Rather, the government has expressed concern that China may not have access to all the required technological know-how, underlining its multidimensional efforts to secure this know-how via engagement with international partners.

Acknowledgements Research for this chapter was financially supported by the German Federal Foreign Office within the framework of the project 'Geopolitics of the Energy Transformation – Implications of an International Hydrogen Economy' (GET Hydrogen), funding reference number AA4521G125.

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US Hydrogen Policy: Paving the Way for Energy Independence, Technology Leadership, and Decarbonization

Laima Eicke

Abstract The U.S. is a key player in the current hydrogen economy and holds substantial geo-economic potential to shape the global clean hydrogen market. The U.S. hydrogen strategy has been shaped by the ambition to balance (a) energy independence (b) the fight against climate change, and (c) expanding technology leadership. The landmark legislative packages of the Bipartisan Infrastructure Law (2021) and the Inflation Reduction Act (2022) reflect these priorities and include large-scale investments and financial incentives to promote the supply of clean hydrogen at lower costs, to strengthen innovation, and domestic value chains. The U.S. has been pioneering policy instruments for scaling up domestic clean hydrogen production and use cases across multiple sectors, which raised significant interest among policymakers and industrial actors worldwide. However, following President Trump's re-election, policy uncertainty surrounding the future of the U.S. hydrogen sector has grown, although blue hydrogen may be in a more secure position than green. The international dimension of the U.S. hydrogen strategy has received much less attention in the U.S. policy debate and is less defined. Nevertheless, the U.S. has fostered bilateral partnerships on hydrogen and strengthened its hydrogen-related engagement in international organizations and multilateral initiatives in the past five years. Emerging priorities for the United States' international collaboration on hydrogen include international demand creation and management, upscaling investments, international research collaborations, and joint efforts on regulation, standards, and certification. These efforts can be seen as the first steps toward the U.S. long-term goal to export hydrogen and related technologies to regional and global partners from the 2030s onwards.

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R. Quitzow and Y. Zabanova (eds.), *The Geopolitics of Hydrogen*, Studies in Energy, Resource and Environmental Economics, https://doi.org/10.1007/978-3-031-84022-7_4

1 Introduction

The United States (U.S.) is the second largest producer of hydrogen today, after China. The U.S. possesses significant geo-economic potential to lead in the global clean hydrogen economy. The U.S. benefits from vast resources for green hydrogen production, namely a high potential for renewable energy generation especially in the coastal areas but also sufficient freshwater resources. Additionally, related economic activities led to high technological capacity and a skilled labor force, which might foster innovation and enable technological leadership (Eicke & De Blasio, 2022). Furthermore, the U.S. has been pioneering policy instruments for scaling up domestic clean hydrogen production and use cases across multiple sectors, which raised significant interest among policymakers and industrial actors worldwide.

Traditionally, hydrogen has been promoted by Democratic and Republican administrations alike—in contrast to the strong shifts in U.S. climate policy featuring the country's withdrawal from the Paris Agreement during President Trump's first term in office, its reentry under President Biden, and a second withdrawal following Trump's re-election. This continuity in support for the clean hydrogen economy benefited from differing political agendas and policy objectives that nevertheless aligned with the same goal. Relevant drivers include, among others (a) energy independence (b) the fight against climate change, and (c) enhancing economic leadership based on export-oriented industrial competitiveness and innovation. However, it remains uncertain whether this continuity will last during President Trump's second term in office which began in January 2025.

This chapter provides an overview of the policy landscape and its drivers, focusing particular attention on its external dimension. It elucidates how competing policy objectives have been guiding the U.S. hydrogen strategy. The chapter summarizes key domestic policy instruments to achieve these policy objectives. Building on this, it then assesses how foreign policies and international initiatives relate to these policy objectives and how the US positions itself in relation to other world regions regarding hydrogen trade and technological development. This review is based on publicly available U.S. hydrogen strategy and policy documents as well as interviews with stakeholders involved in the implementation of the United States' hydrogen strategy.

The review is structured as follows. The next section analyzes the role of hydrogen in the U.S. economy and the future potential for clean hydrogen production. The third section analyzes the three overarching policy objectives guiding the U.S. hydrogen policy. The fourth section describes the regulatory landscape governing hydrogen in the United States. The fifth section assesses the most important policy instruments employed domestically, whereas the sixth section elucidates how the United States approaches hydrogen-related foreign policy. The seventh section concludes.

2 The Role of Hydrogen in the U.S. Economy

The U.S. is a leading actor in today's hydrogen economy. According to the Hydrogen Council, the U.S. had an installed hydrogen production capacity of around 10 million metric tons per year in 2021, only surpassed by China (Department of Energy, 2023d). Over 95% of hydrogen produced in the U.S. is labeled as "gray"; it is produced through steam methane reformation of natural gas. Moreover, the majority of currently committed clean hydrogen projects, that are either already operational or have reached the final investment decision are labeled as "blue" and combine fossil fuels with carbon capture and storage technologies (Marcu et al., 2024). However, the number of projects producing green hydrogen, by splitting water molecules into hydrogen and oxygen using renewable electricity, has been increasing recently; over the past five years, 11 projects became operational and 13 more are currently under construction across the country, mostly in coastal areas (IEA, 2023a).

The U.S. aims at scaling up the production of hydrogen based on various production processes. This includes green hydrogen (produced with renewable energy), blue hydrogen (produced from natural gas using carbon capture and storage), pink hydrogen (produced based on nuclear energy), and hydrogen from waste. Most policy documents refer to clean hydrogen, which can include all the above-mentioned sources.

For now, hydrogen is primarily used in industrial processes including petroleum refining, petrochemical manufacturing, glass purification, and fertilizer production. Furthermore, hydrogen is used in combination with fuel cells to power 16,000 cars, around 60,000 forklifts, and 80–150 buses and as storage for backup power, e.g., for telecommunications (Department of Energy, 2023d). The U.S. Department of Energy's Hydrogen and Fuel Cell Technologies Office estimates that hydrogen consumption in the U.S. is expected to grow from about 8 million metric tons per year in 2020 to around 20 million metric tons per year by 2040 and 50 million metric tons by 2050 (Department of Energy, 2023d).

According to the U.S. Department of Energy, the U.S. has the potential to produce over 50 million tons of clean hydrogen per year by 2050 and set an interim target of 10 million tons by 2030. The renewable energy potential as well as freshwater resources are large enough to meet the internal energy demand and enable the production of green hydrogen at scale for export (Eicke & De Blasio, 2022; Pflugmann & De Blasio, 2020). In 2021, renewable energy sources provided 19% of the countries' electricity production (EIA, 2022); the current targets foresee a share of 80% carbon emission-free electricity generation by 2030 and 100% by 2035 (The White House, 2021a).

The U.S. long-term strategy includes a leadership role in the export of clean hydrogen (Department of Energy, 2023d). The export of hydrogen could be facilitated by existing infrastructure, including pipelines, ports, and storage facilities. More than half of the global hydrogen infrastructure is currently located in the U.S., with pipelines of more than 2600 km in length and the largest volume of hydrogen storage capacity worldwide (IEA, 2019). The country also has a well-established natural gas export industry, which can presumably be leveraged for hydrogen export. The U.S. National Renewable Energy Laboratory (NREL) estimates that by 2050, the U.S. could produce and export up to 4 million metric tons of hydrogen per year, based on the assumption that 20% of renewable energy generation is directed toward hydrogen production. The National Clean Hydrogen Strategy and Roadmap plans concrete actions for hydrogen exports in the time frame of 2030 through 2035 (Department of Energy, 2023d). However, the first projects aiming for regional and global clean hydrogen exports are already being built in Louisiana (Department of Energy, 2023d).

3 Policy Objectives Guiding U.S. Hydrogen Policy

U.S. hydrogen policy has been guided by three overarching policy objectives throughout the past decade: energy independence, the fight against climate change, and the promotion of industrial leadership.

The quest for energy independence has represented a central pillar of U.S. energy policy since the first oil crisis in 1973. To reduce energy dependency, the U.S. started promoting renewable energy sources. In this context, the idea of a "hydrogen economy" first received political support under Democratic President Carter (Piria et al., 2021). Green hydrogen was seen as an important piece in this endeavor because it can serve as a flexible source of power to compensate for fluctuations in renewable generation. In addition, it can be used as backup power for critical facilities, stationary power in remote areas, or medium and long-duration power storage. In the early 2000s, Republican President George W. Bush further supported R&D on hydrogen solutions in the mobility sector as a strategy to reduce oil imports (Romm, 2004). However, the U.S. quest for energy independence led to less pressure to act in subsequent years as the shale gas revolution led to a strong decline in oil and gas prices and turned the U.S. from an energy importer into a net exporter of energy in 2019 (Piria et al., 2021).

Climate policy has represented a second driver of the ambitious hydrogen policy. The interest in hydrogen renewed with the urge to address climate change when Democratic President Obama signed the Paris Agreement in 2016. The U.S. has pledged to reduce its carbon emissions by 50–52% relative to 2005 in its Nationally Determined Contribution to the UNFCCC (The United States of America, 2021). The DoE estimates that increasing the U.S. clean hydrogen production and utilization by 500% by 2050 could reduce the country's total GHG emissions by approximately 10% relative to 2005 levels (Department of Energy, 2023d).

The promotion of industrial leadership is a third driver of hydrogen support policies. The first presidency of the Republican Trump resulted in a backlash against policies aimed at the decarbonization of the U.S. economy. The federal programs on the hydrogen economy were continued but realigned with Trump's vision to "make America great again." In this context, hydrogen was framed as a new sector in which the United States can become leading in terms of technology development and energy exports (Department of Energy, 2020, 2023d). Accordingly, domestic hydrogen production was seen as an enabler to increase domestic manufacturing jobs (Department of Energy, 2023d).

Under President Biden, the U.S. hydrogen policy combined the three above-mentioned policy objectives. The U.S. rejoined the Paris Agreement in 2021 and brought the fight against climate change back onto its policy agenda. The government announced the decarbonization of the electricity sector by 2035 and plans to aim for climate neutrality by 2050. In this context, the Biden Administration framed clean hydrogen as a key factor in enabling decarbonization goals (The White House, 2021a). In addition, the Biden Administration continued to push for clean hydrogen in the context of an industrial strategy to strengthen the U.S. as a clean technology exporter (The White House, 2021a). The strategic framing of hydrogen regulations to strengthen domestic manufacturing and local job creation was key to passing investment packages such as the Inflation Reduction Act (IRA) (see Sect. 5) (Jackson & Hellmich, 2022). This framing was seen as necessary to unify all Democrats in a situation in which the Biden Administration depended on a majority by one vote in the Senate before the Midterms in 2022. Additionally, President Biden depended on the support of labor unions, which formed a strong alliance with climate advocates over the last decade (Jackson & Hellmich, 2022). These developments led to a strategic linking of policy objectives, promising that hydrogen can simultaneously serve the objectives of climate protection and economic competitiveness. Furthermore, the goals of industrial leadership and energy independence became increasingly interlinked. The rise of China as the primary supplier of many renewable energy technologies and the dependency on Chinese imports of critical raw materials has raised concerns among Democrats and Republicans alike. This "over-reliance" on Chinese imports has increasingly been framed as a threat to national security (Jackson & Hellmich, 2022). Thus, strengthening domestic hydrogen technology supply chains is framed as a measure to enhance industrial leadership and independence from foreign suppliers (The White House, 2021a).

It remains open, however, how the U.S. hydrogen policy will develop during Trump's second presidency. Trump has actively sought to dismantle the clean energy policies of his predecessor, ordering to freeze all funding under the Inflation Reduction Act in January 2025. In May 2025, the Republican-dominated House Ways and Means Committee proposed to repeal the 45V hydrogen tax credit for projects beginning construction after December 31, 2025 (Fuel Cell Works, 2025). On the other hand, several of the IRA's policy objectives—such as expanding domestic energy production and supporting industrial jobs in hydrogen hubs—align with Trump's broader agenda of strengthening the U.S. economy. In fact, a 2024 study found that Republican congressional districts had benefited the most from IRA-incentivized new investments (Shaw, 2024). For a number of Republican states, such as Texas, Louisiana or West Virginia, continued support for hydrogen remains important. As a result, moderate Republican lawmakers have repeatedly urged to preserve the clean energy tax credits under the IRA (Park, 2024; Siegel & Bikales, 2025; Volcovici & Groom, 2025). Overall, significant policy uncertainty surrounds the future of federal funding for clean energy in the U.S., including support for hydrogen, though blue hydrogen appears to have a more secure position.

4 Governing Hydrogen

Public and private actors have been collaborating to scale up hydrogen production and use in the United States. The Energy Policy Act of 2005 established the Department of Energy (DOE) as the federal lead agency for directing and integrating activities on hydrogen. Within DOE, the Hydrogen and Fuel Cell Technologies Office coordinates research and development activities and aligns the activities of the four relevant DOE offices (Office of Energy Efficiency and Renewable Energy, Office of Fossil Energy, Office of Nuclear Energy, and Office of Science). DOE also collaborates with stakeholders, including industry, academia, local and tribal communities, and civil society groups, on hydrogen regulation. This inclusive strategy aims to address potential environmental and social justice concerns.

State-level agencies have also taken the initiative to promote the development and use of hydrogen (in all states but in Kansas), mostly with a focus on promoting hydrogen in the mobility sector (Department of Energy, 2023c). California is the most progressive with more than 50 laws and incentives related to the use of hydrogen. It introduced a low carbon fuel standard to foster growth in the fuel cell electric vehicle market as well as incentives such as carbon credit allowances. An executive order requires all vehicles sold by 2035 to release zero emissions. Furthermore, the state provides funding for R&D, as well as the deployment of hydrogen fueling infrastructure.

The following section concentrates on the federal government's policy instruments to foster the development of a hydrogen economy. Table 1 provides an overview of federal legislative acts and policies that significantly guided and supported the production and use of hydrogen in the United States. In addition, several programs, plans, and roadmaps describe in more detail how policy instruments should contribute to the guiding visions for a U.S. hydrogen economy. The most relevant plans include the Hydrogen Posture Plan (Department of Energy, 2006), the Hydrogen and Fuel Cells Program Plan (Department of Energy, 2011), the Hydrogen Program Plan (Department of Energy, 2020), the Energy Earth Shots Initiative, which includes plans for the Hydrogen Shot (Department of Energy, 2021) and the National Clean Hydrogen Strategy and Roadmap (Department of Energy, 2023d).

The following section provides an overview of the policy instruments included in these legislative packages and described in the plans. The main focus of these instruments lies on measures to bring down the costs of clean hydrogen. Several policy instruments aim to leverage economies of scale in clean hydrogen production and to foster R&D and innovation. These measures are partly combined with policies strengthening domestic manufacturing capacity to localize clean hydrogen supply chains, which are described thereafter. Lastly, policy instruments focusing on the decarbonization of high-impact end uses are described.

Table 1 Key legislative acts and policies on hydrogen

Year	Policies and acts	Description
1992	Energy Policy Act	The act initiated an R&D program for fuel cells and related transportation system applications
2005	Energy Policy Act	The act set the basis for an R&D program on technologies related to hydrogen production, purification, distribution, storage, and use, focusing on fuel cells
2007	Energy Independence and Security Act	The act creates incentives for R&D on hydrogen production, storage, distribution, and utilization
2022	Infrastructure Investment and Jobs Act	The Act is also known as the Bipartisan Infrastructure Law (BIL). The BIL comprises \$62 billion of which \$8 billion is dedicated to regional clean hydrogen hubs, \$1 billion to a clean hydrogen electrolysis program, and \$500 million to incentivize clean hydrogen manufacturing and recycling
2022	Inflation Reduction Act (IRA)	The Inflation Reduction Act (IRA) is the single largest investment package to combat climate change in the history of the United States with an estimated volume of \$369 billion and fosters the production of hydrogen via tax credits
2022	Clean Hydrogen Production Standard (CHPS)	The draft CHPS gives guidance on hydrogen production standards and associated emission levels, in accordance with the BIL

Source Author's own compilation based on U.S. federal government legal documents

4.1 *Scaling up Hydrogen Production*

The initiative H2@scale was launched by the Hydrogen and Fuel Cell Technologies Office in 2016 to enhance hydrogen cost reductions by promoting economies of scale (Department of Energy, 2023b). The initiative brings together diverse stakeholders and channels funding for projects advancing the scale-up of hydrogen production (Department of Energy, 2023b).

The Bipartisan Infrastructure Law (BIL) provides more than \$7 billion in direct grant funding for scaling up hydrogen applications in seven regional clean hydrogen hubs across the country. These hubs aim to create synergies via the creation of networks between hydrogen producers, consumers, and local connective infrastructure, which might further facilitate information exchange and innovation (The White House, 2023a).

Additionally, the Inflation Reduction Act (IRA) is a landmark legislation providing approximately \$369 billion to combat climate change. The IRA provides large-scale investment to foster the upscaling of clean hydrogen production in the United States. However, what is defined as clean hydrogen remains under discussion. While the BIL defines clean hydrogen as hydrogen that has been produced with less than $2kgCO_2e/kg\ H_2$ at the site of production, hydrogen with lifecycle emissions below $2kgCO_2e/kg\ H_2$ is supported as "clean hydrogen" in the IRA. In

September 2022, DOE released a draft for the Clean Hydrogen Production Standard (Department of Energy, 2022b). The Clean Hydrogen Production Standard is not a regulatory standard but is intended to guide (not necessarily determine) DOE's funding decisions. The draft proposes to define clean hydrogen as hydrogen produced with a carbon intensity equal to or less than 4 kg of carbon dioxide-equivalent emissions per kilogram of hydrogen during its lifecycle. According to this definition, all the above-introduced types of hydrogen would be considered "clean" (Department of Energy, 2022b) based on a comparison with the carbon intensity of today's predominantly used gray hydrogen of around 10 kg CO_2e/kg H_2 (Yan et al., 2022). However, the support mechanisms in the IRA do not treat all clean hydrogen equally but provide increasing tax incentives with lower life cycle emissions (see Table 2). The U.S. Congress authorized the U.S. Treasury Department to decide upon the detailed rules for accounting emissions from hydrogen production, which will be essential for determining the volume of granted tax credits under the IRA. After repeated delays, the final rules for the so-called "45V Clean Hydrogen Production Tax Credit" were released on 3 January 2025 (Department of the Treasury, 2025), just weeks before Trump's inauguration. Echoing EU-level regulation, they integrate requirements for the additionality of clean electricity, its deliverability, and hourly time matching designed to ensure actual emission reductions in comparison to gray hydrogen production (Department of the Treasury, 2023; Esposito et al., 2023).

The IRA allows hydrogen producers in the United States to choose between a production tax credit (granting a fixed credit per kilogram of produced hydrogen) or an investment tax credit (granted for a fraction of their capital expenses). These tax credits are granted from 2023 through 2033 and can be combined with additional credits for renewable energy investments in the case of green hydrogen production and with additional credits for carbon sequestration for blue hydrogen (The White House, 2023b). Instead of pricing the emission of carbon-intensive energy, the subsidies reduce the price difference between clean hydrogen and gray hydrogen. They are sufficient to achieve cost-competitiveness with gray hydrogen in current applications and are expected to make green hydrogen the lowest-cost hydrogen production type in the United States by 2025 (see Fig. 1) (Nationaler Wasserstoffrat, 2022).

Table 2 IRA tax credits based on carbon emissions

kg CO_2/kg of hydrogen	Production tax credit per kg of H_2	Investment tax credit in %
< 0.45	$3.00	30
< 1.5	$1.00	10
< 2.5	$0.75	7.5
< 4.0	$0.6	6

Source Author, based on Krupnick, A., Bergman, A. (2024, September). Incentives for Clean Hydrogen Production in the Inflation Reduction Act. *Resources for the Future Report*. https://www.rff.org/publications/reports/incentives-for-clean-hydrogen-production-in-the-inflation-reduction-act/

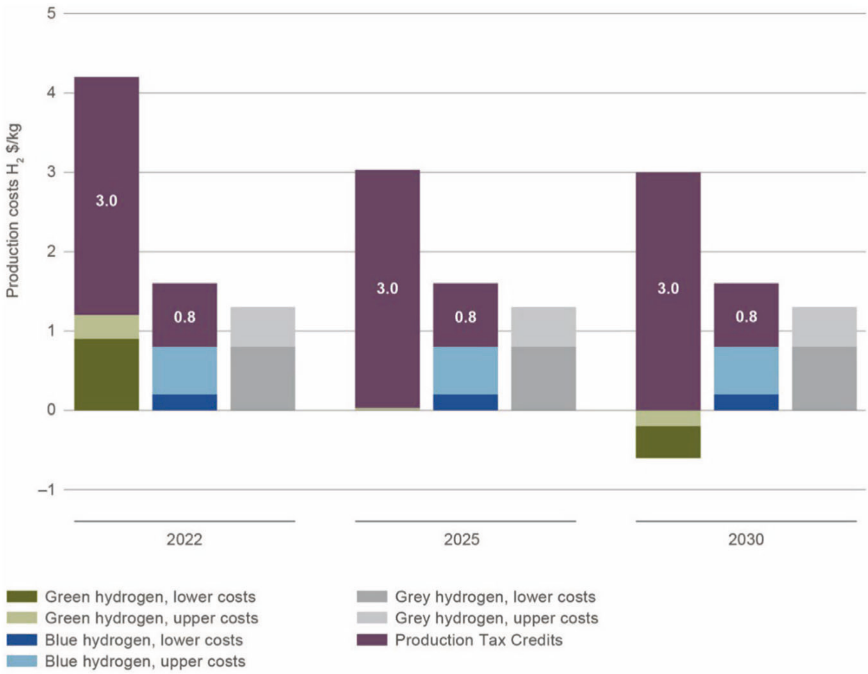

Fig. 1 IRA's effect on hydrogen production costs. *Source* Author, based on Nationaler Wasserstoffrat (2022)

Cost estimates suggest that clean hydrogen production in the United States would be among the most economically viable worldwide and might foster an industrial leadership role for the U.S. in the sector (Nationaler Wasserstoffrat, 2022). However, as discussed earlier, the future of the IRA's hydrogen tax credits is currently uncertain.

In comparison to these supply-side measures, measures targeting hydrogen use are still at a relatively early stage. A 2023 White House briefing note acknowledged the need for further demand-side policies, given the low number of offtake contracts so far (The White House, 2023c). A recent notice of intent from the Department of Energy announces investments in additional measures of up to 1 billion USD to further stimulate demand for clean hydrogen through the Regional Hydrogen Hubs Program financed through the BIL (Department of Energy, 2023a). The DoE will decide upon demand-side policies and their design based on public input from diverse stakeholders; currently, a consortium is tasked with designing and implementing demand-side policies; the current plans include $1bn for a subsidy scheme for clean hydrogen users (Collins, 2024). Potential policies include contracts for difference, "pay-for-delivery contracts, offtake backstops, feasibility funding to support analysis for off-takers" to increase revenue certainty for Hydrogen Hubs (Department of Energy, 2023a). Another step in this direction is the provision of vouchers worth $3.2 million in February 2024 to small businesses for investments in clean hydrogen under the Technology Commercialization Fund (Hydrogen & Fuel Cell Technologies Office, 2024b).

4.2 R&D and Innovation

Hydrogen R&D is seen as a key enabler for further cost reductions along the supply chain. The Hydrogen Shot initiative aims to reduce the costs of clean hydrogen from currently \$5 to \$1 per kilogram in a decade (Department of Energy, 2021). Strategic R&D funding is supposed to lead to a global leadership role concerning technology development, e.g., via the funding of first-of-its-kind projects. Funding for hydrogen-related R&D is channeled via a consortium under the H2@scale initiative, which includes various stakeholders. The consortium aims to identify promising hydrogen applications by reviewing and comparing proposed approaches based on their technical and economic viability, scalability, and value. The consortium supports the development of promising early stage hydrogen applications by leveraging funding based on partnerships with national labs and the provision of data from industry-led demonstrations. Furthermore, the consortium disseminates information on the progress of these projects (Department of Energy, 2023b). Moreover, the DOE announced \$8 million of funding for RD&D projects for electrolyzer and fuel cell manufacturing targeting partnership between an industrial entity and two or more national labs to strengthen domestic manufacturing, (Hydrogen and Fuel Cell Technologies Office, 2024c).

4.3 Building Domestic Manufacturing Capacity

Several policy instruments strengthen the buildup of local supply chains for hydrogen technologies. The IRA is expected to create more than 9 million jobs related to clean energy (Ellerbeck, 2023). To achieve this, it includes several forms of local content requirements. While they are not directly linked to electrolyzers, there are still several local content provisions that can be relevant for clean hydrogen projects. These include provisions in the new "Advanced Manufacturing Production Credit," that refer to the domestic production and sale of qualifying solar, wind, inverter, and battery components that are relevant for green hydrogen production. The provisions set a minimum requirement of domestic content, e.g., 20% for offshore wind facilities or 50% for battery components. The required shares of domestic production increase over time. Exceptions are granted if the quantity or quality of local production does not suffice or would increase the total construction costs by more than 25%.

Another example is the provision of "bonus" tax credits: if a clean energy project uses 100% domestically manufactured iron and steel, it is granted a bonus of 10% on top of the original tax credit value. Furthermore, the IRA includes provisions to increase the domestic supply of critical minerals for battery components and electric vehicles but also proton exchange membrane (PEM) electrolyzers and PEM fuel cells (Klevstrand, 2022). One instrument is the exclusion of projects from tax credits if battery components or critical minerals are sourced from a "foreign entity of concern"[1] (The White House, 2023b). Due to the free trade agreement with Canada and Mexico, the local content requirements on hydrogen technologies in the IRA can, for example, also be met via production in these two neighboring countries (The White House, 2023b).

Furthermore, the BIL entails domestic content procurement guidelines for all federal infrastructure project funding, based on a provision named "Build America, Buy America" (BABA). Accordingly, all infrastructure projects receiving financial assistance are required to source domestically produced iron, steel, and construction materials (EPA, 2021). This might also be relevant for the buildup of hydrogen infrastructure. In turn, the BIL includes $500 million to support the buildup of local clean hydrogen equipment manufacturing and recycling (Department of Energy, 2023d). These provisions aim to create good-paying union jobs and target disadvantaged communities in particular (Department of Energy, 2023d).

4.4 Decarbonization of High-Impact End-Uses

The U.S. clean hydrogen strategy focuses on the decarbonization of high-impact end uses of hydrogen, foremost in industry, transport, and the power sector. Multiple initiatives focus on the decarbonization of the industrial sector. The Regional Clean Hydrogen Hubs Program is a key instrument of the BIL to create networks of hydrogen producers, consumers, and local connective infrastructure to accelerate the decarbonization of heavy industries. To date, seven potential hubs have been selected for award negotiations for funding of up to $1 billion for each hydrogen hub, five of which have received a funding decision (see Fig. 2 for an overview). The pre-selected hydrogen hub projects are dispersed across multiple regions of the United States and target diverse high-impact end uses, including ammonia and fertilizer production, refineries, marine, and aviation fuel production as well as glass and steel production (Department of Energy, 2023c). Moreover, the Industrial Demonstrations Program supports clean hydrogen projects for the decarbonization of energy-intensive industries, including chemicals and refining, steel, aluminum and other metals, cement, and concrete with $1.7 billion (Department of Energy, 2024; Martin, 2024).

Additionally, the DOE's Advanced Manufacturing Office and Hydrogen and Fuel Cell Technologies Office have organized several stakeholder workshops to identify key challenges and opportunities for the decarbonization of the steel sector. To

[1] The exact definition of a foreign entity of concern is still under discussion. The latest proposal (March 21st, 2023) from the US Department of Commerce would deem any entity—including a U.S. based or incorporated entity—of which a Chinese person/company directly or indirectly holds at least a 25% voting interest a foreign entity of concern; it might further refer to entities that are "owned by, controlled by, or subject to the jurisdiction of North Korea, Russia, and Iran (Lovells & LaFianza, 2023).

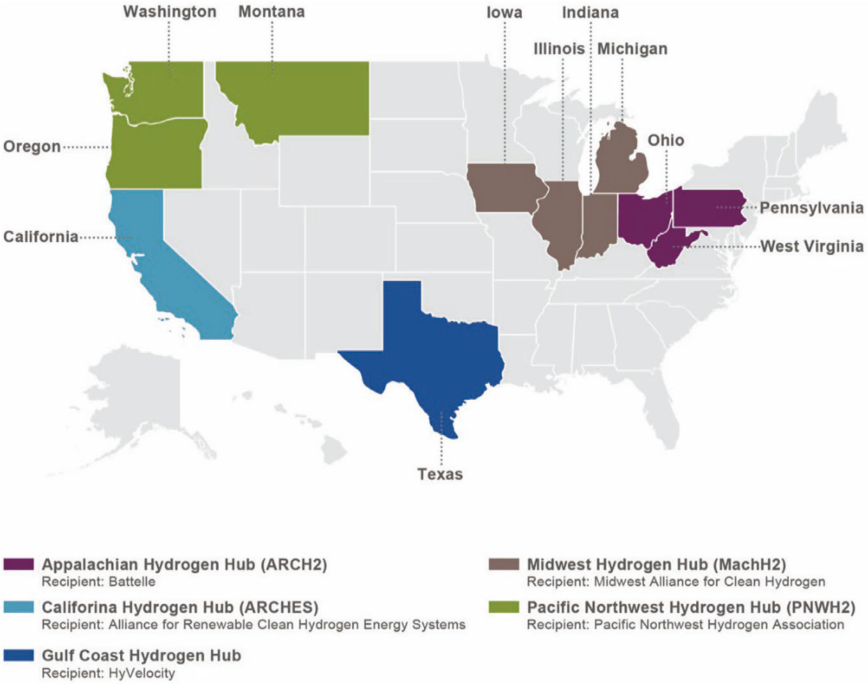

Fig. 2 Regional hydrogen hubs with funding decisions, November 2024

jumpstart the use of hydrogen in steel production, the DOE initiated two projects that optimize the use of clean hydrogen to produce 5000 tons of steel per day. Targeting the chemical sector, the DOE supported the analysis of cost and life cycle emissions for hydrogen derivatives, including methanol, ammonia, and methylcyclohexane. Furthermore, it provides funding for innovation in ammonia production, e.g., based on modular, scalable solutions (Department of Energy, 2023d).

Transport To reduce emissions in the transport sector, the DOE and other federal agencies collaborate with industry and academia through the twenty-first-century Truck Partnership. The partnership fosters exchange among stakeholders. Furthermore, the DOE initiated the Million Mile Fuel Cell Truck Consortium (M2FCT) in 2020, which also brings together partners from industry and academia, with a focus on the durability and costs of fuel cells for the decarbonization of long-haul heavy-duty trucks. Additionally, the Super Truck Program focuses on demonstration projects under real-world operating conditions. Furthermore, the DOE and the Federal Transit Administration jointly support fuel cell buses by collecting and evaluating deployment data to strategically identify transport corridors in the United States to guide infrastructure development of fueling stations and storage. The provision of hydrogen fueling stations is also a key component of the National Zero-Emission Freight Corridor Strategy; the development of corridors is guided by the seven selected hydrogen hubs (Joint Office of Energy & Transportation, 2024). To this end, several projects jointly received $90 million of grants for the establishment of a hydrogen corridor connecting California and Texas (Hydrogen & Fuel Cell Technologies Office, 2024a).

To fully decarbonize aviation fuel demand by 2050, medium- and long-term goals for the hydrogen demand in the sector are set to facilitate planning and strategic investment for private actors. Furthermore, the DOE supports demonstration projects exploring the direct use of hydrogen in uncrewed aerial vehicles In collaboration with an industrial partner and the U.S. DRIVE partnership, a Net-Zero Tech team compares and analyzes the costs and emissions of different technology pathways to identify high-potential fuels among different biofuel and power-to-liquid fuels (Department of Energy, 2023d). Additionally, Hydrogen Aviation Strategy Act initiates consultations among the Federal Aviation Administration industry partners, airlines, and hydrogen producers and establishes a new advisory committee to develop recommendations on the adoption of hydrogen for aviation technologies (Ossoff, 2024).

Power sector Hydrogen applications in the power sector are meant to ensure a secure and stable supply of energy and are funded via the Regional Clean Hydrogen Hubs Program (Department of Energy, 2023c). Furthermore, DOE is funding RDD&D and actively collaborates with industrial partners to quantify the economic benefits that hydrogen storage might provide under specific grid conditions given high shares of renewable energy sources. To this end, DOE has established test facilities in national laboratories to demonstrate the integration of electrolyzers in the power grid with electric and thermal sources as well as nuclear power plants to support grid stability. Another instrument is the provision of loan guarantees for first-of-its-kind hydrogen applications, such as a clean hydrogen production and storage facility which might provide long-term seasonal energy storage in a salt cavern in Utah. Such pilot schemes aim at de-risking technological development to facilitate additional private sector investment and to foster the commercialization and market adoption of new hydrogen applications. Furthermore, DOE funded the deployment of hundreds of fuel cell applications as backup power (Department of Energy, 2023d).

5 International Cooperation on Hydrogen

Besides the promotion of domestic clean hydrogen production, the U.S. engages in bilateral and multilateral cooperation on hydrogen. However, the international dimension of the U.S. hydrogen strategy has received much less attention in the policy debate and is therefore less defined. Accordingly, the national roadmap for hydrogen-related actions includes no references to international actions in the near future until 2026. While the United States aims to export hydrogen and related technologies to regional and global partners, this vision is defined as a long-term goal (Department of Energy, 2023d). Thus, the national roadmap includes more references to international actions in later periods. The U.S. plans to focus more on the international harmonization of codes and standards related to hydrogen technologies in the period between 2026 and 2029. The development of market structures and regulatory guidance for clean hydrogen exports is foreseen for the period between 2030 and 2035 (Department of Energy, 2023d).

Emerging priorities for the United States' international collaboration on hydrogen are outlined in the draft for the national clean hydrogen strategy (Department of Energy, 2020). The priorities include (a) demand creation and management, (b) finance and investment, (c) research and innovation, and (d) regulation, standard, and certification. The following section provides an overview of hydrogen-related U.S. foreign policy activities concerning these priority areas.

5.1 Demand Creation and Management

The United States aims to strengthen the coordination with other countries and private actors to increase the scale and visibility of hydrogen demand signals. Ensuring off-takers for potential hydrogen exports is important for infrastructure investments, building investor confidence, and avoiding supply chain risks and stranded assets.

So far, the United States has collaborated with partners in several world regions on hydrogen demand creation and management. All bilateral partnerships focusing on hydrogen-related collaboration cover foreseen activities related to scaling up hydrogen deployment and related infrastructure. Partnering countries include future hydrogen importers, such as Germany or Japan as well as potential future hydrogen export competitors, such as Australia, Saudi Arabia, or the United Arab Emirates. The partner countries are all high- or middle-income countries. Table 3 delivers an overview of partner countries, formats, and joint hydrogen-related activities.

Furthermore, the US has engaged in multilateral initiatives focusing on demand creation and management. The closest collaboration exists within North America where the U.S. collaborates with Canada and Mexico to establish a joint hydrogen market. The United States-Mexico-Canada Agreement (USMCA) includes provisions related to the cross-border trade of hydrogen and hydrogen-related technologies. The strong existing trade relations have enabled Canada and Mexico to benefit from U.S. policy instruments for establishing economic leadership. As mentioned above, the local content requirements on hydrogen technologies in the IRA can also be met via production in these two neighboring countries (The White House, 2023b).

The U.S. collaborates with the EU Commission on accelerating the deployment of clean hydrogen in a joint task force on energy security, which includes dialogue on scaling up the production of clean hydrogen (The White House, 2022h). Moreover, energy trade between the U.S. and the EU has intensified since the Russian war in Ukraine started in 2022. Newly built infrastructure for additional LNG imports from the United States is meant to be adjustable for future clean hydrogen imports (EU Commission, 2022b).

However, several policy measures to increase hydrogen demand while strengthening local industries have created tensions between both regions. To reduce the economic disadvantage of more expensive clean hydrogen-based industrial production compared to fossil-based production, the EU employs carbon pricing. To guarantee a level playing field between European industries and their international competitors, the EU will apply import taxes based on carbon content (CBAM). In turn, the U.S. focuses on tax credits for clean production within the country, which are often paired with local content requirements, for example in the IRA. Both measures are criticized as harmful to free trade and fair competition and might result in conflicts within the WTO (Jackson & Hellmich, 2022).To ease these tensions, the EU-U.S. Task Force on the Inflation Reduction Act was launched in October 2022. The task force addresses concerns on both sides; the first success of these negotiations has been granting access to IRA subsidies for commercial clean vehicles for EU companies (EU Commission, 2022a). Despite differences, there has been a recent convergence between EU and U.S. policy approaches. The production subsidies included in the U.S. IRA have been an important driver for the EU Net-Zero Industry Act, while EU approaches targeting demand creation for hydrogen have inspired the U.S. to advance demand-side support policies (The White House, 2023c).

5.2 Finance and Investment

The scope of investments in clean hydrogen is too small in relation to the needs for a global hydrogen economy, especially in developing countries. The United States aims to increase international coordination and visibility to scale up investments in hydrogen worldwide.

The U.S. bilaterally partners with several countries on scaling up investments in hydrogen worldwide (see Table 3). In a joint "Strategic Clean Energy Partnership" with India, the U.S. works on leveraging investments in clean energies and clean hydrogen in particular (Office of International Affairs, 2022b). The "Partnership for Accelerating Clean Energy (PACE)" with the United Arab Emirates aims to mobilize $100 billion in investments and other support to deploy 100GW of clean energy worldwide, of which parts are foreseen to finance hydrogen production (The White House, 2022g).

Additionally, the United States provides foreign aid and investment to other countries to support the development of hydrogen projects and associated infrastructure. Several initiatives focus on Africa. The programs "U.S-Africa Partnership in Supporting Conservation," "Climate Adaptation," and "Just Energy Transition" foster investments in the deployment of hydrogen in African countries (The White House, 2022d). The "U.S.-Africa Clean Energy Finance initiative" aims at mobilizing private sector investment in clean energy projects in Africa, including hydrogen projects. The "Global Partnership for Climate-Smart Infrastructure" supports the development of hydrogen projects in emerging economies. It provides funding for feasibility studies and other project-planning activities (USTDA, 2021). While these activities are a contribution to energy security worldwide, they are also part of an export-oriented strategy aimed at enhancing economic leadership in global hydrogen markets. Accordingly, the Global Partnership for Climate-Smart Infrastructure also identifies market opportunities for U.S. companies by facilitating the deployment of transformative U.S.-made technologies and services in partner countries (USTDA, 2022). Consistently, the Export–Import Bank of the United States provides financing and insurance for U.S. companies exporting hydrogen and hydrogen-related technologies (EXIM, 2010).

5.3 Research and Innovation

The United States aims to accelerate innovation in hydrogen technologies by strengthening international cooperation on research and development and including more countries in existing collaborative approaches. A focus of international R&D collaboration is diverse and scalable pilot and demonstration projects.

All its bilateral partnerships on hydrogen include initiatives to foster joint hydrogen-related R&D (see Table 3). The U.S. further cooperates on hydrogen-related R&D with its Northern American trading partners Canada and Mexico (Valero de Urquia, 2023).

Furthermore, the U.S. has been fostering international research and innovation projects in several multilateral forums. The U.S. acts as co-lead for the hydrogen initiatives under the auspices of both the Clean Energy Ministerial and Mission Innovation (Clean Energy Ministerial, 2023; Mission Innovation, 2023). Being a founding member of the International Energy Agency (IEA), the United States has engaged in collaborative hydrogen research and development since 1977 in a specialized Technology Collaboration Program (Hydrogen TCP). Current projects focus on underground hydrogen storage or conversion technologies. The United States has supported these joint research activities by holding the Chairmen position in the Executive Committee of the Hydrogen TCP from 1995 through 2002 and by hosting numerous Committee meetings (IEA, 2023b).

5.4 Regulation, Standards, and Certification

Internationally accepted and implemented standards and certification schemes are seen as essential enablers for international trade along hydrogen value chains. However, definitions of clean hydrogen currently vary internationally, concerning the emission thresholds and system boundaries considered in the calculation of emissions. The U.S. supports clean hydrogen, with lifecycle emissions of less than 4kgCO_2e/kg H_2, including upstream methane emissions but not distribution to end users. The European Union's Renewable Energy Directive sets a lower lifecycle emission target of approximately 3.4 kgCO_2e/kgH_2 for clean hydrogen and targets

Table 3 U.S. partnerships and dialogues on hydrogen

Country	Year	Type of partnership and hydrogen-related activities
Australia	2022	The "Net-Zero Technology Acceleration Partnership" collaborates on clean hydrogen applications in heavy vehicles, in the mining sector, on certification, and CCUS. The U.S. "National Renewable Energy Laboratory" (NREL) partners with the Australian "Commonwealth Scientific, Research, and Industry Organization" (CSIRO) on hydrogen R&D (Department of Energy, 2022a)
Brazil	2024	The Brazil-U.S. Partnership for the Energy Transition supports the production of clean hydrogen in both countries as well as clean energy technology supply chain development (The White House, 2024)
Germany	2021	The "U.S.-Germany Energy Partnership" supports the development and deployment of clean energy technologies, including collaboration on scaling up the deployment of sustainable hydrogen (The White House, 2021b)
India	2022	The"Strategic Clean Energy Partnership" was launched in 2018; this partnership led to the creation of a joint public–private "hydrogen taskforce" in 2022 to leverage clean energy investments and accelerate the deployment of hydrogen technologies (Office of International Affairs, 2022b)
Indonesia	2022	The U.S. and Indonesia have been collaborating in a strategic partnership since 2015. In 2022, the partnership was enhanced by new initiatives, covering collaboration on green hydrogen. Accordingly, the U.S. International Development Finance Corporation announced to invest in green hydrogen projects in Indonesia (The White House, 2022c)
Israel	2022	The U.S.-Israel "Strategic High-Level Dialogue on Technology" aims to establish a partnership on critical and emerging technologies, including joint R&D on clean and renewable hydrogen production, delivery, infrastructure, storage, fuel cells, and multiple ends uses as well as the support of the commercialization of hydrogen projects (The White House, 2022f)
Japan	2022	The U.S. and Japan created a "Climate Partnership" to foster clean hydrogen deployment for industrial decarbonization (The White House, 2022e). The joint "Clean Energy and Energy Security Initiative" (CEESI) focuses on energy supply with hydrogen and fosters innovation and marketization of related technologies, e.g., with joint safety standards (Office of International Affairs, 2022a; The White House, 2022a)
Netherlands	2020	The U.S. and the Netherlands collaborate on hydrogen R&D, the harmonization of safety codes, and standards in emerging areas like hydrogen and natural gas blending (Government of the Netherlands, 2020)
Saudi Arabia	2022	The "Bilateral Partnership Framework for Advancing Clean Energy" focuses, among others, on green hydrogen. The partnership aims to leverage public and private sector collaboration to enhance the deployment of green hydrogen and to accelerate R&D on innovative technologies (The White House, 2022b)

(continued)

Table 3 (continued)

Country	Year	Type of partnership and hydrogen-related activities
South Korea	2021	The U.S.-Korea "Energy Security Partnership" supports the development of clean energy technologies, including hydrogen; it fosters ministerial collaboration to support R&D on hydrogen storage (The White House, 2021c)
United Arab Emirates	2022	The U.S.-UAE "Partnership for Accelerating Clean Energy (PACE)" aims to mobilize investments to deploy clean energy worldwide. The joint work on hydrogen includes R&D on CCUS for blue hydrogen, and cooperation on nuclear energy for pink hydrogen production (The White House, 2022g)

less than 3.0 $kgCO_2e/kgH_2$ under its Taxonomy Regulation on sustainable investment and also considers emissions from distribution to end users (Collins, 2023b; Department of Energy, 2022b), which makes an international comparison difficult. Therefore, the U.S. aims to increase the coordination of existing workstreams across different countries and international initiatives on the topic, to identify and address potential challenges, and to increase the inclusion of stakeholders.

Several bilateral hydrogen partnerships include workstreams on hydrogen regulation, standards, and certification, including partnerships with Australia, Japan, and the Netherlands. The U.S. also works closely on this topic with Canada and Mexico, as joint regulation, standards, and certification are crucial for the foreseen North American hydrogen market. The U.S. works with the EU Commission on a joint methodology for tracking emissions embedded in carbon-intensive steel and aluminum products, which will be key to quantifying potential emission reductions due to clean hydrogen applications in the sector (EU Commission, 2021).

Furthermore, the U.S. works on regulation, standards, and certification within the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE). The United States is a founding member of IPHE, which was established in 2003, and served as chair of the IPHE steering committee from 2003 through 2007 and from 2018 through 2021. Currently, the country serves as vice-chair of the steering committee and takes an active part in two working groups on Regulations, Codes, Standards, and Safety, and on Education and Outreach, as well as in the Hydrogen Production and Analysis (H2PA) task force, which is developing joint methods of lifecycle analysis for hydrogen production (Department of Energy, 2023d). As of 2023, the partnership has assembled 22 countries, including several European countries, Australia, Brazil, Canada, Chile, China, Costa Rica, India, Japan, Korea, Russia, and South Africa (IPHE, 2022) (Table 3).

6 Conclusion

The U.S. is a leading actor in today's hydrogen economy. The U.S. hydrogen strategy aims to secure and expand this position in a global transition toward clean energy to prevent dangerous consequences of climate change. The U.S. has been pioneering hydrogen policy instruments driven by the pursuit of energy independence to meet the rising internal demand and to eventually export clean hydrogen in the next decade. A further key driver of U.S. hydrogen policy has been to enhance economic leadership based on export-oriented industrial competitiveness and technology leadership via the promotion of R&D and localized supply chains. The recent landmark legislative packages BIL and IRA reflect these priorities and include large-scale investments and financial incentives to promote the supply of clean hydrogen at lower costs, to strengthen innovation, and domestic value chains. These policies are characterized by large-scale investments to foster mission-oriented innovation (e.g., in the Hydrogen Shot Initiative) and share a strong focus on supply-side instruments to scale up production of clean hydrogen. The focus on "clean" instead of green hydrogen enables the support of certain types of blue hydrogen production despite the danger of creating path dependencies and carbon lock-in effects. U.S. hydrogen policy under President Trump is likely to further shift the balance toward blue hydrogen technologies. The U.S. further aims to manifest this technological openness in international standards.

International policymakers and companies have observed these recent regulatory schemes closely, especially concerning the introduction of tax credits as subsidies for clean hydrogen production and their pairing with local content requirements to gain more independence from Chinese clean technology suppliers. Since the IRA was passed, several large European companies such as Enel, Volkswagen, BMW, NEL, and Freyr have announced their intentions to newly build or expand almost 20 clean energy manufacturing plants in the U.S. (Collins, 2023a; Wessner & Khemka, 2023). Partly in reaction to U.S. developments, other governments have indicated that they plan to enhance subsidy schemes in their jurisdictions. For example, India has announced the development of its own subsidy schemes (Singh, 2023). For its part, the EU has continuously expanded the range of exceptions under which Member States may grant national subsidies for industrial decarbonization and cleantech manufacturing. In parallel, the EU has introduced demand-side policies such as quotas to incentivize the uptake of green hydrogen and derivatives in hard-to-abate sectors (EU Commission, 2023). But while large economies such as China, the U.S., and EU have the capacities to compete for green leadership, most other countries will lack the resources to match the subsidy model put forward by the United States.

The international dimension of the U.S. hydrogen strategy has received much less attention in the U.S. policy debate and is therefore less defined. This is apparent in comparison with other actors, such as a much more outward-oriented European Union, which reached out to numerous countries as potential trading partners for much-needed hydrogen imports. In contrast, the United States currently focuses much more on building up domestic hydrogen value chains, enabled by a favorable resource endowment. Nevertheless, the U.S. has fostered bilateral partnerships on hydrogen and strengthened its hydrogen-related engagement in international organizations and multilateral initiatives in the past years. Emerging priorities for the United States' international collaboration on hydrogen include international demand creation and management, upscaling investments, international research collaborations, and joint efforts on regulation, standards, and certification. These efforts can be seen as the first steps toward the U.S. long-term goal to export hydrogen and related technologies to regional and global partners from the 2030s onwards.

Acknowledgements Research for this chapter was financially supported by the German Federal Foreign Office within the framework of the project "Geopolitics of the Energy Transformation – Implications of an International Hydrogen Economy" (GET Hydrogen), funding reference number AA4521G125.

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Japan: Putting Hydrogen at the Core of Its Decarbonisation Strategy

Yuma Osaki and Llewelyn Hughes

Abstract Japan has led efforts to promote hydrogen and derivatives as options for supporting decarbonisation globally. Domestically, the Japanese government has positioned hydrogen as playing an important role in helping achieve the country's 2050 net-zero emissions commitment. The government is supporting technology development on both the supply side and in end-use sectors, notably in relation to power generation. The Japanese government is also championing hydrogen internationally, including by promoting it as a decarbonisation option in Southeast Asia, whilst examining the feasibility of different options for enabling maritime trade in hydrogen. This suggests that new patterns of trade and investment may emerge, although there remain crucial questions about commercial feasibility.

1 Introduction

At the 2019 meeting of the G20 hosted by Japan, energy and environment ministers committed to work to enable hydrogen as a low-carbon source of energy. The enthusiasm of the Japanese government in promoting multilateral cooperation in hydrogen reflected its domestic priorities. The government released a National Hydrogen Strategy in 2017—the first amongst a large number of hydrogen roadmaps announced globally (International Renewable Energy Agency, 2022)—followed by a hydrogen and fuel-cell strategy roadmap in March 2019 (Deliberative Council on Hydrogen & Fuel Cells, 2019; Government of Japan, 2017). Japan's hydrogen strategy is distinguished by its strong emphasis on the need to develop international supply chains for hydrogen and other vectors in the near-term in order to enable imports at scale, combined with a focus on the use of hydrogen across multiple sectors, notably in power generation.

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R. Quitzow and Y. Zabanova (eds.), *The Geopolitics of Hydrogen*, Studies in Energy, Resource and Environmental Economics, https://doi.org/10.1007/978-3-031-84022-7_5

This chapter reviews Japan's hydrogen strategy. It begins by outlining Japan's international commitment to reduce economy-wide greenhouse gas emissions. The chapter then reviews policy settings within Japan designed to support the deployment of hydrogen in power generation, transport, and industrial uses. The development of supply chains in hydrogen is a central part of the Japanese government's strategy to develop a domestic hydrogen economy. The chapter then reviews the strategy the government is using to enable the development of international supply chains, with the focus on bilateral technology partnerships and activities within multilateral forums. It concludes with a discussion of the geopolitical implications of Japan's hydrogen strategy.

2 Hydrogen as a Technology Option for Domestic Decarbonisation and Energy Security

The Japanese government submitted an updated Nationally Determined Contribution (NDC) in 2021 under the Paris Agreement of the United Nations Framework Convention on Climate Change (UNFCCC). In doing so, it joined a number of other countries in the Asia–Pacific region in committing to a net-zero target for economy-wide greenhouse gas emissions (GHG). The government also committed to the mid-term target of reducing GHG emissions on an economy-wide basis by at least 46% by 2030 relative to 2013, equivalent to a 25.4% in emissions reduction relative to 2005. This new mid-term commitment represented a substantial increase in ambition from the 26% emissions reduction commitment for the same time period made in Japan's first NDC submission.

A core challenge facing Japan in achieving its net-zero GHG emissions reduction target is the stagnation of nuclear power within the electricity sector, following the earthquake and nuclear disaster of 11 March 2011. Prior to the disaster, nuclear power was positioned as a core technology enabling decarbonisation of the electricity sector whilst meeting energy security goals at reasonable cost (Government of Japan, 2010). In 2010, nuclear energy represented 15% of Japan's Total Primary Energy Supply (TPES) and 25% of electricity generation. This was reduced to zero in the wake of the disaster. Today Japan's energy system is dominated by fossil fuels. In 2019, fossil fuels made up 88% of Japan's TPES and 71% of electricity generation, despite an increase in renewable electricity generation centred on solar photovoltaics and the re-entry of some nuclear generation units into service (International Energy Agency, 2021).

The more ambitious GHG emissions reduction commitment triggered a review of the policy settings supporting decarbonisation, including the role of hydrogen and associated energy vectors such as ammonia. Under the 2001 Basic Law on Energy, the Japanese Cabinet is required to review Japan's mid-term energy policy settings every three years through the Basic Energy Strategy (BES). In the 2014 BES, the Japanese Cabinet identified a need to conduct a detailed assessment of the potential role of hydrogen as a decarbonisation option. Through the 2021 BES, hydrogen and ammonia were then positioned as key long-run solutions to decarbonisation across a wide-range of end-uses, including power generation, transport, industry, and the commercial and household sectors. Indeed, in the case of Japan the 2021 BES establishes a target for hydrogen/ammonia of 1% of generated electricity in 2030 (Government of Japan, 2021; Agency for Natural Resources & Energy, 2022). The emphasis on enabling ammonia and hydrogen use in power generation contrasts with the national hydrogen strategies of other countries, which do not emphasise hydrogen and ammonia as fuels in the existing fleet of thermal power stations.

An important justification given for a focus on hydrogen in the energy mix is energy security. The Japanese government has long been concerned about the lack of geographic diversification associated with fossil fuels. Hydrogen is positioned as an energy carrier which can be produced using a variety of energy sources and which can be stored and transported. The current role of hydrogen in the Japanese economy is nevertheless limited. Around 1.9 million tonnes (Mt) of hydrogen were produced in Japan in 2022, with the majority used on-site within the refining industry. In 2019, the Japanese industry used around 1.08 Mt of ammonia—a vector of hydrogen—with 80% produced domestically and the remainder imported, mainly from Indonesia and Malaysia (Japan Agency for Natural Resources & Energy, 2022).

2.1 *Hydrogen as Industrial Strategy*

A second motivation for supporting hydrogen and ammonia is industrial policy (Renewable Energy Institute, 2022). Japanese companies are leading holders of patents related to hydrogen production, storage, distribution, and use (International Renewable Energy Agency, 2022, 56). The 2023 National Hydrogen Strategy emphasises Japanese firms' competitive advantage across five areas identified for public support: (1) hydrogen production and related infrastructure in international supply chains; (2) hydrogen and ammonia for use in power generation; (3) fuel-cell technologies; (4) the direct use of hydrogen in steel, chemicals, and shipping; (5) e-methane and e-fuels. Japan's industrial policy ambitions are supported by quantitative targets, including reducing the cost of alkaline and proton exchange membrane (PEM) electrolysers to ¥52,000 and ¥65,000 per kilowatt, respectively, by 2030, and securing 15 gigawatts (GW) of electrolyser sales by 2030 domestically and internationally. These targets are backed by public funding programmes in research, development, and deployment (Government of Japan, 2023a, 2023b, 2023c).

The government also identifies an export opportunity focused on Southeast Asia, where there is a substantial fleet of coal-fired power generation. The Japanese government foresees a potential global market size of ¥1.7 trillion annually by 2050, with the primary opportunity outside fertiliser production identified as the co-combustion of ammonia in coal-fired power stations. The export opportunity is identified as ¥500 billion of investment in technologies enabling co-combustion, assuming 10%

of Southeast Asia's coal plants were retrofitted. In addition, the Japanese government identifies an opportunity for hydrogen in power generation and aims to accelerate the commercialisation of hydrogen power generation turbines domestically and internationally (Government of Japan, 2021).

Given the importance placed on energy security and green growth opportunities from hydrogen and ammonia, the Japanese government, led by the Agency for Natural Resources and Energy (ANRE) within the Ministry of Economy, Trade, and Industry (METI), has worked with industry and other stakeholders to establish a mix of policy measures to support their uptake, underpinned by quantity and price targets. This includes embedding hydrogen in a broader suite of green industrial policies (GIPs) developed in support of decarbonisation. In December 2020, the government announced a Green Growth Strategy focused on 14 sectors, including hydrogen and ammonia (Government of Japan, 2020). Japan's suite of GIPs was updated through legislation that entered into law in June 2023 and which required it to develop a Green Transformation ("GX") Strategy. The GX Strategy identifies hydrogen and ammonia as key technology options that can be flexibly used across power generation, transport, and industry and that can contribute to energy security by increasing domestic production and absorbing excess renewable electricity generation. The GX Strategy places particular emphasis on the use of hydrogen and ammonia through co-combustion with fossil fuels in order to reduce CO_2 emissions in the power sector (Government of Japan, 2023a). In support of this broad vision, the GX Strategy proposes ¥7 trillion in research and development (R&D) and infrastructure development support over 10 years, including ¥5 trillion for the building of large scale and resilient supply chains domestically and internationally to enable trade in hydrogen and ammonia. In addition, in 2023 the government revised its National Hydrogen Strategy (NHS). The revised NHS included quantitative targets of 3 Mt of hydrogen and ammonia use annually by 2030, 12 Mt by 2040, and 20 Mt annually by 2050. In addition, it included a 2030 price target of ¥30 per Nm^3 (around ¥334/kg), falling to ¥20 per Nm^3 by 2050, with the latter set to compete with gas-fired power generation (see Table 1 for an overview of Japan's hydrogen-related policy targets). The NHS also emphasised the need to develop Japanese firms' competitive advantage across core technologies in hydrogen and ammonia, including establishing a target for Japanese firms to operate 15 GW of electrolyser capacity domestically and internationally. In July 2023, the government increased state capacity by creating a hydrogen/ammonia-focused division in the Agency for Natural Resources and Energy (ANRE)—Japan's key agency responsible for energy policies—to lead policy implementation.

Table 1 Japan's hydrogen-related policy targets

Target	Year
Price targets	
30 yen/Nm^3 of hydrogen	2030
20 yen/Nm^3 for hydrogen	2050
52,000 yen/kW for alkaline electrolysers	2030
65,000 yen/kW for PEM electrolysers	2030
500,000 yen per commercial and industrial fuel-cell unit	2030
Hydrogen consumption and use targets	
3 million tonnes of domestic hydrogen consumption	2030
12 million tonnes of domestic hydrogen consumption	2040
20 million tonnes of domestic hydrogen consumption	2050
1% of generated electricity, including 6.7 TWh of hydrogen and 8.2 TWh of ammonia	2030
Technology deployment targets	
15 GW of global electrolyser capacity deployed by Japanese firms	2030
800,000 equivalent fuel-cell passenger vehicle sales	2030
1000 hydrogen refuelling stations	2030

Source Government documents

3 Envisioned End-Uses for Hydrogen and Ammonia

As outlined above, the Japanese government assigns an important role to hydrogen as a vehicle for decarbonising a number of end-use sectors. This includes not only applications in mobility and industry, but, in contrast to other major economies, also power generation.

3.1 Power Generation

The International Energy Agency (2019, p. 151) projects that the co-firing of ammonia will have a limited role to play as a transitional measure to reduce GHG emissions from coal-fired power plants. The climate benefit of co-combusting ammonia also depends heavily on the hydrogen production technology. Indeed, it has been estimated that the use of unabated natural gas for producing ammonia through steam methane reforming coupled with the Haber Bosch process would not reduce aggregate emissions, once upstream fugitive emissions are taken into account (Stocks et al., 2022). The Japanese government nevertheless assigns hydrogen and ammonia an important role in its decarbonisation strategy for the power sector, arguing their use does not create emissions at the point of combustion. Next to the adoption of

CCUS technologies, the 2023 NHS envisions ammonia co-combustion as an important option for decarbonising thermal generation to 2050 (Government of Japan, 2023b). Scenario assessments of decarbonisation pathways reviewed within ANRE envision a potentially long-term role for hydrogen and ammonia in meeting Japan's Net-Zero commitment. In the reference case from the Research Institute of Innovative Technology for the Earth (RITE), hydrogen and ammonia are modelled as making up 21% of the total primary energy supply (TPES) by 2050, including 13% of generated electricity. Other scenarios examined by the government include hydrogen and derivatives, representing from 16 to 26% of TPES by 2050. In the 100% renewable electricity scenario, hydrogen and derivatives range from 20 to 26% of TPES by 2050 (Agency for Natural Resources & Energy, 2021a).

In the near to medium term, the government established a target for hydrogen and ammonia to make up around 1% of generated electricity, with hydrogen at 6.7 TWh and ammonia at 8.2 TWh by 2030 (see Table 1). This is planned through ammonia co-combustion within Japan's existing thermal power generation fleet and the direct use of hydrogen turbines (Agency for Natural Resources & Energy, 2021c). The New Energy Development Organisation (NEDO)—Japan's primary energy-related public research organisation—funded a three-year demonstration project to support the ammonia co-combustion target—collaborating with electricity utilities to deploy burners capable of injecting ammonia as fuel into the existing coal fleet. Japan's largest operator of thermal power generation, JERA, is responsible for demonstrating the feasibility of 20% co-combustion of ammonia within an existing power generation unit. It concluded a successful trial at a 1GW unit of the Hekinan power plant in Aichi Prefecture in June 2024. Commercial operation is planned for the latter half of this decade. JERA is also planning to test the co-combustion of a minimum of 50% of the fuel load beginning with a demonstration phase in fiscal year 2028 and with commercial operation to begin in the first part of the 2030s. The project is being developed with IHI and Mitsubishi Heavy Industries and commenced in 2021 (JERA, 2022).

The government is also investing R&D funds in turbine technology with the goal of enabling the direct combustion of hydrogen. Mitsubishi Heavy Industries has a turbine of more than 10MW under development and has developed a burner capable of co-combusting 10% of the fuel load with hydrogen. JERA is also trialling the use of hydrogen within gas generation. A feasibility study, which commenced in October 2021, foresees the construction of hydrogen supply facilities and a burner enabling the co-combustion of hydrogen and LNG in an existing gas turbine, with the intention to begin testing co-combustion of 30% of the gas fuel load on a volumetric basis, or 10% on a heat basis, from FY2025 (JERA, 2022). Other electricity utilities are also planning entry into the market for hydrogen technologies. Kansai Electric is intending to participate in hydrogen across the value chain, including production internationally, the operation of hydrogen import facilities and using hydrogen in power generation. It is carrying out a feasibility study utilising funds from NEDO to examine combusting hydrogen in an existing gas turbine, including examining the feasibility of supply, storage, and regasification (Kansai Electric Power Company, 2022).

3.2 Mobility

Sectoral policies also target a role for hydrogen and ammonia in transport. A focus has been passenger vehicles, where the Japanese government's approach to reducing emissions centres on the technology neutral concept of "next generation vehicles" (NGV), defined to include battery electric vehicles (BEV), fuel-cell vehicles (FCV) and hybrid vehicles. For FCV, the 2010 NGV strategy established a deployment target of 1% of vehicles on the road by 2020 and 3% by 2030 (Bose Styczynski & Hughes, 2019). Deployment rates fell short, however, with FCV sales of passenger vehicles stagnating at around 6600 units by March 2022 (Japan Agency for Natural Resources & Energy, 2022). Implicitly recognising the lack of demand, the 2023 revision to the NHS shifts emphasis to technology leadership in fuel cells and gives priority to commercial vehicles, where more demand for hydrogen is expected and the advantages of FCVs may be more easily exploitable (Government of Japan, 2023b). The new strategy targets the equivalent of 800,000 fuel-cell electric vehicle sales by 2030 and introduces a price target of 500,000 yen per commercial or industrial fuel cell by 2030.

The government has argued that one barrier to FCV uptake is the need for fuelling infrastructure. Accordingly, the BES stated the need for public investment in the deployment of hydrogen fuelling stations to help the deployment of FCVs and fuel-cell trucks. As of March 2022, 169 hydrogen stations were installed domestically, with a policy target of 1000 stations by 2030. ANRE provided a subsidy of ¥11 billion in fiscal year 2021 and ¥12 billion in FY2020, covering up to two-thirds of installation costs. Given the high cost of installing hydrogen fuelling stations, an additional cost target was created to reduce the installation cost to ¥200 million per station as the mean 2021 installation cost, down from ¥330 million (Agency for Natural Resources & Energy, 2021b).

Additional areas of development are shipping and aviation. The Green Innovation Fund includes ¥35 billion over ten years in R&D support for the development of "zero emissions" shipping through hydrogen and ammonia-fired engines, including the development of tanks and supply infrastructure, with commercialisation targeted for the latter part of the 2020s (MLIT, 2024). Additional funds are allocated to R&D in the use of hydrogen in aircraft.

3.3 Industry

Japan was the fourth-largest producer of crude steel in 2021, manufacturing more than 96,000 tonnes of crude steel, which represented around 5% of global production. Japan was also the second-largest exporter of semi-finished and finished steel products in the same year, exporting more than 33.7 thousand tonnes of products and a 7.3% share of global exports (World Steel Association, 2022). In 2021, the Nippon Steel Corporation was the fourth-largest producer globally, manufacturing around 49.5 Mt of steel. Japan's JFE Steel Corporation was the 13th-largest steel manufacturer globally, producing almost 27 Mt of steel in the same year (World Steel Association, 2022).

Steel is the largest emitter of carbon dioxide within the Japanese industrial sector, and hydrogen is being tested as a technology for reducing marginal emissions from the sector. The primary initiative for reducing CO_2 emissions is the industry-led CO_2 Ultimate Reduction System for Cool Earth 50 (COURSE50), supported by NEDO and involving Nippon Steel, JFE, Kobelco, and Nippon Steel Engineering. COURSE50 is implemented through a series of five-year plans beginning in 2008 and is supported by GX investments. Near-term measures focus on improving the efficiency of the steel manufacturing process. In the medium-term, hydrogen is proposed to be used in the process for reducing iron ore, cutting CO_2 emissions from the blast furnace through the injection of hydrogen as a partial substitute for coking coal. Carbon dioxide would then be separated from the blast furnace gas, with a target of reducing 30% of carbon dioxide emissions from steelmaking by 2030 relative to a 2013 baseline (Agency for Natural Resources & Energy, 2021c). Longer-term research and development spending focuses on the direct reduction of iron using hydrogen (H_2-DRI). Given the cost implications if importing large quantities of hydrogen, a further option is to relocate iron-making processes to countries that have abundant and low-cost sources of renewable energy available for use in green hydrogen production (Devlin and Aidong, 2022), although this option is not currently being considered by the government. In contrast to power generation and mobility, Japan has not set any quantitative policy targets for hydrogen use in the industrial sector.

4 Supplying Hydrogen and Ammonia

Japan has historically been almost wholly reliant on trade to supply the energy commodities, chiefly oil, coal, and gas, used as inputs into economic activities (Government of Japan, 2023c). From an energy security perspective Japan's National Hydrogen Strategy supports the domestic production of hydrogen, potentially through the use of otherwise curtailed renewable electricity. However, it does not identify a national target for domestic hydrogen production. Instead, the strategy targets the deployment of 15 GW of *global* electrolyser capacity by Japanese firms by 2030, without prioritising domestic deployment.

In line with this, the Japanese government expects the availability of domestically produced hydrogen to be insufficient to meet the policy target of up to 30 million tonnes of hydrogen demand by 2030, 120 million tonnes by 2040, and 200 million tonnes by 2050 (Government of Japan, 2023b). As a result, imports play a central role in the hydrogen strategy. The government is taking a technology-agnostic approach towards hydrogen production when supporting the development and testing of supply chains for hydrogen. Whilst the substitution of hydrogen and ammonia for emissions intensive processes within Japan results in a reduction of emissions domestically regardless of production method, the government is taking an interest in shaping the rules governing the emissions intensity of hydrogen through global technical regulations under the International Partnership for Hydrogen and Fuel Cells in the Economy and other forums (see below). This includes committing to introducing an emissions intensity standard domestically that is broadly consistent with those adopted by other countries.

4.1 Developing Global Supply Chains for Hydrogen

International trade plays a central role in Japan's hydrogen strategy, requiring large capital investments in transport technologies such as transforming hydrogen from gaseous form into liquid hydrogen, the use of ammonia, or the use of a liquid organic hydrogen carrier such as methylcyclohexane (MCH). A core focus of government policy is building supply chains for hydrogen and ammonia as internationally traded commodities, making Japan's GIP in support of hydrogen interdependent with those of other countries (Meckling & Llewelyn, 2018). Japanese government and industry are pursuing bilateral partnerships with the aim of testing the techno-economic feasibility of different hydrogen transport technology pathways. The International Renewable Energy Agency (2022) notes there are important geopolitical implications that emerge from the construction of new value chains in hydrogen. An interesting feature of efforts to build international supply chains is that some are occurring through partnerships with countries with which Japan currently trades energy-related commodities.

The interdependent nature of enabling the development of hydrogen supply chains is reflected in structure of the financial scheme developed to support hydrogen uptake. The Hydrogen Promotion Act[1] passed through the Japanese parliament in May 2024, establishes the legal basis for the introduction of a Contract-for-Difference (CfD) scheme, managed by the Japan Organisation for Metals and Energy Security (JOGMEC). The CfD is proposed to provide for a 15-year support window to subsidise domestic or international projects supplying hydrogen for use in Japan. The scheme provides up to USD20 billion in funding to bridge the difference of between a strike price for hydrogen production and transport and the reference, which is determined by the fossil fuel being substituted for by hydrogen. The scheme's first round of tenders was launched in December 2024.

Reflecting Japan's technology-agnostic approach, the CfD allows for hydrogen produced via steam methane reforming coupled with carbon capture and sequestration, in addition to hydrogen produced via electrolysis. In line with this, Japan has engaged with the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE) to support the development of standards and rules that cut across different production pathways. The forum functions as an intergovernmental

[1] Formerly the 'Act on Promoting the Supply and Use of Low Carbon Hydrogen and Derivatives for Smooth Transition to a Decarbonised Growth-Oriented Economic Structure'.

negotiating platform, and the Japanese government has been a member of the taskforces focused on developing a common method for calculating embedded emissions and low-emissions hydrogen certification and focused on trade rules. It has also contributed to the taskforce on skills development, along with IPHE working groups on education and outreach, regulations, codes, and standards. From 2019, the IPHE Hydrogen Production Analysis Task Force worked to develop a common methodology for determining emissions intensities of different hydrogen production technologies that could form the foundations for a certification scheme, whilst leaving emissions intensity thresholds for national governments to determine. The 2023 NHS revision notes the government intends to adopt an approach to measuring hydrogen emissions intensity that is aligned with methodologies developed through the IPHE. It also proposes using a Well-to-Production-Gate method for calculating emissions embedded in hydrogen, with a standard of 3.4 kg/CO_2e, set for defining hydrogen as low emissions, and using a Gate-to-Gate approach for ammonia (including the emissions from hydrogen production) with low ammonia proposed to be defined as below 0.84kg/CO_2e/kg-NH3.

4.2 Bilateral Partnerships

The Japanese government is taking a technology-agnostic approach to hydrogen production and transport technologies and is testing different approaches through supporting a series of bilateral partnerships, financed by the GI Fund with up to ¥300 billion. The government has also increased its capacity for delivering on hydrogen and ammonia projects. The Japan Organisation for Metals and Energy Security (JOGMEC) supports early project development in natural resources, and in 2022, the law governing JOGMEC was revised to broaden the scope of investment and loan guarantees to include hydrogen and ammonia. A unit focused on hydrogen and carbon, capture and storage (CCS) was also established to facilitate lending. Through the new structure, JOGMEC can provide lending of up to 50% of capital requirements, and up to 3/4 of total capital requirements to companies building hydrogen/ammonia production and storage facilities for projects identified as nationally significant. It can also provide loan guarantees to companies that obtain private sector financing. The Japan Bank for International Cooperation (JBIC) also reorganised internally in 2022, creating an Energy Transformation Strategy Office to invest in hydrogen and ammonia.

A key strategy incorporated in the NHS is the testing of different hydrogen carriers in international supply chains through to 2025. Liquid hydrogen is being tested at a demonstration scale through the Hydrogen Energy Supply Chain (HESC) project, involving Japanese and Australian partners. On the Japanese side, it is financed through the Hydrogen Energy Supply-chain Technology Research Association "HySTRA" project, which has included Shell Japan, Iwatani Corporation, Kawasaki Heavy Industries, J-Power (2016–2023), Marubeni Corporation (2016–2023), ENEOS Corporation (2016–2023), and Kawasaki Kisen (2019–2023). The project is examining the feasibility of shipping liquid hydrogen produced via coal gasification from Latrobe Valley in the Australian State of Victoria to Japan using dedicated shipping technology. In Japan, a receiving terminal in Kobe Port was completed in June 2020, and regasification infrastructure was finished in October 2020. Subsequent steps include construction of storage tanks, an increase of the carrying capability of the dedicated tanker and testing of direct hydrogen combustion (Japan Agency for Natural Resources & Energy, 2022). The project has committed to commercialisation only with the application of CCS. Any residual emissions from the hydrogen production process would be accounted for under Australia's emissions commitments, given national accounting for carbon emissions under UNFCCC processes.

A second project led by Chiyoda Corporation and subsidised by NEDO examines the feasibility of MCH as a liquid organic hydrogen carrier for transportation, in partnership with Brunei. Mitsubishi Corp and Mitsui Corp are participating in the demonstration project, in addition to the shipping company NYK Line. Under the project hydrogen is extracted from methane using SMR and combined with Toluene (C_7H_8) before being shipped and dehydrogenated. The technology is being championed by Chiyoda Corporation under the SPERA Hydrogen label.

There are a number of other projects examining the commercial viability of long-range transport of hydrogen and ammonia. Tokyo Gas and Osaka Gas are examining the possibility of enabling hydrogen transport through methanation, in which hydrogen is reacted with CO_2 to produce synthetic methane. Osaka Gas has developed a test facility with Japanese energy sub-major INPEX, with costs partly offset by NEDO. The demonstration project will begin operations in FY2024, with the syngas used in the local gas supply network. If the project is successful, INPEX has announced the next phase will seek to demonstrate the feasibility of methanation at a commercial scale outside Japan. A pre-feasibility, commercial-scale study has been announced between INPEX and Australia's Commonwealth Scientific and Industrial Research Organisation (CSIRO), as part of the Japan-Australia Carbon Recycling Cooperation Memorandum signed between the two governments in 2019. Feasibility studies are also being conducted with Japanese companies and partners in Malaysia, North America, and the Middle East (Japan Agency for Natural Resources & Energy, 2022).

Mitsui is also conducting a feasibility study for a project in Western Australia that would produce one million tonnes of ammonia annually and is proposing to use depleted gas wells for storing CO2. The project is being considered with Australian company Wesfarmers, with final investment decision expected in 2025 (Mitsui & Company, 2022). In another project, Mitsui is partnering with French Engie to develop a 10 MW electrolyzer project to produce renewable ammonia for offtaker Yara Pilbara Fertilisers, with construction scheduled for completion in 2025. Mitsui is also developing an ammonia project in Louisiana, United States, in partnership with ammonia producer CF Industries, signing a post-feasibility study, front-end engineering design (FEED) contract in November 2022. The ammonia would be produced using methane and CCS, with an offtake agreement with ExxonMobil completed and the intention to begin production and marketing from 2027 (Mitsui & Company, 2022).

Additional studies and demonstration projects are under way with the goal of testing the feasibility of international transport of hydrogen and ammonia at scale. Kansai Electric is carrying out a feasibility study for the development of green hydrogen supply chain between Japan and Australia, partnering with the Iwatani industries, Kawasaki Heavy Industries, Australia's Stanwell Corporation, and others. Idemitsu Corporation is testing the feasibility of a hydrogen supply chain in the United Arab Emirates (UAE) using hydrogen produced from methane, with the waste CO_2 from the SMR process captured and used in enhanced oil recovery (EOR). Idemitsu Renewable Development Australia is also examining the feasibility of hydrogen exports through the Port of Newcastle Hydrogen Hub in Australia (Idemitsu, 2022).

International partnerships at the project level are supplemented by a growing number of bilateral agreements between public entities. JBIC has been particularly active, signing more than 20 Memoranda of Understanding (MoU) related to hydrogen by January 2024 with a wide array of governments and public bodies internationally, including the Clean Energy Finance Corporation (Australia), The Chilean Ministry of Energy, the Inter-American Development Back, Indonesian state-owned oil and gas company PT Pertamina (Indonesia), UK Export Finance, the state government of Western Australia, and others. JOGMEC has also signed hydrogen-related agreements with PetroVietnam, Saudi Aramco, Petronas, PT Pertamina, and others. In April 2021 the governments of Japan and the UAE signed a memorandum of understanding (MoU) focused on cooperation in hydrogen. The MoU focus on information sharing on policy settings, including regulation and standards, as well as reaching agreement on the need to support the development of a hydrogen supply chain. In November 2022, JOGMEC Signed a MoU with the Vietnamese national oil company PetroVietnam that includes facilitating opportunities to explore ammonia and hydrogen production, along Carbon Capture, Use and Storage (CCUS) opportunities between the two countries. In December 2022, JOGMEC has also signed a memorandum of understanding with the state government of WA that is designed to facilitate investments in hydrogen and ammonia, in addition to other technologies.

In addition, the Japanese government has signed a number of intergovernmental agreements, with primary focus on information sharing rather than project development. Since the 2019 NHS the government has announced bilateral arrangements involving hydrogen with the United Arab Emirates (2021), Brunei Darussalam (2022), Singapore (2022), the European Commission (2022), Chile (2023), and Saudi Arabia (2023). Notably, in February 2024 the Director-General of Japan's Energy Conservation and Renewable Energy Department, Agency for Natural Resources and Energy, METI, and the Director-General, of the Hydrogen Economy Policy Bureau, at South Korea's Ministry of Trade, industry and Energy also agreed to establish a bilateral dialogue on hydrogen and ammonia to facilitate cooperation.

4.3 Shaping Hydrogen Governance Through Multilateral Forums

A second component of Japan's international hydrogen strategy is supporting the uptake of hydrogen and ammonia as decarbonisation options in multilateral forums. The G7 Climate, Energy and Environment Ministers Joint Communiqué in 2023, when Japan was host, identified the potential role of hydrogen in decarbonising hard-to-abate sectors. Notably, the final draft stated the use of hydrogen and ammonia in thermal power generation should be aligned with a 1.5 °C pathway, with the goal of achieving a predominantly decarbonised power sector by 2035. The conditional nature of the statement reportedly reflected concerns from other governments about the use of hydrogen and ammonia as decarbonisation options in the power sector being championed by the Japanese government (Yamazaki & Abnett, 2023).

In addition to the IPHE (see above), a key initiative pioneered by the Japanese government is the Asia Zero Emissions Community (AZEC), announced in 2022 by the Kishida Administration as a Japan-led multilateral programme focused on Asia–Pacific region. The first ministerial meeting under the AZEC banner was held in March 2023 in Tokyo, with representation from Australia, Brunei, Cambodia, Indonesia, Laos, Malaysia, the Philippines, Singapore, Thailand, and Vietnam. The ministerial statement released noted there are "various and practical pathways toward carbon neutrality/net-zero emissions depending on the circumstances of each country" and that the AZEC initiative promotes cooperation in decarbonisation strategies and technologies including hydrogen and ammonia. An important initiative within AZEC is the Public–Private Investment Forum. At the ministerial meeting, Memoranda of Understanding were announced under the AZEC initiative, of which many focused on bilateral collaboration in the power sector, with some focusing on the potential for ammonia co-combustion regionally. An MoU was signed between Japanese firm IHI and Pupuk Indonesia, for example, to carry out a technical study and feasibility assessment for the construction of a green ammonia production plant at a fertiliser facility near Surabaya in Indonesia, coupled with a technical study on the potential to co-combust ammonia in the existing coal-fired power plant at the location. Another announcement was signed between Japanese companies Mitsubishi Corporation (Thailand), Chiyoda Corporation, and Mitsui OSK lines, with the Electricity Generating Authority of Thailand (EGAT) to jointly study the development of a supply chain for ammonia and hydrogen in Thailand's southern provinces, including production, storage, transport, and utilisation.

5 Conclusion

Japan has been at the forefront of global efforts to increase the role of hydrogen and ammonia as an option for supporting decarbonisation. Japan's government is positioning hydrogen as playing a large role in its overall decarbonisation strategy in support of its mid-century, net-zero emissions reduction goal. In this context, the Japanese government is supporting the development of technologies on both the supply and demand side, informed by its understanding of feasible decarbonisation pathways domestically and the industrial policy opportunities it has identified to promote Japan's technological leadership. Key features of Japan's strategy are the central focus on the need to import hydrogen and ammonia and the emphasis domestically on the use of hydrogen and ammonia co-combustion in existing thermal power generation as a transition technology, which is not emphasised in other countries' national hydrogen strategies.

In addition, the Japanese government is championing hydrogen and ammonia internationally through forums such as AZEC, which includes proposing ammonia as a technology option for reducing emissions from the power sector in the Asia–Pacific. A key near-term focus on the supply side is testing the feasibility of different technology options for hydrogen transport, based on the strong emphasis on hydrogen and ammonia imports within Japan's hydrogen strategy. Coupled with the potential for exporting technologies for hydrogen use, this suggests that new patterns of trade and investment may emerge, although there remain crucial questions about commercial feasibility in addition to technical challenges. Indeed, Japan's hydrogen strategy is predicated on the ability to build international supply chains at scale. These are currently being enabled by public investment in early-stage projects to test different technology options to enable the export of hydrogen to Japan to support domestic decarbonisation. Another challenge lies in unlocking hydrogen demand given that processes using hydrogen and ammonia remain more expensive than alternatives in most cases. A case in point is FCVs, in which consumer demand remains far lower than envisioned. In response, the Japanese government is developing a series of policies to reduce the gap between hydrogen and ammonia and best available technologies. The revised 2023 NHS also signalled a shift towards emphasising Japan's technology leadership in fuel cells and taking a more neutral approach towards end-use sectors. We can expect Japan's National Hydrogen Strategy to continue to develop in response to the effectiveness of policies implemented domestically and internationally to increase the demand for, and supply of hydrogen and associated vectors.

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The UK Hydrogen Strategy: Industrial Decarbonization and Industrial Policy

Silvia Weko

Abstract The UK hydrogen strategy aims at making the UK a leader in green industries and improving national energy security. Its "twin track" approach simultaneously promotes hydrogen from natural gas with carbon capture and hydrogen from low-carbon electricity. Despite the UK's initial focus on applying hydrogen to industry, it has since emphasized creating demand by using hydrogen for heating and transportation. Exporting hydrogen itself was not considered until relatively late, and potential connections to Europe have been pushed by industry rather than government. Given the rise in industrial policy measures including for hydrogen in other countries, the UK's goal of becoming a major hydrogen player seems unlikely without a significant change in policy clarity and ambition.

1 Introduction

The UK's position on hydrogen is firmly couched in industrial policy: hydrogen development was point 2 in the UK's 10-point plan for a green industrial revolution, launched in November 2020 in response to the economic downturn. This document, and the 2021 UK Hydrogen strategy, see hydrogen as an opportunity to develop an internationally competitive hydrogen industry within the UK. The strategy aims to use not only "green" hydrogen produced with renewable electricity, but also "blue" hydrogen with carbon capture and storage. It emphasizes the economic opportunities of hydrogen, especially for jobs in peripheral areas and for growing British industries in an emerging market. For this, the UK has emphasized exporting technologies and products, like propulsion technologies, electrolyzers, and fuel cells rather than hydrogen itself (UK Government, 2021, 2023a). This focus on industrial policy is

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R. Quitzow and Y. Zabanova (eds.), *The Geopolitics of Hydrogen*, Studies in Energy, Resource and Environmental Economics, https://doi.org/10.1007/978-3-031-84022-7_6

an important shift for the UK, where previous approaches to decarbonization were largely driven by legally binding emissions targets and prices.

Since the war in Ukraine, the UK doubled its hydrogen ambition to 10 GW of low-carbon hydrogen production capacity by 2030 citing the need for energy security—higher than most European countries. The goal is to use this hydrogen at home to build its competences in hydrogen services and applications. Although the strategy envisions industry as the main end-use sector, in practice significant support has gone to uses such as domestic heating, despite doubts regarding their relative inefficiency and emissions intensity (Howarth & Jacobson, 2021; Rosenow, 2022). While there are many green and blue hydrogen projects announced, final investment decisions are few and favor small-scale green hydrogen production projects. Further revenue support will be provided by levies on energy consumption, the future of which is still uncertain. Civil society and research have questioned why the government does not prioritize industrial uses and whether blue hydrogen deserves public sector investment. Critics argue that the government's hesitation to support industry will lead to the UK falling behind in the global green race for technological leadership, comparing it unfavorably to other players like Germany and Japan (UK E3G, 2023a; Steel, 2022a, 2022b).

The UK's focus on developing its internal hydrogen capacities rather than import is also reflected in its relatively limited engagement in the international arena. Its efforts are largely focused around increasing international hydrogen demand to promote a market for its technologies and encouraging foreign firms to invest in the UK. Unlike other European countries, it does not participate formally in dialogues on ports (Clean Energy Ministerial, 2020), and plans for hydrogen interconnections with Europe for hydrogen trade have been led by firms in the gas sector rather than the government (Project Union, 2022). Yet, since 2023, there is evidence for increased interest in hydrogen trade with Europe, and the UK government has increased its efforts to connect with selected European partners such as Germany and Norway. At the same time, the UK has increased its presence in dialogues around harmonizing regulatory standards to enable future trade.

The remainder of this chapter provides a detailed review of the UK hydrogen policy, including domestic and the emerging international elements. It first outlines the current state of the UK's climate and energy policy and reviews the status of hydrogen development. It then looks closely at the UK hydrogen strategy and policy, including key funding initiatives and the debate over hydrogen use prioritization. It elaborates on the external dimensions of the UK's hydrogen strategy, which is comparatively inward-facing, but nevertheless hints at a future interest in trade with the European continent. It then outlines key conclusions for international hydrogen politics.

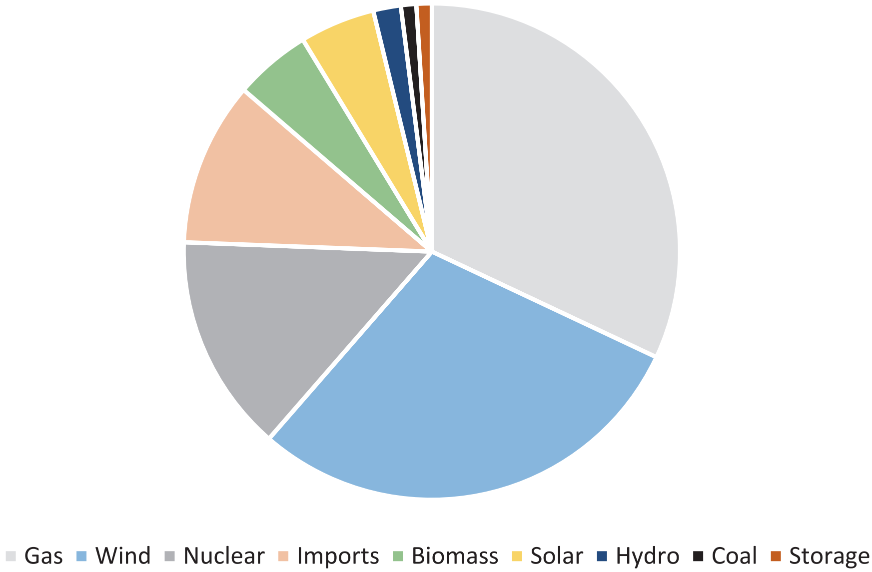

Fig. 1 Total UK electricity generation by source, 2023. *Source* Author, based on data from the UK National Energy System Operator

2 The State of Climate and Energy Policy in the UK

The UK has historically been a fossil-fuel producer and used its indigenous resources (coal, gas, and oil) to fuel its industries and ensure energy security. Following the discovery of oil and gas reserves in the North Sea in the 1970s, companies such as Shell and BP have gone on to become important players in the UK and the global political economy (Christophers, 2020). However, today most of the gas used in the UK is no longer produced domestically, but is imported from Norway and Qatar (EIA, 2022).[1] As domestic resources have fallen, the UK has increasingly focused on "low-carbon" options including nuclear and renewable energy. Its 2008 Climate Change Act established legally binding obligations to reduce emissions and respond to climate change; the UK is a leading member of the Powering Past Coal Alliance and aims to fully decarbonize its electricity system by 2035. In 2023, its electricity mix was dominated by renewables and nuclear (55%), with the remainder largely made up of gas (32%) and imports (11%) (see Fig. 1).

Before Brexit, the UK was closely aligned with the EU on the development of its electricity market, engaging in real-time electricity trade across the Channel and

[1] In 2021, the UK produced 934,000 barrels per day in total liquid fuels and 1.1 trillion cubic feet of natural gas. This travels to in pipelines to its 1.2 million b/d of refining capacity and is exported in the form of crude oil mainly to Europe, as well as refined motor gasoline and fuel oil (see also: UK EITI, 2022).

with Ireland. While energy trade continues, the UK's sometimes contentious relationship with the EU has impacted climate and energy cooperation. The UK's goal to re-negotiate rules on electricity trading and interconnections with the EU has been stymied due to the UK suggesting it would go back on its previous agreements regarding the Irish border (Kuzemko et al., 2022). A further blow to energy cooperation was the UK's announcement of a crisis contingency plan that would allow it to reduce energy exports if needed following the Russian invasion of Ukraine. Emergency measures would mean that National Grid could shut off interconnectors to Europe and stop gas flows (Lawson, 2022). In spite of this, there are promising signs for future energy cooperation. 2021 saw new electricity interconnections with Norway and France, and the UK imported large amounts of electricity from Europe (around 24.6 TWh), while exporting 4.2 TWh to Europe (Martin, 2022). Further cooperation can be seen in the UK's MOU with the North Seas Energy Cooperation—therefore effectively re-joining the group, although it can no longer be a formal member (Blondeel et al., 2022).

Beyond Brexit, the UK's climate and energy strategy faces increasing challenges, exacerbated by the 2022 energy crisis. Chief among them is decarbonizing heating: 85% of homes use gas for heating, accounting for 15% of the UK's carbon footprint (HoC, 2022). More gas in the UK is used by domestic consumers than any other user, including power generation (Mettrick & Ying, 2022). A further challenge for UK climate policy is industrial decarbonization of important industries including chemicals and pharmaceuticals, metals, and glass. The UK has a strong interest in maintaining these industries and has made efforts to balance decarbonization with industrial policy aims. Industry is supported with incentives to decarbonize, such as the Renewable Heat Incentive, which spent £684 million per year on commercial, industrial, and public premises in 2019–2020 alone. Industries are also given free allocations under the UK Emissions Trading System (ETS), including cement, steel, and chemicals.[2] The UK has increased its focus on industrial policy since Brexit, creating the Department for Business, Energy, and Industrial Strategy (BEIS) in 2016. Its mandate included "helping to ensure that the economy grows strongly in all parts of the country, based on a robust industrial strategy… it will make the most of the economic opportunities of new technologies, and support the UK's global competitiveness." (May, 2016) This is a shift in tone for the UK, which had not consistently prioritized competitiveness in low-carbon industries (Lockwood, 2022).

In 2023, the UK saw another shift in its ministerial landscape when BEIS was transformed into the Department for Energy Security and Net Zero (DESNZ), highlighting the renewed importance of energy security.[3] The UK is seeking to increase fossil fuel as well as hydrogen production. The government and UK Oil and Gas authority (now renamed the North Sea Transition Authority) portrayed the continued

[2] For full list 2021–2025 see https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1137620/uk-ets-allocation-table-november-2022.csv/preview.

[3] Although DESNZ has now replaced BEIS, most of the UK's hydrogen policy documents were published by BEIS. Therefore I occasionally refer to BEIS rather than DESNZ documents.

exploitation of fossil fuels as necessary for energy security. It also frames it as integral to the energy transition, since British fossil fuels have a lower carbon footprint (NSTA, 2022). In 2022, the government scrapped the moratorium on new fossil-fuel extraction that had been in place since 2019 and began licensing for new extraction including coal, fracked gas, and offshore oil and gas (Cavcic, 2023). The current Labor government does not plan on revoking these licenses, although they may be subject to legal action under the legally binding Climate Change Act. Hydrogen is therefore appealing for the UK as a way to address its energy security, decarbonization, and industrial development goals.

3 The Current Status of UK Hydrogen Development

The UK has taken a "twin track" approach where it promotes both blue and green hydrogen, with the hope that this can help address the difficulties of decarbonizing industry and heating. It defines "low-carbon hydrogen" as green hydrogen made with renewable electricity, blue hydrogen from natural gas with carbon capture and storage (CCS), and biomass and waste conversion with or without CCS.[4] It also remains open to other ways of generating hydrogen, i.e., from nuclear power.

Hydrogen is used at around 30 industrial sites in the UK with approximately 2.5 GW capacity (BEIS, 2022f). Of this, around two-thirds were by-products of industrial processes like oil refining and steelworks which were then used onsite (BEIS, 2022a, 2022b, 2022c, 2022d, 2022e, 2022f, 2022g, 2022h, 2022i, p. 24). The remaining third is produced via steam methane reforming without carbon capture and used as feedstock for ammonia production at a few large sites. BEIS therefore suggests that the hydrogen-producing sites could decarbonize by retrofitting their facilities with carbon capture technology subsidized by the Industrial Carbon Capture Business Model (ICC BM), a longstanding support scheme for industry which includes capital grants as well as revenue support (BEIS, 2022b). Those sites that currently generate hydrogen for ammonia production could instead purchase low-carbon hydrogen. According to a government report in 2021, less than 1% of hydrogen production capacity in the UK was from electrolysis (BEIS, 2021c, p. 117).

Before it launched its official hydrogen strategy, the UK government funded several programs targeting hydrogen production and use. The ultra-low emission vehicles in the UK package of £500 million, which ran from 2015–2020, included funding for hydrogen use in transport (DfT, 2014). Further projects, like the hydrogen-powered double decker buses for London, received additional co-funding from the EU. In addition, the BEIS Energy Innovation Program, which ran from 2015 to 2021, funded several low-carbon hydrogen projects. These included the 2018 low-carbon hydrogen supply competition, which received £33 million in funding

[4] According to the April 2023 "Low Carbon Hydrogen Standard"; to be considered low-carbon, hydrogen must have a GHG emissions intensity of 20 g CO_2e/MJLHV of produced hydrogen or less.

to develop hydrogen supply projects that could improve carbon capture rates or lower prices for other forms of "low-carbon" (electrolytic or other) hydrogen (BEIS, 2022i). Another keystone project was the £25 million Hy4Heat project, launched in 2017. The project aimed to establish whether residential and commercial gas could be replaced with hydrogen in homes and businesses and included community trials (DESNZ, 2023a).

Here, it is important to note that the "devolved administrations" of Scotland, Wales, and Northern Ireland have their own hydrogen strategies, interest groups and developments. Several flagship hydrogen projects took place in Scotland, and the Scottish Government published its own hydrogen policy statement in December 2020 before the UK, as well as developing a Hydrogen Action Plan and £100 million investment program. Similarly, the Welsh government has published different hydrogen documents and is home to large wind farms and industrial collaborations. Northern Ireland has also received EU and UK funding for hydrogen transportation projects and has favorable hydrogen production and storage conditions. While acknowledging that the UK hydrogen strategy may be informed by the activities of devolved administrations as well as other local actors, the focus in this chapter is the UK's government hydrogen strategy.

With the election of a new government in July 2024, the UK's hydrogen strategy may yet shift significantly. For example, Keir Starmer pledged during his campaign to double the UK's green hydrogen target to 10 GW (Parkes, 2023), and a key point of Labor's manifesto is "making Britain a clean energy superpower" (The Labor Party, 2024) seeking to increase renewable energy installation and supporting green hydrogen. Similarly, the government aims to set up "Great British Energy," a publicly-owned energy production company to drive the transition (UK Government, 2024a). However, the precise ways in which the UK's hydrogen strategy may evolve was not yet decided at the time of writing (September 2024). This chapter therefore primarily focuses on what has been done by the previous Conservative government; further work can explore the ways in which Labor's approach differs—or not—once more concrete measures have been put into place.

4 UK Hydrogen Policy: An Inward-Facing Strategy

4.1 Hydrogen Policy Overview

DESNZ is the most important actor in UK hydrogen policy and is responsible for roadmaps related to hydrogen use, such as industrial decarbonization, heating, and transport. The strategy for the UK's hydrogen policy was established by the Ten Point Plan in November 2020. It defined a target of 5 GW of low-carbon hydrogen production capacity by 2030 and launched the Net Zero Innovation Portfolio of £1 billion, to be shared across priority areas, which include hydrogen. The government's stance established in the Ten Point Plan is that green hydrogen will be more expensive than blue hydrogen in the short term—which it has not changed despite rising gas prices since the Russian invasion of Ukraine (BEIS, 2021a).

The 2021 Hydrogen Strategy specifies the next steps for hydrogen and its use in hard-to-decarbonize sectors. It projects that hydrogen could make up between 20 and 35% of total final energy consumption by 2050. The goals of the hydrogen strategy are clearly stated as green industrialization, good jobs, and technological leadership. For example, by 2030, the UK aims to develop four industrial clusters ("SuperPlaces"). Under the scheme, sites in northern England, Scotland, and Wales with automotive manufacturing, steel and chemical production will receive funding for the deployment of carbon capture and storage technologies. The goal is to maintain these industries in the UK, while creating a new carbon capture and storage industry with an estimated 50,000 jobs by 2030. The aim is to support "good jobs" and address deindustrialization in the UK heartland. The strategy does not express an interest in exporting hydrogen in the shorter term, but rather stimulating domestic supply chains which could then create export opportunities for UK businesses serving international demand for goods and services (BEIS, 2021c, p. 8).

As tensions with Russia increased, so did the UK's focus on energy security and the importance and ambition of its hydrogen targets. In the British Energy Security Strategy, launched in 2022, the government announced that it was doubling its low-carbon hydrogen ambition to 10 GW by 2030, at least half of which should be electrolytic, and introduced an interim target of 1 GW of electrolytic hydrogen to be under construction or in operation by 2025 (BEIS, 2022a). Yet at least in the short term, the natural gas used for blue hydrogen would largely be imported. The energy security strategy estimates that there are 7 years of gas reserves remaining in the UK, including "yet to find" resources (IEEFA, 2022). Therefore, only green hydrogen production could be conceived of as contributing to UK energy security.

The July 2022 Hydrogen Update to the Market lays out a strategy to reach these 10 GW and has an increased focus on energy security, while maintaining its industrial policy framing. Moreover, it states that industrial hydrogen producers will be sufficiently incentivized by the Industrial Carbon Capture Business Model (ICC BM) and the ETS to decarbonize. It therefore concludes that there is no need for a previously envisioned phaseout plan for carbon-intensive hydrogen nor a research and innovation facility for hydrogen use in industry (BEIS, 2022f, p. 8). This document only briefly mentions the potential to export excess low-carbon hydrogen, retaining its focus on developing domestic hydrogen production and use. Outside of the UK, hydrogen trade—both imports and exports—is not foreseen until after 2030, but continental Europe is named as a potential partner. A further update to the market, issued in December 2022 (BEIS, 2022e), mainly highlights the importance of building local markets, while mentioning that the UK could eventually export hydrogen to Europe. This document adds that this interconnection could also be used to import hydrogen to build supply chain resilience.

The government's approach to hydrogen exports appears to further shift toward exports in August 2023, stating that "We want to play a key role in exporting hydrogen to others, including to continental Europe where we see increased hydrogen demand, alongside established energy trading and interconnection with the UK" (DESNZ, 2023b, p. 18). To enable this trade, the government is aiming to develop legal frameworks for connecting hydrogen produced offshore to Europe via pipeline (DESNZ, 2023c). However, in terms of official plans for infrastructure, the government is still letting business lead the way (see Sect. 5.4).

Also in 2023, the government took a more concrete position on hydrogen transmission and storage infrastructure, arguing that the future system operator should "take on a central strategic planning role" (DESNZ, 2023d, p.7). However, problems with infrastructure planning remain due to uncertainties about hydrogen use cases which will influence what infrastructures are needed. A 2022 study (BEIS, 2022d) commissioned by the Government illustrates this issue. Its estimates of infrastructure requirements vary significantly depending on what uses are foreseen for hydrogen. For example, it estimates that between 0.6 and 13.2 TWh of salt cavern storage and anywhere between 700 km and 26,000 km of pipeline would be needed by 2035, depending on the chosen end-use scenario. 24,750 km of potential transport infrastructure is estimated for hydrogen use in buildings alone. This differs again from the plans proposed by the UK's National Grid plc and National Gas Transmission (NGT). Their "Project Union," which focuses on connecting key industrial clusters, would be 2000 km, equivalent to approximately 25% of the UK's current gas pipelines. They claim that repurposing existing pipelines to connect clusters in England, Wales, and Scotland would be up to five times more cost-effective compared to new build (Project Union, 2022, p. 8).

The UK hydrogen strategy sees hydrogen as "essential for achieving net zero," though sustainability elements seem to play a less important role in the policy's framing than industry development and energy security. Nevertheless, the April 2023 UK low-carbon hydrogen standard sets a maximum threshold for emissions intensity of hydrogen production that is lower than that agreed by the EU. It sets a maximum a GHG emissions intensity of 2.4 kg CO_2e per kg of hydrogen to be considered "low carbon," and therefore able to participate in funding initiatives (DESNZ, 2023e).[5] In addition, the UK Environment Agency publishes guidance on green and blue hydrogen production techniques (UK Government, 2023b, 2024b). Companies applying for an environmental permit to produce hydrogen may follow these best practices, or propose an alternative approach to the regulator, which has the same or greater level of protection to the environment.

In general, the hydrogen standard and strategy consider blue hydrogen as an important option, and the narrative in policy documents and discourse is that the government will not pick winners but enable both pathways. A further narrative is that blue hydrogen will enable the scale-up of innovations in carbon capture and storage, which will be an important local industry. Civil society and think tanks have publicly criticized this stance on blue hydrogen and urged the government to focus on green hydrogen. While the UK Committee on Climate Change (CCC) sees a role

[5] The original standard has been updated, with the main substantive difference that there are now more eligible hydrogen production pathways, including 'gas splitting producing solid carbon'. See https://questions-statements.parliament.uk/written-statements/detail/2024-01-29/hlws211.

for blue hydrogen in reducing emissions, they note that the use of blue hydrogen would need to be reduced beginning in the late 2030s (Ambrose, 2021).

Data on the current project pipeline are difficult to find. The UK Government's Hydrogen Investment Roadmap, published in February 2024, estimates a potential cumulative production capacity of over 25 GW by 2030, based on the known pipeline of over 250 hydrogen projects (UK Government, 2024c). While it does not share specific information on these projects, the pipeline appears to be dominated by green, rather than blue hydrogen: by 2030, the estimated production capacity for electrolytic hydrogen is around 17 GW, versus just under 10 GW of CCUS-enabled hydrogen. This would represent a major shift from a report published a year prior, where the UK's hydrogen pipeline consisted of 84% blue hydrogen projects, none of which had achieved FID at that time, however (Westwood Global Energy Group, 2023).

4.2 Key Funding Initiatives

In order to develop hydrogen markets, the government has support mechanisms along the value chain. The first is funding innovation and demonstration projects. The second are capital subsidies for hydrogen production projects on the small to medium scale. Finally, the government will also provide revenue support to hydrogen production projects via the Hydrogen Production Business Model. This contract-for-difference-style program guarantees revenues, thereby aiming to provide certainty for investors, with the first round promising £2 billion in support. Of this, £90 million will come from the Net Zero Hydrogen Fund (NZHF), while the rest will be funded by the so-called hydrogen levy, though the exact design of this remains uncertain. At a later stage, the government may also provide subsidies for hydrogen transport and storage. A large share of funding for hydrogen innovation and demonstration projects come from the £1 billion Net Zero Innovation (NZIP) portfolio. This funding was announced by Boris Johnson in 2020 as part of his plan for a "green industrial revolution" and promotes a broad swath of technologies such as wind and CCS, as well as hydrogen (including the £240 million NZHF). Additional schemes for industrial decarbonization and CCUS also include hydrogen-related technology development (see Table 1).

In the innovation sphere, the main goal of funding schemes is to increase technology-readiness levels (TRLs) for developing technologies. Key partners here include UK Research and Innovation (UKRI) which mainly focuses on engineering and physical sciences funding for lower TRLs, through lab-based research. The Innovate UK program, which supports scaling-up solutions with higher TRLs that are not yet commercially viable. The UK government is also supporting local technology manufacturing with the £960 million for a Green Industries Growth Accelerator, which includes funding for several low-carbon technologies such as nuclear, CCS, and offshore wind as well as hydrogen. According to news reports in March 2024, this funding may be increased to £1.1 billion in the UK's Spring Budget (Norris, 2024).

Table 1 Key UK funding initiatives including hydrogen

Funding Program	Amount	Funding source	Description
Hydrogen-specific funding initiatives			
Net zero Hydrogen fund (NZHF)	£240 million	NZIP	Innovation, DEVEX, and CAPEX support
Hydrogen production business model	First round provides £2 billion	Government-funded until hydrogen levy comes into effect. Round 1 (£2 billion draws £90 million from NZHF)	Revenue support based on contract for difference-style long-term agreements, funded by Government likely until 2025 (DESNZ, 2023f). First round promises £2 billion in support, 7 rounds total planned until 2029
Hydrogen transport business model	Unknown	Unknown	Feedback closed February 2024, to launch in 2025. Will apply to onshore large-scale piped infrastructure; may include subsidy (Hydrogen Transport Revenue Support Contract)
Hydrogen storage business model	Unknown	Unknown	Feedback closed February 2024, to launch in 2025. May include minimum revenue floor (and/or cap on revenue "Hydrogen Storage Contract". Funding source unknown, potentially levy-based
Low-carbon hydrogen supply 2 competition	£62 million allocated	NZIP	Innovation projects for hydrogen supply
Hydrogen BECCS innovation program	£31 million allocated	NZIP	Innovation in hydrogen BECCS (bioenergy with carbon capture and storage) technologies
Industrial hydrogen accelerator program	£26 million, £13 million allocated	NZIP	Innovation projects for industrial fuel switching
Hydrogen research hubs	£20 million	UKRI Engineering and Physical Sciences Research Council (EPSRC)	Investment in hydrogen research hubs: UK-HyRES Hub and HI-ACT Hub (£10 million each)
Hydrogen storage and distribution supply chain collaborative R&D competition	£4.35 million	Innovate UK	Funding collaborative research and development projects aimed at developing hydrogen supply chains (December 2023 Hydrogen update to market)
Hydrogen innovation initiative (Hii) seed program	£6 million	Innovate UK	R&D collaboration with UK research partners

(continued)

Table 1 (continued)

Funding Program	Amount	Funding source	Description
Hydrogen storage and distribution supply chain collaborative R&D	£4.2 million	Innovate UK	R&D projects related to hydrogen storage and distribution supply chain
Hydrogen skills and standards for heat	Over £2 million	NZIP	Defining safety criteria to repurpose natural gas equipment for hydrogen and train a workforce of hydrogen installers (HVP, 2021)
Other funding initiatives that may include hydrogen			
Direct air capture and greenhouse gas removal program	£10 million allocated to hydrogen	NZIP	Funding for developing technologies that enable the removal of greenhouse gases from the atmosphere
longer duration energy storage	Up to £68 million for all technologies	NZIP	Innovation competition for longer-duration energy storage including power-to-X
Industrial Energy Transformation Fund (IETF)	£289 and £185 million for all technologies	IETF	Support for energy-intensive industries to invest in energy efficiency and low-carbon technologies. Hydrogen fuel switching is only covered under the IETF if industry will switch to hydrogen in the next 5 years (DESNZ, 2023g). IETF extension announced in the Powering Up Britain plan, increasing total grant funding by £185 million
Red diesel replacement competition	£40 million for all technologies, £26 million allocated to hydrogen	NZIP	Innovation competition for low-carbon fuel and system alternatives to red diesel construction, and mining and quarrying sectors
Industrial fuel switching	£57.5 million total, of which 23 million for hydrogen	NZIP	Industrial fuel switching 2 competition has devoted 23 million to hydrogen spending
Green distilleries competition	£12.33 million for all technologies, £6 million allocated to hydrogen	NZIP	Innovation competition for using low-carbon fuel in distilleries

(continued)

Table 1 (continued)

Funding Program	Amount	Funding source	Description
Local industrial decarbonization plans competition	£5 million available for all technologies	Industrial Decarbonization Challenge	Funding for local clusters to develop strategic industrial decarbonization plans and explore technological solutions (some awarded plans include hydrogen)
Clean maritime demonstration competition rounds 1–4	£95 million + £34 million for all technologies	UK Shipping Office for Reducing Emissions (UK SHORE) program	3rd round: 19 projects to conduct technology and system demonstrations in clean maritime solutions, with six projects exploring the use of hydrogen and/or hydrogen-derived fuels. 4th round's scope includes hydrogen as well. (December 2023 Hydrogen update to market)
Clean maritime research hub competition	£7.4 million for all technologies	UK SHORE and Physical Sciences Research Council	Early research in clean maritime applications, including hydrogen-based, to run until 2027
Zero-emission vessel and infrastructure (ZEVI) competition	£77 million for all technologies	UK SHORE and Innovate UK	Funding to accelerate the roll out of zero-emission solutions for vessels and port-side infrastructure that are nearing commercialisation. Hydrogen and hydrogen-related fuels are in scope
Zero-emission heavy goods vehicles and infrastructure demonstrators	£140 million for all technologies of which £85 million for hydrogen	Innovate UK	Funding for research and development fund aimed to increase zero-emission road freight in the UK
Advanced fuels fund	£165 million available, £135 million allocated for all technologies	Advanced Fuels Fund	Support for UK SAF projects through to construction
Advanced propulsion center's (APC) collaborative R&D competition, Round 22: Zero-emission vehicles project	£77.1 million for all technologies	£38.4 million from APC, £38.7 million from auto industry	Funding to develop clean transport technologies. Five projects funded will use hydrogen technologies

(continued)

Table 1 (continued)

Funding Program	Amount	Funding source	Description
Tees valley hydrogen transport hub fund	up to £15 million available	Tees valley hydrogen transport hub fund	Green hydrogen infrastructure for heavy goods vehicles like delivery trucks; and creating hydrogen-powered airport ground-based support vehicles
Green industries growth accelerator (GIGA)	£960 million for all technologies	Strategic manufacturing sectors fund (£4.5 billion total)	Manufacturing support for UK clean energy supply chains: includes carbon capture, utilization and storage, electricity networks, hydrogen, nuclear and offshore wind. May be increased to 1.1 billion
CCUS Infrastructure Fund (CIF)	£1 billion	CIF	Funding for carbon capture projects for industry and power; and for transport and storage networks
Industrial decarbonization challenge (IDC)	£210 million	Industrial strategy challenge fund, CIF	Funding for industrial decarbonization including hydrogen deployment, cluster plans, and innovation. Of this, £40 million provided by CIF
Transition export development guarantees	Unknown (but at least ~ 450 million in loans reported)	UK Export finance	Loan guarantees for working capital, capital expenditure or R&D for clean energy, hydrogen and decarbonization (BEIS, 2021b). Total sums unknown. Examples in December 2023 Hydrogen Strategy Update include underwriting a £400 million loan to global multinational Johnson Matthey for R&D, and a £50 million to boost exports of electric and hydrogen-powered buses

Source Author's own compilation based on government documents

When technologies are commercially viable, funding is also provided to encourage production with CAPEX support via the NZHF, although larger-scale transport and storage are not included in these funding mechanisms. In 2023, the NZHF announced its selection of projects to receive over £58.9 million in total for hydrogen production (DESNZ, 2023h). Of the 22 successful applicants, only two projects were for blue hydrogen, while the rest were for green hydrogen from renewable energy.[6] Of

[6] Note: The only exception is the project "Tees Green Methanol" which will produce hydrogen from EDF's existing nuclear capacity and new-build wind and solar, and captured biogenic carbon.

the projects with formal offtake arrangements, most were for transportation (buses, trucks, port machinery, and local transport fleets). Only two went to industry: one for TATA Chemical Europe (Green Hydrogen Winnington and Middlewich) and another for Pilkington UK's glass production (Green Hydrogen St Helens). Further projects aim to provide industry with hydrogen but did not have formalized offtake agreements at the time of research. Support for blue hydrogen production may also be provided by the CCS Infrastructure Fund, but precise amounts are not yet determined. As of August 2024, negotiations between the UK government and developers were ongoing for the two blue hydrogen projects being considered: BP's Teesside project and Hynet HPP1 (BP, 2024; DESNZ, 2023i).

The UK government is further scaling up its support for hydrogen via its Hydrogen Production Business Model (HPBM).[7] This bears strong similarities to the Contracts for Difference (CfD) model utilized in support of renewable electricity generation in that it is used to cover the difference between the cost of production and the sale price of hydrogen. Projects may only receive subsidies if they meet the requirements of the low-carbon hydrogen standard and if hydrogen is sold for certain qualifying purposes, i.e., power generation, transportation, or industrial use. Export or blending into the gas grid are not eligible (BEIS, 2022i). In early 2024, the winners of the first round of the HPBM were announced ("Hydrogen Allocation Round 1"). This includes 125 MW of capacity for 11 projects, with a total allocation of £2 billion in revenue support; of this, £90 million come from the NZHF (DESNZ, 2023j). The strike price agreed upon by the government is £241/MWh, which is weighted by the total volumes expected to be produced over the contract's lifetime and will vary relative to changes in natural gas prices. Set for 2025, the second allocation round aims to award 875 MW. This is "subject to affordability and value for money," if the same strike price is agreed upon, this would be around £14 billion in revenue support. In total, seven rounds are planned until 2029. The government has committed to covering HPBM costs until 2025, after which alternate funding will be used. A first suggestion was a levy on energy consumption which did not rule out households. Following a backlash from civil society to this plan (Dyson & Britchfield, 2023), the Energy Act scrapped these plans and specified that the relevant market participants are gas shippers, although it leaves further details to secondary legislation.

In addition to support for hydrogen production, the government also has plans to subsidize hydrogen storage and transport. As of mid-2024, the Hydrogen Transport and Hydrogen Storage Business Models were still in planning, with the first allocation rounds foreseen in 2025. For both of these support schemes, the funding sources are unknown but could also be levy-based. Different potential designs have been debated. For hydrogen transport, which would apply to onshore large-scale piped infrastructure, subsidies would be negotiated in a "Hydrogen Transport Revenue Support Contract." For hydrogen storage, a similar contract would be negotiated, potentially including a minimum floor or a cap on revenues with the goal of supporting

[7] Note: the HBPM was formerly called the Hydrogen Business Model (HBM), which was split into separate business models for production, transport and storage.

2 geological storage projects by 2030. This will make up part of a "core hydrogen network" which should help to build competitive markets (UK Government, 2024c).

A new development following the election of the Labor government in 2024 is the proposal of a National Wealth Fund of £7.3 billion, which is aimed at boosting infrastructural investment. Of this, 2.5 billion is intended to finance "clean steel" and 500 million for green hydrogen (Makortoff, 2024). The 7.3 billion for this fund should come from the Treasury, based on a new tax on oil and gas companies. Further details on the bank's structure and funding will be announced in October 2024 at the UK's International Investment Summit (UK Government, 2024d).

4.3 Hydrogen Use Prioritization: Heated Debates

The UK Hydrogen strategy does not set out clear priorities for which sectors should use hydrogen by when, with the reasoning that it does not want to rule out important opportunities. However, its strategy has been accused of being influenced by lobbying interests, as well as criticized for its potentially harmful impacts by civil society.

The 2021 strategy suggests that hydrogen can be used in sectors where electrification is too costly or not feasible, and other decarbonization options are limited, listing examples such as industrial furnaces and heavy transport (BEIS, 2021c, p. 9). Industry is expected to lead the way in early hydrogen use, including fuel switching in the mid-2020s and playing a key role in industrial decarbonization by the mid-2030s. The greatest demand for low-carbon hydrogen is expected by the UK hydrogen strategy to come from the chemicals and steel industry before 2030 (BEIS, 2021c, p. 54). Currently, the chemical and pharmaceutical industry targets emissions reductions of 90% by 2050 based on access to hydrogen, clean electricity, and CCS (CEFIC, n.d.). In 2022, the industry lobby group UK Steel said that switching to hydrogen before 2050 would not be feasible unless there is government support across the value chain to promote R&D and reduce the cost of electricity, hydrogen, and infrastructure (UK Steel, 2022a, 2022b). In the meantime, Tata Steel announced in 2024 that it would close both its blast furnaces and replace them with an electric arc furnace, which is expected to start production in 2027 (Varriale, 2024).

The UK's hydrogen strategy also argues that hydrogen is useful in areas where gas is now used, such as flexible power generation and storage, and envisions hydrogen use for flexible power generation by the late 2020s, as well as for heavy transport and domestic heating, potentially also via blending into the gas grid (BEIS, 2021c, pp. 9–10). The government has decided to allow gas and hydrogen blending of up to 20%, pending the outcomes of industry trials around safety, and will decide on whether hydrogen will be used for heating—in 2026. The decision on hydrogen for heating is contentious. In 2023, the UK's National Infrastructure Commission has recommended to exclude support for hydrogen in residential heating (UK National Infrastructure Commission, 2023). Despite growing public backlash and a number of trial cancellations, the Conservative government continued to push hydrogen for home heating (Harvey, 2023a, 2023b), while the new Labor government has not developed a clear position on this. In addition, in 2022 the government launched a £20 million competition at the Tees Valley Transport Hub which trials hydrogen use for transport and refueling facilities. While such projects fit into the approach of creating "hydrogen markets" within the UK to stimulate demand, they do not fit with the strategy of prioritizing low-regret and strategically important options like industrial decarbonization.

This stance on creating markets for hydrogen by using it for heating and transport has been supported by coalitions of politicians and industry actors. The UK Hydrogen and Fuel Cell Association embraces hydrogen production from all sources and sees hydrogen as playing a valuable role in heating UK buildings. From the public sector, the All-Party Parliamentary Group (APPG) on hydrogen describes itself as "a cross-party group of MPs and Peers that focuses on raising awareness of and building support for large-scale hydrogen projects—such as conversion to a hydrogen domestic gas grid." The administration's secretariat is funded by a list of companies with stakes in influencing hydrogen policy, including gas distribution networks, fossil-fuel companies, and chemicals and engineering corporations such as Bosch and Johnson Matthey.[8] The Chief Executive of Johnson Matthey's Catalyst Technologies business, Jane Toogood, was appointed the government's Hydrogen Champion and co-chairs the Hydrogen Delivery Council alongside the Minister for Energy Efficiency and Green Finance (see Box 1). In her role as Hydrogen Champion, Toogood acts as an independent expert advisor through engagement with industry and investors to enable blue and green hydrogen projects. Toogood has promoted even further government support for CCS and the blending of gas into the national grid and use of hydrogen for heating to create markets for hydrogen and therefore increase demand (DESNZ, 2023k).

The UK Hydrogen Delivery Council

The UK Hydrogen Delivery Council (formerly Advisory Council) is a forum for ministerial engagement with key hydrogen sector actors. Its representatives skew toward actors with an interest in maintaining fossil-fuel systems, including:

- Fossil-fuel extraction representatives (Shell, BP, Equinor)
- 2 industrial gases representatives (BOC Linde, Inovyn)
- 1 CCS firm (Storegga)
- 1 project developer for blue hydrogen and hydrogen heating (Progressive Energy)
- 2 gas network representatives (National Gas, Director of Gas of Energy Networks Association)

[8] In further detail: Equinor, Shell (fossil-fuel companies); Cadent, Northern Gas Networks, SGN (gas distribution networks); EDF and national grid (energy suppliers); Baxi, Energy and Utilities Alliance (gas and boiler firms). See: https://connectpa.co.uk/wp-content/uploads/2022/03/scan.pdf.

In comparison, actors with an interest in developing green hydrogen are relatively minor:

- 1 wind representative (Orsted)
- 1 electrolyzer manufacturer (ITM power)
- 1 green hydrogen supply and distribution company (Ryze)
- 1 green renewable energy supplier (Octopus Energy)

There are also some actors, who have interests in both green and blue hydrogen, with stakes in CCS within the UK. These include:

- 3 energy and energy technology firms (SSE, Siemens Energy, RWE)
- 2 representatives from chemicals and engineering firm Johnson Matthey
- 2 investors (Mitsubishi UFJ Financial Group, Macquarie Capital)

Finally, there are some non-industry actors:

- 3 UK State actors: Minister for Energy Efficiency and Green Finance, UK gas and electricity regulator Ofgem, UK Infrastructure Bank
- 1 Research director (Imperial College).

Source Own research on hydrogen positions using company materials and news sources.

The government's stance on hydrogen end uses has been criticized by civil society, especially researchers, and the UK Climate Change Committee, the independent statutory body established under the Climate Change Act 2008 to advise governments and report to Parliament on progress. In their March 2023 report on decarbonizing power systems, the CCC recommended that the government commit to a cross-sectoral infrastructure strategy and focus on low-regrets hydrogen use, while identifying areas where hydrogen is unsuitable and electricity can be used instead (Climate Change Committee, 2023). The House of Commons cross-party Science and Technology Committee, which was appointed to examine science policy and administration, has also expressed doubts on the current approach to heating and questioned its economic viability (HoC, 2022). In the same report, a representative of the UK Mineral Products Association said that it was important to use low-carbon hydrogen for industry because heating and transport can be electrified, whereas cement and lime production cannot be (p.32). Likewise, the UK's National Infrastructure Commission strongly recommended that the government rule out the use of hydrogen for heating.

Civil society organizations focused on sustainability, like E3G, also highlight the importance of no-regret industrial uses, versus uses which could be replaced by electrification. Further coalitions including affected communities, renewable energy companies and associations, and sustainability organizations have publicly opposed hydrogen for heating and gas blending (see for example E3G, 2023b; Harvey, 2023a, 2023b). Some have also argued that the UK's hydrogen policy has been influenced by fossil fuel and industry lobbying. The former head of the UK Hydrogen and Fuel Cell Association, Chris Jackson, resigned in July 2021 after accusing fossil-fuel companies within the association of making false cost estimates for blue hydrogen production to access billions in taxpayer subsidies (Ambrose, 2021). In 2022, the Guardian reported that there were over 120 paid hydrogen lobbyists operating in Parliament, from multinational oil companies like Shell and BP to smaller hydrogen companies like Ryze (Harvey, 2022).

4.4 Positioning the UK's Hydrogen Industry: Strengths and Weaknesses

To emerge as a hydrogen leader, the UK's strategy highlights a few key points, which would make the UK competitive: its physical advantages for hydrogen production such as energy resources and storage infrastructure; its local demand for hydrogen in industry, and its skilled labor and innovative capacity. Compared to other northern European countries, its project announcements of almost 2.2 Mt by 2030 could make it a leader in production capacity if these reach final investment decisions.[9] Yet, its current policy approach has been criticized by different actors as lagging behind other countries. Inaction on setting strategic priorities, they suggest, can lead to the UK losing its competitive advantage.

The Ten Point Plan and Hydrogen Strategy see the UK's renewable energy potential, especially its offshore wind capacity, as an important advantage in its role as a future green hydrogen producer. The UK has the further geological advantage of good storage potential. Salt caverns, which are geologically relatively rare in other locations in Europe, have been positively assessed in the UK (Williams et al., 2022). This would give the UK a comparative advantage vis-à-vis countries where hydrogen cannot be stored for longer periods. When it comes to blue hydrogen, offshore gas resources, and gas transportation infrastructure are seen as a potential advantage. Disused oil fields in the North Sea are suggested as an opportunity to store carbon from CCS and ease the North Sea transition by re-using existing infrastructure and resources (DBT, n.d.).

Another advantage laid out in government documents is the UK's existing expertise in hydrogen use and the ability to draw on a skilled workforce and well-developed innovation system. Unlike other countries without extensive industry such as chemicals manufacturing and refining, UK firms are experienced in working with hydrogen and can be first movers in adopting this technology. They can also draw on skilled workers in industries that will use hydrogen (chemicals, steel) and industries that will eventually produce hydrogen (oil and gas, renewables) as well as the broader high-skilled labor pool for training and recruiting new workers (see for example CEFIC, n.d.). One of the world's leading electrolyzer manufacturing firms (ITM Power) is also based in the UK, and recently announced its plans to expand capacity (ITM

[9] NW hydrogen report – but important to note that none of these have reached FID, unlike in other countries, and that they are overwhelmingly for blue hydrogen projects (IEA, 2022a).

Power, 2023). More broadly, the UK possesses innovative advantages, due to its long-standing, publicly supported research and innovation infrastructure. Taken together, its industrial experience, skilled labor, and strong innovation system are envisioned as making the UK a leader in adopting low-carbon hydrogen and eventually exporting goods and services.

In parallel to this, the UK hydrogen policy also acknowledges trade-offs between a policy focused on keeping short-term hydrogen costs low and establishing durable competitive advantages to create local industry:

> We recognize that there may be trade-offs within and between some of these principles. For example, the levelized cost of hydrogen using electrolytic production technology is higher today than for CCUS-enabled hydrogen, and it will take time for production to reach industrial scale. That said, with the right support today, this technology presents a genuine opportunity for export of UK expertise and technology, and there is also significant potential for longer-term cost reduction with continued innovation, scale-up of manufacture and access to increased amounts of low-cost renewable electricity. (BEIS, 2021c, p. 18)

By maintaining a broad policy approach—devoting time and funding to both blue and green hydrogen and supporting a wide array of use cases from household heating to transport—the government risks its engagement in hydrogen remaining too shallow and scattered to truly establish advantages. Given that green hydrogen manufacturing competition from Europe is seen as a potential threat to the UK's supply chain position, Wood Mackenzie's analysis for BEIS also suggests supporting electrolysis manufacture and other key technologies (BEIS, 2022h, pp. 81–82). Manufacturing has not been a central focus of the UK's strategy despite its leading electrolyzer manufacturer struggling with supply chain issues and financial difficulties (IEA, 2023)—although new funding for manufacturing from GIGA could eventually begin to address this gap.

Other potential disadvantages of the UK hydrogen landscape are its starting position in terms of innovation and comparatively low levels of funding. The IEA's patent analysis reveals that Japan, the US, Germany, Korea, France, and China all have higher shares of hydrogen-related patents than the UK (IEA, 2023). The only realm where the UK comes close to other economies is for patents in the realms of methanol production and aviation fuels. Out of the top ten global hydrogen innovation clusters, none are in the UK (IEA, 2023, p. 30). A separate Mission Innovation analysis of hydrogen publication outputs shows that although the UK ranks among the top ten in publications on certain value chain areas, it does not make the top ten for publications overall. The same report shows that the UK has committed comparatively little public funding for hydrogen development, and even less for R&D funding.[10] In addition, some existing domestic funding has also not been able to reach recipients: BEIS returned £1.6 billion in unspent R&D funding to the UK treasury in February 2023 (The Engineer, 2023).

[10] These segments are hydrogen production, and storage and distribution (it does not rank overall or for utilization) (Delaval et al., 2022a, p. 8).

Different actors have therefore argued that the UK's lack of clear policy choices and leadership will result in other countries pulling ahead in the "green race." Interestingly, this narrative emerges from different camps (blue vs green, either/or). For example, the UK Steel Net Zero strategy argues that the UK is being left behind in the race toward Net Zero, as they perceive the UK as less supportive than France, Germany, and Canada (British Steel, 2022; UK Steel, 2022, p. 49). Sustainability NGO E3G describes recent policy packages as unlikely to convince investors that the UK will be a leader in the green industrial revolution (E3G, 2023a). The House of Commons Science and Technology Committee, which gathered evidence from different stakeholders, also highlights that the Government's aversion to making decisions on technologies creates a risk of pursing the wrong technologies. It requests that the Government set out clear criteria to identify the potential role of hydrogen in each sector (HoC, 2022, p. 63). The report also summarizes feedback on how the UK compares to other hydrogen leaders, which is not favorable: the policy support in the US, Europe, and Asia enables other countries to build future export industries, while the UK risks falling behind (see for example pp. 56–57, 63–64). Some comments also draw lessons from the UK's failure to retain key parts of the renewable energy industry and want to ensure that the same does not happen for hydrogen.

5 External Dimensions of the UK Hydrogen Strategy

The UK government's hydrogen policy is based on building up a local hydrogen supply and market, placing less emphasis on trade in hydrogen with other countries. The 2021 hydrogen strategy has no substantial international dimension, and exports are only briefly mentioned in policy documents as a potential long-term option once a robust local hydrogen economy is developed. The government's support for hydrogen production does not extend to projects that will export hydrogen, and it has also been less active than other European counterparts in pursuing international partnerships on hydrogen trade. Instead, the most important engagements with the international sphere are setting standards for what constitutes low-carbon hydrogen and increasing investment into the UK hydrogen economy from international actors. Despite this lack of government action on developing international hydrogen trade, private UK gas firms are pushing for greater connections with the European continent via the European Hydrogen Backbone.

5.1 Diplomacy and Political Dialogue

At the international level, the UK has promoted hydrogen at the G7, G20, and the United Nations Framework Convention on Climate Change (UNFCCC). Its G7 presidency in 2021 was the first to achieve a statement of support for the role of low-carbon hydrogen, which became the basis for the so-called Hydrogen Action

Pact (according to BEIS, 2022e). At COP26, the UK led the launch of the Breakthrough Agenda, which included a hydrogen component ("Hydrogen Breakthrough") (Climate Champions, n.d.). The hydrogen component of this agenda was endorsed by 36 other countries including major players like the US, China, the EU, Japan, Korea, and Australia. The key work packages for hydrogen for 2022–23 included coordination on standards and certification, demand creation and management, R&D, finance, and landscape mapping. The coordination of the Breakthrough Agenda has been taken over jointly by Mission Innovation and the Clean Energy Ministerial. The UK is also involved in international political dialogues on hydrogen through its membership in the G20, which recently released a declaration on harmonizing hydrogen standards (Collins, 2023). It has also signed an agreement with Brazil—which holds the 2024 G20 presidency and will host COP30—to create a "hydrogen hub" (see Sect. 5.2).

The UK is further involved in international initiatives through Mission Innovation, where it co-leads the Clean Hydrogen Mission alongside Australia, Chile, the EU, and the US.[11] The national hydrogen strategy frames this role as championing research acceleration and as a "unique opportunity to showcase UK R&I expertise and to leverage its outputs to spur further technological progress" (BEIS, 2021c, p. 94). The Hydrogen Updates to Market also highlight the role that the UK plays as co-lead of the Mission's research activities and its position in shaping the Mission's Action Plan to stimulate investment (BEIS, 2022e, p. 14). It is also involved in the IEA's Hydrogen Collaboration Program, where it participates in different workstreams on energy storage and conversion, underground storage, safety of large hydrogen applications, and technology analysis and modeling (IEA, 2022b).

At the Clean Energy Ministerial, the UK government engages in some projects like the "twin cities" initiative (Kobe, Japan - Aberdeen, Scotland) and as a member of the expert panel for the CEM-led Northwest European Hydrogen Initiative. Although it was not involved in CEM's Global Ports Coalition or the working group on large-scale hydrogen supply chains (see 2021–2022 work plan: Clean Energy Ministerial, 2020), it has since joined the CEM's Hydrogen Trade Forum. The Northwest European Hydrogen initiative is of increasing interest to UK policymakers as the geographic connection to other countries would enable energy trade in the future.[12]

As the NW Hydrogen Monitor report lays out, the UK will need to harmonize its regulatory standards with trading partners in Europe—from hydrogen certification schemes providing evidence of emissions intensity per unit, to blending thresholds, to the definition of what is low-carbon (IEA, 2022a, p. 7). One area in which the UK is less advanced than other NW Hydrogen countries is that it does not yet have a Guarantees of Origin scheme, nor a designated body to issue such certification (p. 79). However, NationalGas documents from early 2022 show that private actors

[11] Launched in 2021, with the goal of reducing end-to-end hydrogen costs to \$2/kg by 2030. For further members see website at http://mission-innovation.net/missions/hydrogen/.

[12] This includes Austria, Belgium, Denmark, France, Germany, Luxemburg, the Netherlands, Norway, and Switzerland. The UK provided funding for the project along with Germany, Luxembourg, the Netherlands, Norway, and Switzerland. See (IEA, 2022a, 2022b).

are highly supportive of establishing such guarantees of origin to facilitate hydrogen trade (NationalGas, 2022). The UK government has now proposed origin guarantees as a part of its low-carbon hydrogen certification scheme, which is expected to be launched in 2025.

Through its participation in the International Partnership on Hydrogen and Fuel Cells in the Economy (IPHE), the UK is also working to develop standards with key frontrunner countries. As set out in its July 2022 update to market, developing common standards in international fora is a key focus for its international work (BEIS, 2022f, p. 24). The December 2022 update reiterates the importance of this partnership and the UK's own plans for standard-setting. IPHE documents show the UK's centrality in this network and its interest in developing common standards and methodologies, in terms of how much hydrogen blending is permitted across countries or the role of electricity imports in the production of renewable fuels (IPHE, 2022). The December 2023 Hydrogen Update links this deepening involvement in standards and certification to an increasing interest in trade. For example, at COP28, the UK signed a declaration of intent on mutual recognition of hydrogen certification schemes with 38 other countries.

5.2 Bilateral Initiatives and Partnerships

In terms of bilateral partnerships and initiatives, the goal of these relationships is to exchange policy and innovation expertise to grow the UK's hydrogen economy and global markets (BEIS, 2022e, p. 14). The UK prioritizes bilateral relationships with countries that are seen as similarly ambitious and with whom the UK has longstanding relationships via government-to-government forums like IPHE and the CEM Hydrogen Mission. Out of the countries participating in these fora, those with whom the UK has announced high-level cooperation are foremost the US and European hydrogen frontrunners. The US-UK cooperation encompasses the strategic energy dialogue, which includes hydrogen, and the official Energy Partnership with the US, which aims to accelerate global hydrogen development.

The UK has also increased its cooperation with European countries with whom it is geographically well-positioned for hydrogen trade. In February 2023, Belgium and the UK signed an MOU to work together on energy, announcing a new cooperation agreement to build a further electricity interconnector, and increasing collaboration on hydrogen, CCS, and offshore wind. In March 2023, these parties held their first annual UK-Belgium hydrogen working group in Brussels (UK Government, 2023c). In March 2023, France and the UK also signed a statement of cooperation on energy, which likewise focused on increasing electricity interconnections as well as cooperation on hydrogen, CCUS and nuclear power. The text of the agreement reveals that work together on hydrogen would encompass cooperation on "low-carbon hydrogen" deployment, market adoption, certification and definitions (UK

Government, 2023d).[13] Since this MOU, there has been little public cooperation on hydrogen however. Ireland and the UK also signed an MOU on the energy transition including hydrogen in September 2023.

The UK has re-engaged more closely with the North Sea countries on hydrogen in the past years. It jointly hosted the North Sea Neighbors Conference in November 2022, which featured CCUS and hydrogen, and rejoined the North Sea Energy Cooperation (UK Government, 2023c). In 2023, it also signed the Ostend Declaration of energy ministers on the North Seas with the intention to develop cross-border projects and hydrogen markets. Particularly close cooperation can be seen with Norway: the UK signed an MOU with the country to further strengthen cooperation on hydrogen, especially CCS and North Sea carbon storage, and expanded its MOU on CCS to include closer collaboration on hydrogen. Denmark and the UK have also signed an MOU for energy cooperation that includes hydrogen, establishing a joint working group to discuss hydrogen grids. According to the IPHE, Norway considers the UK a major cooperation partner for hydrogen blended with gas exports, alongside Germany and the Netherlands (IPHE, 2022). Building on this partnership, the UK and Germany have signed a partnership agreement to accelerate the development of an international hydrogen industry, with five collaboration pillars. These include accelerating project deployment, setting safety standards, research and innovation, promoting hydrogen trade and trade in related goods and services, and joint market analysis for planning and investment (DESNZ and Lord Callanan, 2023). In April 2024, the two governments also agreed to conduct a feasibility study for green hydrogen export from the UK to Germany (Cucuk, 2024).

The turn toward the EU is supported by a report commissioned by UK DESNZ to explore the possibility of hydrogen exports to continental Europe. Published in May 2024, it argues that the UK has a strong possibility to export hydrogen via pipeline to continental Europe, particularly Germany, the Netherlands, and Belgium (Arup, 2024). This is underpinned by Scottish efforts to develop bilateral connections and cooperation with countries and regions in Europe. Before the UK's government signed collaboration agreements, Scotland signed multiple agreements for low-carbon technologies and hydrogen with Denmark (Scottish Government & Government of Denmark, 2021) and German regions including Hamburg, Bavaria, and North Rhein-Westphalia (Scottish Government & Government of Baden-Württemberg, 2022). In other words, sub-national actors within the UK that stand to gain from hydrogen may also drive further collaboration with Europe.

The UK government has also signaled interest in cooperation with more geographically distant hydrogen partners. At COP28, the UK and Brazil signed a joint statement of intent to increase their collaboration through a joint hydrogen hub for knowledge-sharing and technical cooperation (DESNZ, 2023l). In 2023, the UK signed a hydrogen MOU with Kazakhstan as well as a joint statement with Japan on energy cooperation that includes hydrogen. Australia and Korea are also partnering with Innovate UK for collaboration on hydrogen competitions (BEIS, 2022e, p. 15).

[13] Here, low-carbon refers to renewable and other low-carbon sources, definition unclear.

There has been relatively little engagement by the UK with low and middle-income countries. The exceptions are the UK's joint statement with the Republic of South Africa to expand scientific cooperation to include hydrogen. Chile and the UK also discussed hydrogen at the 2022 UK-Chile trade dialogue (DIT, 2022), and the Energy Transition Action Plan announced with Colombia includes hydrogen (UK Government, 2024e).The Mexico-UK PACT has awarded grants to fourteen projects, one of which was on developing a hydrogen roadmap for Mexico (UK Pact, 2021).

In terms of concrete R&D cooperation, most UK R&D funding is for projects based in the UK with the exception of a general science and technology fund (the Fund for International Collaboration, £160 million) (Delaval et al., 2022b, p. 25). Priority partners in this context are China, Canada, South Korea, and the US (UK RI, 2023) and energy features as one area of focus for cooperation with Canada (UK RI, 2021). However, for now, no hydrogen research collaborations have been developed via this mechanism.

5.3 Competing for Hydrogen Innovation Leadership and Investment

Support for developing hydrogen supply chains remains mainly focused on support for UK research and manufacturing (see Sect. 4.2) and on attracting foreign investors to the UK. Initial engagement has come from the Department for International Trade (DIT), which has published an investor roadmap for the hydrogen sector. The DIT has been using the investor roadmap mentioned above to "socialise the UK hydrogen ambition globally…engaging overseas investors and industry stakeholders interested in developing projects in the UK, and also to showcase UK progress toward developing long-term export opportunities" (BEIS, 2022f, p. 14). According to this roadmap, the Office for Investment at DIT and DESNZ are working with potential foreign investors to help them enter UK markets. The DIT now has a dedicated team that promotes hydrogen trade and investment and investigates export opportunities for UK businesses, leading virtual trade missions and press engagement. The department also encourages FDI teams to attract foreign buyers and add to UK supply chains. BEIS has also attempted to attract international investors with its Hydrogen Investor Roundtable.

To support the export of hydrogen products, UK Export Finance has enhanced its Export Development Guarantees to support clean technologies including hydrogen. This includes loan guarantees for working capital, capital expenditure or R&D for clean energy, hydrogen and decarbonization (BEIS, 2021b). While the total support available here is unknown, the December 2023 Hydrogen Strategy Update reveals that it underwrote a £400 million loan to global multinational Johnson Matthey for R&D. The government also guaranteed £50 million for Northern Ireland-based bus manufacturer Wrightbus to support its low-carbon transport exports, which includes hydrogen-powered buses (UK Export Finance, 2023). Both these companies play important roles in the UK hydrogen sphere: Johnson Matthey funds the secretariat of the All-Party Parliamentary Group (APPG) on hydrogen, and its Chief Executive of Catalyst Technologies serves as the government's hydrogen champion and co-chair of the Hydrogen Delivery Council; Wrightbus has been awarded government funding for its vehicles (Wrightbus, 2023), and for hydrogen production through NZHF funding round 1 at the Ballymena Hydrogen Facility (DESNZ, 2024).

In addition to this direct support, the UK is planning a Carbon Border Adjustment Mechanism (CBAM) which would include hydrogen as well as cement, steel, iron, electricity. The planned UK CBAM is undergoing consultation and would apply from January 2027. This measure could shield low-carbon hydrogen produced in the UK from competition from imported "gray" hydrogen. The EU's CBAM also covers hydrogen; therefore, it will be necessary to carefully align UK and EU standards on emissions reporting and pricing.

5.4 *Private Sector-Led Engagement on Hydrogen Trade Infrastructure*

As pointed out above, the national hydrogen strategy does not set out a strategy for international transport infrastructure or hydrogen exports and the UK has only begun seriously considering this at the end of 2023. Also at the international level, the UK has been less publicly engaged in fora around establishing international infrastructure for hydrogen trade. However, there is some indication that private actors are interested in the development of international hydrogen infrastructure for export. Among them are HydrogenUK, which in May 2024 published a report on the UK's hydrogen trade potential; and the European Hydrogen Backbone, an initiative of 33 energy infrastructure operators across Europe, includes the UK's National Grid plc and National Gas Transmission (NGT). The current European Hydrogen Backbone envisions the UK repurposing natural gas pipelines within the country for hydrogen, and that a gas pipeline running from Bacton could be converted to connect the UK to future hydrogen flows with Belgium and the Netherlands. Between 2035 and 2040, further pipelines could be repurposed establishing flows between the UK and Ireland (EHB, n.d.). Belgium and Ireland also mention hydrogen trade with the UK by 2040 in their Hydrogen Backbone plans. Although it is not mentioned in the UK's plan, the overall Hydrogen Backbone study also represents further export routes by 2040 from Norway to the UK by repurposing the Langeled South natural gas pipeline (EHB, 2022, p. 31). The undersea network between the UK, Belgium, and the Netherlands would also connect to Denmark and Germany. However, this publication also highlights the long lead times for such projects of up to 10 years, suggesting the need to begin feasibility studies as soon as possible.

Although this has not been taken up by the UK government, NGT has proposed a connection to European hydrogen networks as part of their UK hydrogen infrastructure plan called "Project Union." Their proposal includes but does not emphasize a connection to the European Hydrogen Backbone project to be operational by the early 2030s (Project Union, 2022, p. 5). NGT proposed a 12-month feasibility study to Ofgem, which has approved £5.626 million in funding (Ofgem, 2023a, 2023b). In the Ofgem project evaluation, the publicly available information makes no mention of interconnection or exports to continental Europe.

6 Discussion and Conclusions

The UK is currently aiming to position itself as a technology leader in the global hydrogen economy, with a focus on developing its local hydrogen use and markets. Yet, there are a number of barriers to its success in becoming a technology leader; within the UK, some have expressed concern that more ambitious actors like the EU and US will pull ahead. The UK's ambitions for leadership in the global geoeconomics of hydrogen will be unlikely to materialize without taking strategic decisions on which technologies and pathways to prioritize.

Within the UK, the government's ambitious vision is supported by a portfolio of £240 million in public funding for R&D, hydrogen production, hydrogen use, and infrastructure development. Further funding mechanisms for industrial decarbonization, innovation, and manufacturing can also be used for hydrogen, but also focus on other technologies like wind and solar. The UK's hydrogen strategy aims to build local demand for hydrogen and hydrogen technologies; these technologies should then be exported around the world. To this end, the UK is also promoting the hydrogen industry in international fora and contributing to standard-setting. However until recently, the government has not yet been active in developing strategies for international infrastructure or supply chains and has largely left strategies for EU interconnections to the private sector. This lagging coordination with Europe could be seen as an extension of the UK's decision to pull away from Europe following Brexit, with consequences for its abilities to plan for emerging hydrogen markets. Alternatively, it could be perceived as the government playing a two-level game: downplaying hydrogen coordination in its national policy in keeping with its UK-first image, while participating in international initiatives and partnerships to develop European connections without much fanfare.

The UK hydrogen policy also exhibits a number of contradictions, as it seeks to balance its stated industrial policy goals with technology openness and cost concerns. It aims to quickly ramp up what it perceives as low-cost options, using blue hydrogen as a bridge until green is cheaper, and continues to consider hydrogen as an option to decarbonize residential heating. Simultaneously, it aims to build up a UK hydrogen industry and become a world leader in technology and applications. However, critics point out that this will require making choices about where to dedicate resources. The openness to any "low-carbon hydrogen" (including blue hydrogen) means that resources may be spread more thinly between areas like carbon capture and storage, on the one hand, and the development and scaling up of the UK's electrolyzer industry. Moreover, the focus on creating "domestic hydrogen markets" by promoting hydrogen for areas of heating and transport where electrification is widely viewed as the more cost-effective option may waste valuable resources. The failure to commit to strategic decisions on certain technologies and key use cases may therefore be an obstacle to industry-building.

The current approach may therefore fail to achieve the UK's goal to become a hydrogen technology leader and promote green local jobs in the UK heartland, especially in industrial decarbonization. In addition, the UK may face increasing competition from the US and the EU, which are now increasing their hydrogen ambition and related industrial policy measures. Realistically, the UK is in no position to compete with the US or the EU in terms of the volumes of subsidies it can devote to hydrogen development. At the same time, its lack of a concerted strategy to cooperate with Europe on hydrogen development or infrastructure may leave it lagging behind other countries in terms of investment, as the EU turns to Northern Africa for its hydrogen imports. It remains to be seen whether the change in government will be able to make the change in the UK's strategy needed for industrial decarbonization and technological leadership.

Acknowledgements Research for this chapter was financially supported by the German Federal Foreign Office within the framework of the project "Geopolitics of the Energy Transformation—Implications of an International Hydrogen Economy" (GET Hydrogen), funding reference number AA4521G125.

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Australia's Emerging Hydrogen Economy: In Search of Export Opportunities

Llewelyn Hughes

Abstract The Australian government foresees an opportunity to scale the hydrogen economy, centred on exporting hydrogen and associated vectors to the Asia–Pacific region. Building on its legacy as an exporter of fossil-fuel commodities, the government has favoured a technology-neutral approach with support for renewable and fossil-based hydrogen production and a strong focus on exports. Within Australia's broader efforts to decarbonize its economy, considerations revolve around which role hydrogen may play in the domestic energy transition, the potential size of its future hydrogen export market, and what opportunities exist for value creation along the entire hydrogen supply chain. In this chapter, we provide an overview of hydrogen development in Australia. We begin with a brief overview of Australia's climate and energy policy and its position in regional and global energy markets. We then discuss the state of hydrogen supply and demand in the domestic economy, before outlining the main policy initiatives and stakeholders. We then consider the external dimensions of Australia's national hydrogen policy, which is closely linked to the opportunity for exports of hydrogen and associated vectors with low-carbon intensity.

1 Introduction

The Australian government foresees an opportunity to scale the hydrogen economy, centred on exporting hydrogen and associated vectors to the Asia–Pacific region. Australia was the third country to release a National Hydrogen Strategy (NHS) in 2019, and policies have been introduced to support the development of a national hydrogen industry (Government of Australia, 2023). Within Australia's broader efforts to decarbonize its economy, considerations revolve around which role hydrogen may play in the domestic energy transition, the potential size of its future hydrogen export market, and what opportunities exist for value creation along the entire hydrogen supply chain.

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R. Quitzow and Y. Zabanova (eds.), *The Geopolitics of Hydrogen*, Studies in Energy, Resource and Environmental Economics, https://doi.org/10.1007/978-3-031-84022-7_7

In this chapter we provide an overview of hydrogen development in Australia. We begin with a brief overview of Australia's climate and energy policy and its position in regional and global energy markets. We then discuss the state of hydrogen supply and demand in the domestic economy, before outlining the main policy initiatives and stakeholders. We then consider the external dimensions of Australia's national hydrogen policy, which is closely linked to the opportunity for exports of hydrogen and associated vectors with low-carbon intensity. Australia's hydrogen strategy also reflects the interdependence of green industry policies, with the focus on export potential in response to traditional commodity trading partners' planning to use hydrogen in decarbonization.

2 Hydrogen Within Australia's Decarbonization Strategy

The federal government elected in May 2022 increased Australia's Nationally Determined Contribution lodged with the United Nations Framework Convention on Climate Change (UNFCCC). The government committed Australia to reducing greenhouse gas (GHG) emissions by 43% by 2030 relative to 2005 levels and achieving net-zero emissions by mid-century. It also set a national renewable energy target of 82% by 2030. The government incorporated the national GHG emissions reduction target into the Climate Change Act that became law in 2022, increasing the credibility of this commitment.

The Climate Change Act requires the government to submit an Annual Climate Change Statement ('Annual Statement') to parliament on progress towards achieving the country's GHG emissions target. Under current policy settings, the 2023 Annual Statement found emissions at 24.5% below 2005 levels, projected to be 42% below 2005 emissions by 2030, thereby broadly in line with its commitments (Commonwealth of Australia, 2023a). The reduction in emissions is driven by the decarbonisation of the electricity sector, for which emissions fell 22.9% between 2005 and 2023 due to a rise in renewable energy deployment and the retirement of emissions-intensive coal-fired power plants.

The Annual Statement also summarises current initiatives undertaken to support Australia's new climate strategy (Commonwealth of Australia, 2023a). Central to achieving the net-zero mid-century target are six sectoral decarbonisation plans focused on electricity and energy, industry, resources, the built environment, agriculture and land, and transport. The role of hydrogen is expected to be made clear through the decarbonisation pathways outlined in these sectoral plans. An important additional element in the government's climate mitigation strategy is a reform of the Safeguard Mechanism, which places an obligation on large GHG emitters—defined as those with Scope 1 emissions of more than 100,000t of CO_2e per year—to keep their net emissions below a baseline that decreases year-on-year and offers a number of options for managing excess emissions.

Australia's legacy energy system is heavily reliant on fossil fuels, however, its abundant low-cost solar and wind resources have enabled the rapid decarbonization of its electricity system. In 2022, around 32% of electricity was generated by renewable energy sources (Commonwealth of Australia, 2023a). A 2010 assessment of Australia's resources notes that "if only 0.1 percent of the incoming radiation could be converted into usable energy at an efficiency of 10 percent, all of Australia's energy needs could be supplied" (Australian Government, 2010). Australia also has abundant resources of offshore wind energy, which are complementary to other renewable energy resources in terms of their daily and seasonal profiles (Australian Energy Market Operator, 2022).

Despite the dynamic development of domestic renewable energy, Australia remains a major supplier of gas and thermal coal to the Asia–Pacific region, as well as coking coal used in steel manufacturing (Fig. 1). Consequential emissions from the use and processing of Australian exports are larger than domestic emissions and have been assessed at around four percent of total global annual emissions (Burke et al., 2022). Governments and industry are now shifting to explore the potential of exporting climate-friendly commodities, with consideration given to hydrogen and ammonia, and increasingly value-added low-carbon products such as green iron and alumina. Yet, despite this interest in an export-oriented hydrogen industry, a 2023 NHS review expressed concern that Australia was falling behind competitors for export markets (Government of Australia, 2023). The review also noted the potential opportunity to establish a green iron ore processing industry using renewable energy and hydrogen, suggesting increased appetite for considering downstream value-added applications of hydrogen. The use of hydrogen to increase value creation in iron and steelmaking in Australia is identified as a large-scale economic opportunity (Jotzo, 2022) and was given emphasis in the revised National Hydrogen Strategy released in 2024 (Government of Australia, 2024). The national government identified the opportunity to shift down the value chain by increasing onshore manufacturing of low emissions products, including by potentially newly establishing an iron ore processing industry based on renewable hydrogen. Australia is currently a bulk commodity supplier, exporting 900 Mt of iron ore annually as the world's largest global producer, but with limited domestic steel production capabilities (Commonwealth of Australia, 2022b).

Another important question is which technologies will be supported through policy frameworks to produce hydrogen for domestic use and exports. Hydrogen can be produced using gas or coal, with or without carbon capture and storage (CCS), as well as through electrolysis using electricity with different levels of carbon intensity. All technology pathways are available to Australia, given the abundant reserves of both fossil fuel and renewable energy resources. The choice of production technology has major implications for GHG emissions from energy inputs as well as fugitive emissions (i.e. leakage) in hydrogen production processes (Longden et al., 2022).

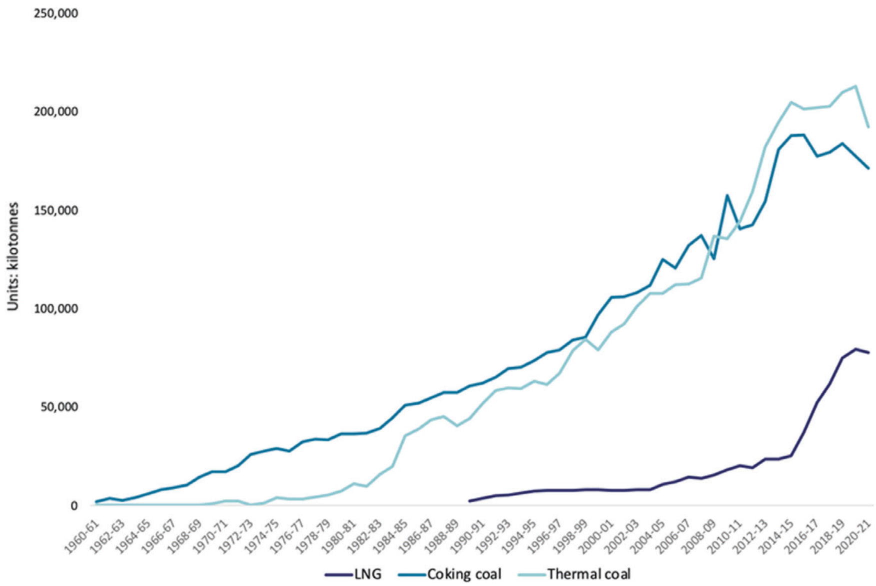

Fig. 1 Australian exports of gas, thermal coal, and coking coal, in physical units. *Source* Author, based on Government of Australia (2022)

3 Australia's Hydrogen Economy: Policy and Market Developments

Hydrogen already plays a role in industrial processes within the domestic Australian economy, acting as a feedstock for ammonia production (~ 65% of total consumption) and refining processes for crude oil (~ 35% of total consumption), along with a number of smaller industrial processes. There is little hydrogen produced for sale on a merchant basis, with the majority used directly in ammonia production and refining processes (Grantham, 2021). The largest facility is located in Western Australia and produces up to 850,000 metric tonnes of ammonia annually using steam-methane reforming (SMR) for domestic fertilisers and mining, as well as for ammonia exports to Asia–Pacific fertiliser markets.

Australia's 2019 NHS identified an expansion of potential end-uses for hydrogen domestically as a pathway to scaling local industry and preparing for the potential of large-scale exports (Commonwealth of Australia, 2021). As of September 2024, there were 98 hydrogen projects, of which 81 were either under development or construction. Of these, 20 projects were designated as having an export focus, with domestic end-uses focused on transport, blending in the existing gas network, and industrial uses (HyResource, 2024a).

A 2022 NHS review of the state of hydrogen industry development found some limited progress on the domestic demand side, hampered due to hydrogen's lack of competitiveness. In the power sector, for example, battery and pumped-hydro options were identified as receiving more attention than hydrogen for load balancing and grid-firming applications. Similarly, the 2022 review reported some progress in the use of hydrogen in mining and off-grid applications, though limited by the continued use of diesel. Likewise, progress was slow in heavy transport given the focus on battery electric vehicles, although governments were collaborating on the development of a hydrogen refuelling network on freight highways. Hydrogen also had not yet been applied in industrial heating processes beyond feasibility studies (Commonwealth of Australia, 2022a).

Reflecting this, a revised NHS released in 2024 focused on a more limited number of end-use cases within the domestic economy centred on heavy road freight in the near term, with longer-term consideration given to research and analysis into possible uses in aviation, shipping, and bunkering, and the power sector. The focus on export potential remains, but with an increased focus on the potential opportunities to use hydrogen domestically in value-adding processes such as the production of green iron for export (Government of Australia, 2024).

The revised 2024 NHS also established a series of quantitative targets to provide greater certainty to the industry, beginning with the goal of producing 15MT of hydrogen annually by 2050, with a stretch target of 30 MT. In addition, the new NHS set an export target of 0.2MT of renewable hydrogen exported by 2040, with a stretch goal of 1.2MT, and put in place an annual reporting process, along with a strategic review every five years.

3.1 Early Stage Project Support

Policies supporting the scaling of the hydrogen industry span the Commonwealth and state governments within Australia's federal system. The initial strategy adopted by the federal government proposed an "adaptive approach" to scaling hydrogen, centred on removing barriers to industry development and increasing domestic demand and supply, while recognising uncertainty about hydrogen's long-term role in decarbonization pathways domestically and globally. Consistent with this, the initial policy phase was designed to scale up production by advancing pilot, trial, and demonstration projects, building hydrogen hubs, assessing supply chain infrastructure, and supporting the development of supply chains for hydrogen hubs (COAG Energy Council, 2019).

Funding has been disbursed through Australia's innovation system support for research, development, and demonstration (RD&D) projects in hydrogen and ammonia. As of September 2024, federal government support specific to hydrogen totalled AUD12.4 billion, with a further AUD29.4 billion available for hydrogen projects that had a more general intent. State governments provided an additional AUD5.0 billion and AUD13.4 billion in hydrogen-specific and hydrogen-eligible support, resulting in a combined total of almost AUD60.2 billion in public funding (HyResource, 2024b).

Two key public investment bodies disbursing hydrogen-specific funding are the Australian Renewable Energy Agency (ARENA), and the Clean Energy Finance Corporation (CEFC) (see information box). ARENA committed more than AUD190 million towards the development of renewable hydrogen projects, including three 10MW electrolyser projects, AUD22.1 for universities and research organisations, and investments in transport-related projects (Commonwealth of Australia, 2022b). In 2023, ARENA also announced AUD50 million in funding for support of renewable hydrogen and low -emissions iron and steel (Australian Renewable Energy Agency 2023), following a 2021 funding round focused on solving technical and logistical challenges related to ammonia, the use of methane as a fuel carrier, hydrogen fuel reciprocating engines, biological hydrogen production, and the use of photovoltaic electrolysis for hydrogen generation (Australian Renewable Energy Agency, 2021a, 2021b).

The CEFC provides debt and equity finance through the Advancing Hydrogen Fund, valued at up to AUD300 million, for projects that develop supply chains, establish hydrogen hubs, and enable domestic demand for hydrogen. The first funding provided by the CEFC under the fund was up to AUD 12.5 million in support of five fuel cell driven trucks and the development of the SunHQ H2 hydrogen hub. The hub is located in Queensland, and in the first phase will produce approximately 140 tonnes of hydrogen via a proton-exchange membrane (PEM) electrolyser, with the hydrogen used to displace heavy vehicle diesel fuel used in the operation of a zinc refinery. In addition to the CEFC, the project is supported by ARENA (AUD 3.02 million) and the state government of Queensland (AUD5 million) and reached Final Investment Decision (FID) in August 2021. Consistent with the inside-out industry development model, the project is initially domestic in scope, but later phases envision an opportunity to export renewable hydrogen to South Korea. A feasibility study was also carried out to examine the possibility of developing hydrogen export facilities at the Port of Townsville, supported by a Memorandum of Understanding signed between the port and Ark Energy as the project proponent.

Public Investment Bodies Engaged in the Hydrogen Sector

Australian Renewable Energy Agency

The Australian Renewable Energy Agency (ARENA) is a Commonwealth corporate entity created in 2012 with the mission "to support the global transition to net-zero emissions by accelerating the pace of pre-commercial innovation, to the benefit of Australian consumers, businesses and workers." ARENA is required by law to develop a funding strategy aligned with its objectives and priorities, with current strategic priorities identified as: (1) optimising the transition to renewable electricity through supporting ultra-low-cost generation, supporting energy storage, large-scale renewables integration, and flexible demand; (2) commercialising clean hydrogen across the value chain; (3) supporting the transition to low-carbon metals; (4) decarbonising land transport.

Clean Energy Finance Corporation

The Clean Energy Finance Corporation (CEFC) is a commonwealth government-owned entity established by the Clean Energy Finance Corporation Act 2012. Through the Act, it is enabled to invest in the development or commercialisation of clean energy technologies, defined as energy efficiency, low emissions, and renewable energy technologies, with a primary focus within Australia. The CEFC Corporate Plan 2022–23 states investments are consistent with decarbonisation pathways, specifically investments in transmission and renewable energy, energy efficiency, electrification, and fuel switching. It also identifies the reduction of non-energy emissions through recycling, biosequestration, and soil carbon in agriculture. The majority of its lending occurs through investment in debt instruments, with the goal of leveraging additional funds from the private sector.

Traditional research funding schemes also play a role. The Commonwealth Scientific and Industrial Research Organisation (CSIRO), for example, manages an incubator programme valued at more than AUD16 million designed to support hydrogen-related pilot projects at an early stage of development. The Australian Research Council (ARC) also supports a number of hydrogen-related projects, including the Heavy Industry Low-carbon Transition Cooperative Research Centre (HILT CRC). The HILT CRC was provided with AUD 39 million in 2021 over ten years, unlocking AUD 175 million in partner investments to support collaboration across companies operating in heavy industry, the research community, and government entities. The centre incorporates a range of different technologies for decarbonising heavy industry, including the use of hydrogen direct-reduced iron (DRI) processes and their applicability to Australian ores. This is crucial for Australia given its important role as a major global exporter of iron ore and coking coal for iron and steel production.

3.2 Support for Large-Scale Project Development and Enabling Infrastructure

In its review of the NHS, the government found that Australia's export-led strategy was under risk from international competition, underlined by increased public investment in the United States and other jurisdictions to support hydrogen production and exports. It also noted that only one project had reached FID by the end of 2022 (Government of Australia, 2023). In response, the federal government created the AUD2 billion Hydrogen Headstart programme to invest in large-scale 100% renewable hydrogen projects. Funding is available for up to 10 years from the date of commissioning and is designed to eliminate the gap between hydrogen production costs and alternative technologies. Six projects were shortlisted for potential support in the first funding round, representing more than 3.5 GW of electrolyser capacity (see Fig. 2 below). In addition, the government identified 11 industrial hubs to enable economies of scale for both domestic and export use-cases through co-locating hydrogen-related infrastructure, and a Regional Hydrogen Hubs Programme committed AUD 526 million of co-investment along with state governments, with total investment of around AUD 1 billion.

Finally, supporting the near and long-term targets of its revised NHS, the federal government made additional commitments to large-scale deployment of hydrogen through the 2024–5 budget, including a Hydrogen Production Tax Incentive (HPTI). The HPTI provides AUD2/kg for up to ten years for renewable hydrogen produced between 2027–8 and 2039–40, with FID required to be reached by 2030 in order to be eligible. An additional AUD1.3 billion investment over ten years was also made available for the Hydrogen Headstart programme, and additional funding was

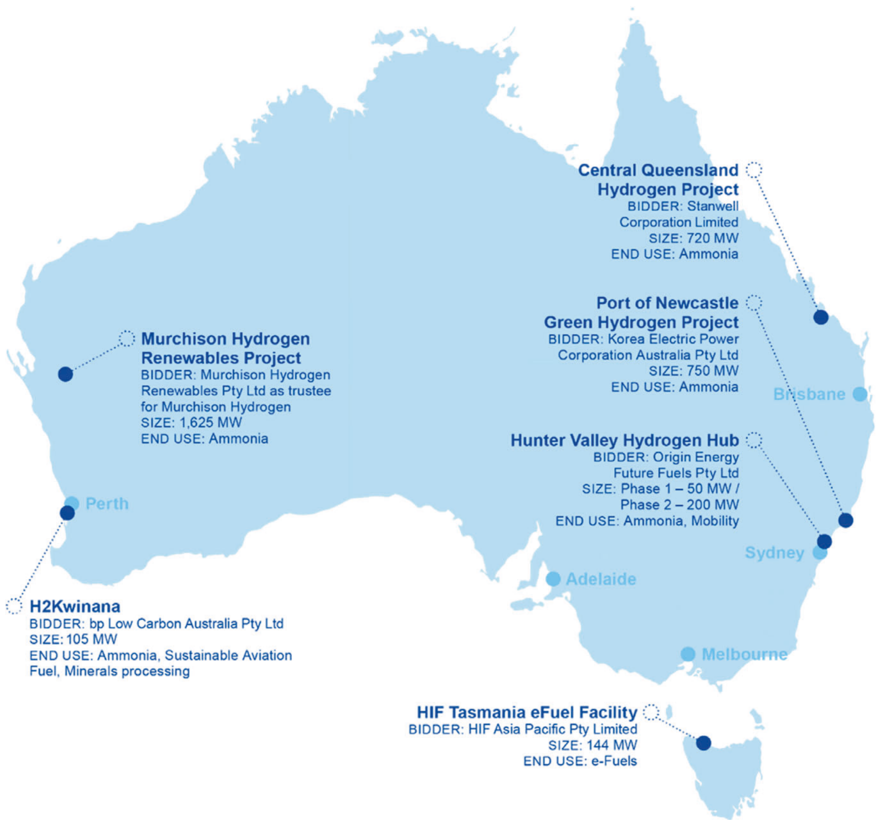

Fig. 2 Projects shortlisted for support under Australia's Headstart Programme. *Source* Author, based on government documents and media reports

allocated in support of the NHS, and for ARENA initiatives including renewable hydrogen (Commonwealth of Australia 2024).

3.3 Technology Selection for Hydrogen Production

Governments face the choice of which hydrogen production technologies should be made eligible for public funding. Reflecting the availability of abundant coal and gas reserves, the 2019 NHS adopted a broad approach by supporting hydrogen produced via electrolysis as well as SMR combined with CCS. The Victorian state government body Invest Victoria, for example, proposed the use of lignite coupled with CCS as a viable and commercially attractive option for enabling hydrogen export, reflecting the states large reserves of lignite and legacy industry from coal mining and power generation. The Hydrogen Energy Supply Chain (HESC) project (see Sect. 7) utilises coal (and biomass) from the Latrobe Valley in Victoria to produce hydrogen for export to Japan, in collaboration with a consortium of Japanese corporate partners. HESC is the only project that foresees producing hydrogen through coal gasification.

The consultation process leading up to the release of the 2019 NHS showed support for enabling multiple technology streams. The major gas producer Woodside supported hydrogen produced through gas coupled with CCS. On the demand side, the Australian Gas Infrastructure Group argued for enabling the blending of hydrogen in existing gas pipeline infrastructure as a strategy for scaling up the hydrogen industry and reducing greenhouse gas emissions from the gas network infrastructure. Against this, a number of organisations opposed the use of fossil fuels in hydrogen production. The Climate Council of Australia, a non-governmental organisation, argued against the inclusion of fossil fuel coupled with CCS, and Beyond Zero Emissions argued that a focus on hydrogen could delay rapid decarbonisation, while recognising that renewable hydrogen has a role to play in decarbonising the steel sector and fertiliser production.

Despite support for a broad range of technology options for hydrogen production, the largest share of new projects focus on the production of hydrogen using electrolysis, and the revised 2024 NHS shifted to prioritise renewable hydrogen, justified by an assessment that it is likely to be the least cost and lowest emissions option in the long run (Government of Australia, 2024). The 2024–5 budget also prioritised renewable hydrogen production. Of the 98 projects under development or construction, 72 are focused on electrolysis as the production method (HyResource, 2024b). Furthermore, applicants to the Headstart scheme were required to ensure the hydrogen production process used electrolysis and was powered fully by renewable energy. ARENA funding programmes also support the production of hydrogen using renewable energy.

Beyond choices about which technology options to support when financing hydrogen production and infrastructure, Guarantee-of-Origin (GO) schemes provide information about embedded emissions, including for hydrogen, enabling consumers to select their preferred products. The Department of Climate Change, Energy, the

Environment and Water has worked to develop an internationally aligned GO scheme encompassing hydrogen that provides an emissions accounting framework, certifying emissions embedded in hydrogen and associated vectors. The proposed GO takes a well-to-delivery gate approach, covering the emissions produced from the supply of materials, production, transport, and storage to the point of consumption or export, with enabling legislation planned for 2024 (Commonwealth of Australia, 2023a, 2023b).

To summarise, the commonwealth government has increased Australia's international climate commitment since entering into government in May 2022 and retained the previous government's focus on hydrogen as a domestic decarbonization option as a first stage towards scale-up for export. A central focus of policy support is the development of hydrogen hubs, combined with a near term focus on examining the feasibility of domestic end-uses, including into the existing ammonia industry. This is aligned with key policy documents that envision hydrogen as a substantial export industry with significant implications for Australia's energy system, given the potential of at least some renewable hydrogen projects to be connected to domestic electricity markets. However, as the scale of future demand for international exports remains highly uncertain, the government's focus until mid-decade lies on scaling up domestic production and demand through an adaptive policy framework. The Labor government, elected in May 2025, is expected to maintain the overall direction of Australian hydrogen policy.

4 Australian State Governments: Policy Settings

The national, state, and territory governments have divided responsibilities in the energy sector under Australia's federal system. State governments have developed a series of hydrogen strategies, underpinning additional RD&D initiatives, as well as human capital development and demand creation (Table 1).

Table 1 State government hydrogen strategies

State/Territory	Document	Year
Queensland	Queensland Hydrogen Industry Strategy	2019[a]
New South Wales	NSW Hydrogen Strategy	2021[b]
Victoria	Victorian Renewable Hydrogen Industry Development Plan	2021[c]
Tasmania	Tasmanian Renewable Hydrogen Action Plan	2020[d]
South Australia	Hydrogen Action Plan	2019[e]
Western Australia	Western Australian Renewable Hydrogen Strategy and Roadmap	2019[f]
Northern Territory	Renewable Hydrogen Master Plan	2021[g]

Source [a] Government of Queensland (2019), [b] Government of New South Wales (2021), [c] Government of Victoria (2021), [d] Government of Tasmania (2020), [e] Government of South Australia (2017), [f] Government of Western Australia (2021), [g] Northern Territory Government (2020)

The 2021 hydrogen strategy released by the state government of New South Wales (NSW) focuses on hydrogen produced using electrolysis. It notes that CCS, which is required to reduce the carbon emissions from traditional SMR-based hydrogen production, would not be commercially deployable before 2030, and that such SMR-based hydrogen would be unlikely to have a price advantage over renewable hydrogen by that time. The NSW plan also establishes targets for 2030. On the supply side, they include the operation of 700 MW of electrolyser capacity, 110,000 tonnes per year of green hydrogen production and a price target of AUD2.80/kg. On the demand side, the strategy targets the deployment of 100 refuelling stations, 10,000 hydrogen vehicles and 10 percent blending of hydrogen in the existing gas network by volume. These commitments are supported by a number of public funding streams, including AUD 3 billion across a mix of subsidies and tax relief for renewable hydrogen production, and funding to support the conversion of a gas-fired power plant for renewable hydrogen, in collaboration with the Commonwealth government (HyResource, 2024b).

While the state of Queensland is a large producer and exporter of gas, its industry strategy also focuses on renewable hydrogen. Key initiatives include AUD 96 million for workforce development and AUD 35 million for a hydrogen industry development fund that supports the development of a renewable hydrogen production facility for use with fuel cell trucks, a demonstration project using wastewater to produce hydrogen via electrolysis, additional trials with heavy trucks and buses, and a project to enable the blending of hydrogen in the gas network. Other hydrogen plans produced in Western Australia, South Australia, and Tasmania similarly emphasise the central role of renewable hydrogen production pathways.

In contrast, Victoria is the state where the HESC project is located. At the demonstration phase, this uses coal gasification to produce hydrogen before liquification for transport to Japan. Victoria has a large resource base of coal in the Latrobe Valley, which has been used historically in the power sector. While the Victorian state government places an emphasis on renewable hydrogen in its 2020 industry development plan, it notes that it also supports other forms of hydrogen production and has provided AUD 50 million for the pilot phase of the HESC project (HyResource, 2024b).

4.1 Hydrogen Exports and Implications for Domestic Energy Markets

The role of hydrogen in the Australian economy is partially linked to future demand for hydrogen within other countries' decarbonization pathways, reflecting the interdependent nature of policies being pursued by the respective governments. In this vein, a key question is the scale of future demand. A 2018 study commissioned by ARENA on the potential market for Australian hydrogen exports found that core demand was likely to be located in China, Japan, South Korea, and Singapore. It also found that under different demand scenarios, Australian exports could reach between

620,000 and 3.2 million tonnes (MT) by 2040, including 390,000 to 2 MT to Japan. The total value of these exports was estimated to amount to around AUD 2.6–13.4 billion (ACIL Allen Consulting, 2018). The large range shows both the potential for growth in hydrogen, and the high degree of uncertainty around future export demand.

If hydrogen is scaled through electrolysis and the use of renewable electricity, this requires a large increase in electricity generation, creating a link between the export market for hydrogen and Australia's domestic energy markets. Model results suggest additional electricity demand from hydrogen exports of 39 TWh to 200 TWh by 2040 (ACIL Allen Consulting, 2018). The 2024 NHS notes that the bulk of Australia's renewable hydrogen projects are likely to be unconnected to the transmission grid. If this is not the case, coupling the National Electricity Market (NEM) and West Australian Electricity Market (WEM) with power generators used to drive electrolysers producing hydrogen for export could have important implications for domestic electricity markets, depending on the scale of deployment and locational choices made by project developers.

The Australia Energy Market Operator (AEMO) produces an Integrated System Plan (ISP) for the NEM bi-annually as a "whole-of-system plan for the efficient development of the NEM power system for a planning horizon of at least 20 years" (Australian Energy Market Operator, 2022). The NEM is responsible for about 80 percent of total consumed electricity. The 2022 ISP consists of scenarios for the development of the domestic electricity market, including a "Hydrogen Superpower" scenario that would almost quadruple the amount of energy within the NEM in order to support large-scale exports of hydrogen. Under this scenario, hydrogen use in the domestic economy drives an additional electricity demand of 2 TWh in 2030, rising to 132 TWh in 2050. Renewable electricity used for hydrogen production to meet export demand would increase electricity demand by 49 TWh in 2030 and 816 TWh in 2050, making up 64 percent of total modelled underlying domestic electricity consumption in 2050. Installed capacity of utility-scale solar and wind power would need to increase under the "Hydrogen Superpower" scenario to more than 250 GW for each by 2050. This compares to around 60–70 GW in the "Step Change" scenario, which models rapid decarbonisation without large hydrogen export growth. The potential implications of large-scale hydrogen exports for the domestic electricity sector, both in terms of investment and operations, are thus substantial.

5 Promoting International Hydrogen Supply Chains

The revised 2024 National Hydrogen Strategy notes that Australian trade partners have committed to making hydrogen a core component of their decarbonisation strategies and that the country is well positioned to be an important supplier in the global hydrogen economy due to abundant low-cost renewable energy, a skilled workforce, and low investment risk. It also points to the need to develop projects at scale and secure foreign direct investment in order to scale up Australia's hydrogen industry (Commonwealth of Australia 2024). International partnerships are a core part of the strategy given the focus of Australia's hydrogen policy on export potential. In the near term, policy has focused on the development of bilateral partnerships with the goal of testing the feasibility of supply chains and creating opportunities for technical collaboration in R&D (Government of Australia, 2021a). In the federal budget for 2021–2022, AUD 565.8 million was set aside for "building strategic international partnerships to make low emissions technologies cheaper than high emitting alternatives."

Currently, bilateral partnerships are being pursued between Australia and Japan, Germany, South Korea, and Singapore. A key remaining question is the extent to which Australia successfully enables the development of new supply chains in value-added products such as green iron and alumina, in addition to hydrogen and ammonia.

5.1 Japan

Bilateral collaboration between Japan and Australia has been underpinned by two agreements. In January 2020, the two countries signed a "Joint Statement of Cooperation on Hydrogen and Fuel Cells," committing their governments to collaborate on supply chain development and in multilateral fora, including the Hydrogen Energy Ministerial Meeting, the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE), the Clean Energy Ministerial, and Mission Innovation. In June 2021, the two governments also signed the "Japan–Australia Partnership on Decarbonisation through Technology." The agreement is a statement of intent to collaborate on shared decarbonization objectives with a technology focus and identified, amongst other things, "clean fuel ammonia" and "clean hydrogen" as potential areas for joint action. The document notes the willingness of both countries to commit financial support to their joint objectives, albeit not referring to any specific projects or funding instruments.

In terms of supply chain development, a key initiative is the HESC project, already mentioned above. It was announced in 2018 and involves a pilot phase, as of 2019, when a plant for hydrogen production was constructed in the Latrobe Valley, Victoria to produce hydrogen via coal gasification. The generated hydrogen is transported by road in pressurised trailers to a loading terminal at the Port of Hastings, where it is liquefied and shipped to Japan. The consortium delivering the project consists of the Australian federal government, the state government of Victoria, and AGL Energy on the Australian side, while the Japanese project partners are the Japanese Ministry of Economy, Trade and Industry, the New Energy and Industrial Technology Development Organisation (NEDO), Kawasaki Heavy Industries, J-Power, Iwatani Corporation, Marubeni Corporation, and Sumitomo Corporation.

In its pilot phase the project produced hydrogen from a mix of lignite and biomass. The first shipment of 2.6 tonnes of liquefied hydrogen was delivered to the Port of Kobe in Japan in February 2022. The Australian federal government and the state government of Victoria provided AUD100 million of the total AUD500 million cost of the project. According to plans announced by the project partners the decision whether to scale up and commercialise the endeavour is scheduled for the 2020s. Should the project reach FID, commercial operations would begin in the 2030s. If operating at commercial scale, HESC is modelled to produce 225,000 tonnes of liquid hydrogen per year. In March 2023, it was announced that the project will be supported by the Japan Clean Innovation Fund to scale up to producing between 30–40,000 tonnes per annum of hydrogen, beginning in the late 2020s.

One key concern is the emissions resulting from hydrogen generation through coal gasification. During the pilot phase, there is no scheme in place to remediate GHG emissions resulting from the production process, although the consortium delivering the project has undertaken to purchase carbon offsets with the stated aim of compensating emissions from coal gasification. Referring to the scaled-up project phase, the consortium notes that "HESC Project Partners, the Victorian Government, the Australian Government and the Japanese Government would not support or proceed with a HESC project without CCS" (Hydrogen Energy Supply Chain, 2022).

There are additional projects between Australian and Japanese partners examining the feasibility of hydrogen and ammonia exports to Japan. Stanwell Corporation, in conjunction with Japanese firms Iwatani Corporation, Kawasaki Heavy Industries, Marubeni Corporation, Kansai Electric Power Company, and the APA Group, is carrying out a feasibility study of the potential for liquid hydrogen exports using electrolysis, near Rockhampton, Queensland. With the support of ARENA, the October 2020 study examined installing a 10 MW electrolyser as a demonstration project. It found that the project was technically feasible but would require subsidising the capital costs of the electrolyser, and that there were limited opportunities for securing an offtake agreement domestically. The project then shifted to examining the feasibility of the construction of a 300 MW electrolyser and liquefaction facility to enable the export of liquid hydrogen to Japan and to supply industrial customers domestically, with the potential to scale to 3GW in the early 2030s, with funding for the study provided by ARENA and Japan's Ministry of Economy, Trade, and Industry. In early 2025 the new Queensland government announced it would not provide additional funding for the project, and Stanwell is is currently reviewing next steps.

In addition, in March 2021, Sumitomo Australia, the Australian subsidiary of Japanese conglomerate Sumitomo Corporation, signed a Memorandum of Understanding with the Australian Gas Infrastructure Group, Central Queensland University, Gladstone Ports Corporation, and the Gladstone Regional Council to explore the development of a hydrogen ecosystem in Gladstone, Queensland. This would entail examining the feasibility of domestically focused demand, including through blending of up to 10 percent hydrogen in the existing gas network while considering the option of enabling exports at scale by 2030.

Independently, Australian resources companies Rio Tinto and Japan's Sumitomo Australia are constructing a hydrogen pilot plant in Gladstone, Queensland for use at Rio Tinto's Yarwun aluminium refinery. Mitsui and Company and the Japan Oil, Gas and Metals National Corporation (JOGMEC) are also conducting a feasibility study for hydrogen production with CCS in Western Australia and have signed an MoU with Australia's Northern Territory Government for cooperation on hydrogen, ammonia and CCS-related projects. Finally, Mitsui has reached an agreement with the Australian company Wesfarmers Chemicals, Energy & Fertilisers to examine the technical and commercial feasibility of the production and export of SMR-based ammonia coupled with CCS in depleted gas fields owned by Mitsui E&P Australia. In 2024, the partners reported the first injection of CO2. There are thus numerous projects at the early stage of development involving investment by Japanese firms in hydrogen production in Australia, with many receiving funds from Japanese public investment bodies.

5.2 Germany

A second bilateral partnership pursued by Australia is with Germany. In September 2020, the Australian and German governments signed an agreement to examine the feasibility of a renewable hydrogen supply chain between the two countries, called HySupply. The project is funded by the Australian Department of Foreign Affairs and Trade and (then) Department of Industry, Science, Energy and Resources, and by the German Federal Ministry for Education and Research. The HySupply project is a two-year study administered on the Australian side by a mix of research and private sector partners. The feasibility study analyses hydrogen production costs using renewable electricity across a number of different sites in Australia, options for storage and transport, hydrogen recovery and distribution, and potential end-use sectors. It has produced an indicative cost breakdown across the value chain for hydrogen imported to Germany and shipped from Australia (Daiyan et al., 2021).

In addition, in June 2021, the Australian and German governments signed a Declaration of Intent referred to as the "Australia-Germany Hydrogen Accord." There are three initiatives under the agreement. The HyGate initiative supports pilot, trial, and demonstration projects between Australia and Germany, with Australia committing AUD50 million and the German government committing EUR50 million. The stated objectives of HyGATE are to "[f]acilitate collaboration between Australian and German partners, expedite scale up and commercialisation, enable the demonstration of new technologies through trials or demonstration projects in Australia, and support the development of a renewable hydrogen supply chain between Australia and Germany." (Australian Renewable Energy Agency, 2022). In addition, ARENA is administering the competitive distribution of funding in Australia to identify priority projects, consistent with the near-term goal of developing an understanding of supply chain opportunities for Australia in hydrogen by 2025. Amongst other things, priorities include reducing the cost of hydrogen production, transport, and end-uses across the value chain, planning and operating large-scale electrolysers combined with renewable electricity generation, working on conversion and conversion technologies supporting the shipping of hydrogen and associated vectors, and the sustainable production of industrial intermediate products, such as green ammonia or green steel (Australian Renewable Energy Agency, 2022, 5). Notably, the initial funding round for the HyGATE project only allows for hydrogen produced using renewable electricity.

A second component of the Accord is the facilitation of trade in hydrogen and associated vectors between the two countries. This includes plans for an auction focused on renewable ammonia, to be channelled through H2Global, the German initiative to facilitate long-term agreements for the purchase of hydrogen and its derivatives. In September 2024, the German and Australian governments signed a Declaration of Intent to negotiate a 400 million Euro funding window for European buyers of Australian hydrogen. The countries agreed to carry out a hydrogen auction for 2025, with subsequent annual auctions scheduled to begin in 2027–2028. The third component is a commitment to facilitate German participation in demonstration projects at Australia's hydrogen hubs.

5.3 South Korea

The third bilateral partnership Australia has initiated is with South Korea. The two governments signed a letter of intent in September 2019, agreeing to cooperate on hydrogen development. This was followed by the "Australia-Republic of Korea Low and Zero Emissions Technology Partnership" signed in October 2021 and reaffirmed by the leaders of both countries in December of the same year through the "Australia-Republic of Korea Comprehensive Strategic Partnership." In the latter, then-Prime Minister Scott Morrison and then-President of the Republic of Korea Moon Jae-in agreed to collaborate in the low-carbon energy transition, noting that "early priorities include supply of clean hydrogen (including hydrogen-based compounds), low emissions iron ore and steel, and carbon capture, use and storage" (Government of Australia, 2021b).

Bilateral collaborative work on supply chain development under the partnership has commenced. In September 2022, the Han-Ho-H2 consortium was formed through the signing of a Memorandum of Understanding between Ark Energy, which is Australia-based and owned by South Korean Korea Zinc, petrochemical firm Hanwha Impact, and SK Gas (Ark Energy, 2022). The project targets the development of 3 GW of solar PV and wind power in Collinsville, Queensland to produce one million tonnes of renewable ammonia annually by 2032. The project is supported by a feasibility study of up to AUD4.2 million, with FID expected around 2027.

5.4 Singapore

The fourth significant bilateral partnership in Australia's emerging hydrogen strategy has been developed with Singapore. As with the other partnerships, it is undergirded by a number of headline agreements. The Singapore and Australian governments signed a Memorandum of Understanding on Low Emissions Technologies in 2020, which included a commitment to cooperate on examining hydrogen and hydrogen-based energy supply chains, shaping international hydrogen standards, and hydrogen R&D. This was followed by the announcement of an AUD30 million partnership in June 2021 to facilitate collaboration on the decarbonisation of maritime and port operations through the use of low-carbon fuels. Under the partnership, governments from both countries are committing up to AUD10 million to fund industry-led pilot and demonstration projects over five years. Moreover, in October 2022, the new Australian federal government and the Singaporean government signed the "Australia-Singapore Green Economy Agreement." The broad-ranging agreement presages cooperation across a wide range of areas of relevance to decarbonisation, including trade and investment, standards setting, green and transition finance, technology, skills development, and innovation, business, and other partnership development.

6 Multilateral Engagement

A key problem to be managed as hydrogen is traded across national borders is defining and accounting for emissions across the entire supply chain, including those released during the production of hydrogen. One strategy for managing this problem is the implementation of a GO scheme, which provides transparency on the emissions embedded in a given hydrogen product as well as other environmental impacts (COAG Energy Council, 2021). An issues paper developed by the Australian government noted that a GO scheme enables consumers to understand the emissions embedded in hydrogen, although it left open whether government or industry should develop and administer the scheme.

Given the export focus of Australia's hydrogen strategy, its government has an interest in shaping multilateral frameworks governing the assessment of the carbon intensity of different hydrogen production methods. A key multilateral body through which governments are determining methodologies for calculating the emissions intensities of different production technologies has been the Hydrogen Production Analysis Taskforce (H2PATF), which is part of the International Partnership for the Hydrogen Economy (IPHE). There, Australia has been the lead country for developing the carbon accounting methodology for coal gasification with CCS, with Japan, South Africa and the United States as members of the working group. Australia has also participated in the working group examining SMR with CCS, along with the United Kingdom, the European Commission, and The Netherlands, led by France. The final report of H2PATF was released in November 2022. The methodology proposes calculating the GHG emissions per kilogramme of hydrogen ($kgCO_2e/kgH_2$) and includes fugitive emissions from the extraction of feedstock and emission from the transmission grid (IPHE Hydrogen Production Analysis Task Force, 2022).

In addition to the H2PATF, Australia has actively participated as a member of several multilateral organisations involved in information-sharing and capacity-building. Australia has acted as the co-lead with Germany and the European Commission, for example, in the "Innovation Challenge 8: Renewable and Clean Hydrogen" at Mission Innovation (MI), centred on information-sharing around the benefits of hydrogen hubs (termed "Hydrogen Valleys"). A second MI initiative focuses on innovation in hydrogen with the goal of reducing well-to-grave costs to USD2/kg by 2030 through promoting RD&D and demonstrating and disseminating knowledge about technology-push and demand-pull innovation. The initiative incorporates innovation targeting CCS, consistent with Australia and some other countries' position towards hydrogen production technologies. Australia has also acted as the co-chair along with Chile, the United Kingdom, the United States, and the European Commission (Mission Innovation, 2022). The Australian government has also been involved in the Centre for Hydrogen Safety, which promotes information sharing about hydrogen and fuel cell safety and has participated in energy ministers' meetings and working groups on climate sustainability and energy transition through the G20and the APEC Working Group on creating a Low-Carbon Hydrogen International Standard. On the industry side, the Australian Hydrogen Council is a founding member of the Global Hydrogen Industrial Association Alliance (GHIAA), which focuses on information sharing between peak hydrogen industry bodies across 13 different countries.

7 Conclusion

For decades, Australia supported economic growth in the Asia–Pacific region through the export of carbon-intensive fuels such as coal and gas, along with commodities used in emissions-intensive processes such as steelmaking. At the same time, the country has abundant, low-cost renewable energy resources, which could play a role not only in decarbonizing its domestic economy but also in facilitating the reduction of GHG emissions in the region. For Australia, decarbonization is thus a challenge both for the domestic economy and for trade and export-linked investments.

A key policy issue lies in overcoming the economic and technical barriers to enabling the rapid deployment of these resources to support decarbonization at home, while building international supply chains for large-scale export of low-cost renewable energy. It is in this context that hydrogen has emerged as a central vector for Australia's transition towards a net-zero economy, enjoying broad support from both national and state governments and industry. Hydrogen is being trialled as an option for supporting decarbonizing of the domestic economy, with developments in its use as a chemical feedstock, electricity grid support, mining and off-grid applications, and in blending in gas networks. However, a large part of the interest in developing a hydrogen industry is linked to its export potential, including the potential for increasing the share of value-added metals using hydrogen, such as green iron and alumina.

Australia's external hydrogen strategy reflects this export focus. Australia's first NHS was released following major trading partner Japan's 2017 launch of its hydrogen strategy, and national and state government support for industry development has a substantial—although not exclusive—export focus. The most advanced partnership is with Japan, with a March 2023 announcement of additional investment from Japan to enable commercialisation of a pilot project using hydrogen produced from a mix of coal and biomass. Moreover, Australia has the largest number of announced hydrogen projects globally. However, by 2023, only one project reached FID, and there has been concern that Australia's inherent advantages in terms of proximity to markets in the Asia Pacific, land availability, and abundant low-cost renewable energy may not lead to a substantial hydrogen export industry without additional measures put in place. The Hydrogen Production Tax Incentive and Hydrogen Headstart programmes sought to respond to increased international competition, and the Australian government and industry bodies have been actively involved in negotiating frameworks for governing the calculation of emissions embedded in different hydrogen production methods.

An additional issue facing government and industry is the technology choice for hydrogen production. The first NHS committed the government to supporting "clean hydrogen", which it defined as hydrogen produced using electrolysis and SMR coupled with CCS. The state of Victoria has even supported unabated coal gasification technology within the large-scale HESC project. These developments are consistent with the fact that Australia has abundant fossil fuel resources in addition to low-cost renewable energy, both of which can be used in the production of hydrogen. Public consultations leading up to the adoption of the 2019 NHS also showed substantial support amongst industry for the use of fossil fuels in the production of hydrogen. More recent policy developments, including the revised 2024 National Hydrogen Strategy, and substantial incentives included in the 2024–2025 federal budget, show a shift by the federal government towards an emphasis on renewable hydrogen.

Another question that remains unanswered is how competitive these different forms of hydrogen production will be in export markets and the role of hydrogen in the broader long-term decarbonization efforts across the region. The size of the emerging regional hydrogen market and the competitiveness of Australian hydrogen production within it also have important implications for its domestic economy, given the enormous growth in electricity demand implied by a large increase in Australian exports of low-carbon hydrogen.

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Hydrogen Policy in Brazil: Emerging Path to Green Re-Industrialization?

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Abstract Brazil has set the ambitious goal of becoming the world's most competitive hydrogen producer by 2030, leveraging its vast renewable energy potential. The development of a market for low-carbon hydrogen and ammonia is central to Brazil's green industrial policy and its new strategy for re-industrialization. While the country holds strong prospects for green hydrogen production, it presently lags behind current frontrunners, with most low-carbon hydrogen projects still in early stages. The recently introduced Hydrogen Act and accompanying tax credits are pivotal in shaping a policy framework, fostering low-carbon hydrogen production and usage. In the absence of a national hydrogen strategy, some states, most notably Ceará, have pushed ahead attracting considerable investments for hydrogen production and export in the past years. Internationally, Brazil has begun reasserting its engagement in hydrogen governance, hosting key global forums, and advancing bilateral and multilateral hydrogen cooperation. This chapter elaborates on these trends and provides a comprehensive review of policy objectives and initiatives, stakeholders, pilot projects, and international cooperation efforts related to the endeavor of creating a market for low-carbon hydrogen in Brazil.

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R. Quitzow and Y. Zabanova (eds.), *The Geopolitics of Hydrogen*, Studies in Energy, Resource and Environmental Economics, https://doi.org/10.1007/978-3-031-84022-7_8

1 Introduction

With its high share of renewables in the energy mix, abundant resources for a further expansion of renewable energy capacities, and an increasingly friendly political environment for regional and international cooperation, Brazil is well-positioned to become a future frontrunner in a global clean hydrogen economy. The country has recently signaled strong ambitions to develop a domestic market for hydrogen, adopting a favorable policy framework and attracting pilot projects, particularly in the coastal regions.

Broad support for hydrogen across Brazilian administrations has shielded the country's hydrogen policy from recent fluctuations in its climate and energy politics. From Dilma Rousseff's backing of the Paris Agreement to Jair Bolsonaro's strained ties with the EU over environmental protection, and Lula da Silva's renewed focus on the energy transition, the commitment to developing a hydrogen economy has remained in place. This resolve stems from a convergence of objectives: Hydrogen promises investments, economic and energy security, and climate change mitigation through industrial decarbonization. Developing a domestic market for hydrogen further feeds into the country's ambitions for rebuilding its industrial capacities.

This chapter offers a comprehensive overview of Brazil's hydrogen policy objectives and initiatives, relevant stakeholders, and international cooperation efforts. It thereby sheds light on current hydrogen projects and future ambitions at the federal and state levels. It further explores the interplay of the diverse policy objectives shaping the country's approach to hydrogen governance and elaborates on pivotal policy initiatives that align with these goals.

The chapter is structured as follows: Sect. 2 discusses the current and potential future role of hydrogen in Brazil's economy. Section 3 then delves shortly into the overarching goals driving the country's hydrogen policy. Section 4 outlines strategies and policy initiatives at both the federal and state levels. Section 5 focuses on investment and provides an overview of existing pilot projects and stakeholders. Brazil's efforts for international cooperation in the development of a hydrogen economy are addressed in Sect. 6. The final section of the chapter provides concluding remarks.

2 The Current Role of Hydrogen in the Brazilian Economy and Future Potentials

Hydrogen already plays an important role in Brazil's industry. Latin America, in general, consumes about 5% of the global demand for hydrogen, and approximately 10% of this is consumed in Brazil (IEA, 2021). This makes Brazil one of the four largest consumers of hydrogen in the region. This hydrogen is currently still mostly produced from natural gas via steam methane reforming (SMR) in refineries, particularly those belonging to the country's national oil company Petrobras. As of 2022, 87% of the hydrogen produced in Brazil came from SMR, being mostly used in the refineries themselves and, occasionally, also for fertilizer production. In refineries, hydrogen is primarily used in the hydrotreating of fuels (MME, 2022).

While the country's production of hydrogen in refineries is expected to remain stable in the foreseeable future (MME, 2022), new initiatives have been ramped up throughout the country to produce low-carbon hydrogen and its derivatives. As of October 2024, the International Energy Agency (IEA) registered 42 low-emission hydrogen projects in Brazil (IEA, 2024). While this is only a share of what firms in frontrunner countries such as Germany or the United States have initiated, no other country in the region, except Chile, registers as many projects as Brazil (see Fig. 1). Most of them, however, are still at an early stage of development. Almost half of the projects are expected to generate ammonia, underscoring the country's ambition to become a leader in the production of green fertilizers (see Sect. 3).

According to recent estimations, green hydrogen produced in Brazil could have one of the lowest levelized costs in the world (Bhashyam, 2023). Particularly the regions in the Northeast and South are projected to be one of the most promising locations globally for producing clean hydrogen and its derivatives (Agora Hank et al, 2023; Industry et al, 2024). Brazil's energy mix already relies strongly on renewable energy (including hydropower and biomass), accounting for 49% of the country's total energy supply and 89% of its electricity supply (IEA, n.d).

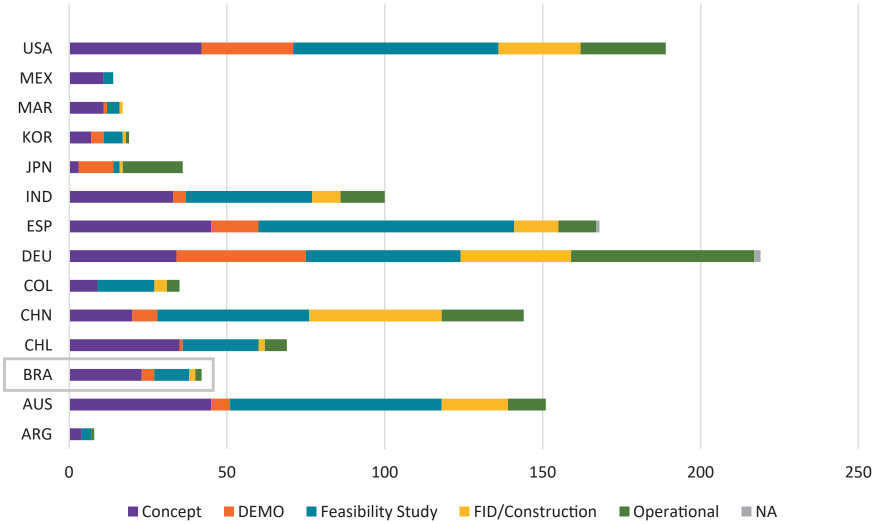

Fig. 1 Number of low-emission hydrogen projects by development stage in selected countries. *Source* Authors, based on data from IEA (2024)

3 Policy Objectives Guiding Brazil's Green Hydrogen Ambitions

Brazil's hydrogen policy is steered toward three overarching objectives: strengthening economic and energy security; achieving decarbonization; and attaining economic growth, competitiveness, and re-industrialization by attracting green investment. Over the past years, these interrelated goals have guided policymaking to varying degrees.

The pursuit of economic and energy security[1] has a long history in the country and is associated with two political strategies employed in the recent past: First, Brazil has made repeated efforts to gain sovereignty over its energy resources and related rents. The most important decisions taken in this context were the creation of Petrobras, the country's national oil company, in 1953 and the establishment of Eletrobras, its national utility company, in 1962. Second, Brazil has invested strongly in a diversification of its energy mix to safeguard the country against supply fluctuations and price shocks, particularly in oil and gas. In reaction to the oil crisis of the 1970s, it passed the *Pro-Álcool Program* with the aim of substituting petroleum-based fuels with ethanol. The program has widely been considered a success (Oliveira, 2002). The country has also promoted hydropower and nuclear energy early on to reduce its heavy reliance on fossil fuels. In 1985, both the Itaipu Hydroelectric Dam and the first Angra Nuclear Power Plant were opened. More recently, the country started the exploration of the pre-salt oil and gas layers starting in 2010.

The promotion of green hydrogen promises to feed these demands for economic and energy security in two ways: First, Brazil's agriculture industry demands large amounts of fertilizer and, so far, strongly depends on imports. As of 2023, the country imported about 80% of its fertilizer, which turned out to be costly when Russia's war in Ukraine caused a global supply crisis (Ysamat, 2023). In reaction, the Bolsonaro administration drafted the *National Fertilizer Plan* in 2022, whose central aim is to reduce import dependencies (Brazil, 2022). The production of green fertilizers—with green ammonia as the main feedstock—could therefore serve to reduce both import dependencies and greenhouse gas (GHG) emissions. Second, hydrogen could contribute to enhancing the stability of Brazil's energy system. It relies strongly on hydropower and other renewable sources, which tend to be subject to output fluctuations. In times of low supply, particularly in the dry season, stored hydrogen could balance these fluctuations (Agora Industry et al, 2024).

Another important objective for Brazil's hydrogen strategy (particularly since 2023) is decarbonization, frequently mentioned in official documents, at both the federal and state level. The country's current president Lula da Silva has, in public statements, repeatedly linked Brazil's green hydrogen ambitions with the government's renewed drive toward environmental protection and decarbonization, signaling intensified interests in the development of sustainable hydrogen compared to the previous administration of Jair Bolsonaro (Brazil, 2023c; 2023a; 2023b). This

[1] Economic security is for the purpose of this chapter understood as the reduction of exposure to foreign trade (McCaffrey & Poitiers, 2024).

discursive shift might also be beneficial for fostering international cooperation, as a pro-decarbonization government might have more leverage to sell the ambition for developing a national hydrogen economy.

Sectors such as transportation and hard-to-abate industries like steel, petrochemical, and cement are seen as important targets for decarbonization through hydrogen (MME, 2023; Brazil, 2024d). Decarbonized industrial products might be consumed domestically or exported, particularly green fertilizer. The Brazilian government considers hard-to-abate sectors as objects of a long-run decarbonization mission, which could be addressed through the building of experimental hubs within the framework of a national energy transition policy. This could allow for the building of synergies “between energy generation and related infrastructure, seeking to catalyze national efforts for the decarbonization of hard-to-abate sectors” (MME, 2023). It should be noted, however, that green hydrogen is only one decarbonization pathway that the government is pursuing. The production of biofuels, so-called fuels of the future also plays an important role in the government’s decarbonization policy (Brazil, 2024a).

The third objective that is linked to the promotion of hydrogen in Brazil is the quest for re-industrialization, competitiveness, and economic growth. The country’s high potential for low-cost clean hydrogen promises to deliver jobs, growth, and even industrial leadership in a future green hydrogen economy. In this vein, the Brazilian government is strongly invested in international cooperation for the development of an export market for hydrogen and hydrogen-based industrial and chemical products (see Sect. 6). These ambitions for growth and competitiveness are embedded in Brazil’s agenda for “neo-industrialization” spelled out in its New Industry Brazil (NIB) Program (Brazil, 2024a), launched in January 2024. After experiencing decades of deindustrialization, the program’s central goal is to strengthen the country’s competitiveness in new and established industries. Supporting the development of a clean hydrogen economy is expected to serve this objective (Brazil, 2024a, 2024b). Moreover, its support for clean hydrogen is driven by concerns about competitiveness in future decarbonized international markets. Brazil’s industry needs to secure the supply of low-carbon hydrogen to not risk losing access to markets that are increasingly adopting GHG-related import requirements. Several industrial products exported to the EU, the UK, and potentially to other markets will fall under carbon border adjustment mechanisms (CBAMs) planned by these jurisdictions (Perdana et al, 2024).

Thus, Brazil’s approach to hydrogen, which is strongly embedded in its green industrial policy, seeks to balance these three overarching objectives. Although it remains unclear to what degree the mitigation of GHG emissions is prioritized over the others, there seems to be no general conflict between strengthening economic and energy security, achieving decarbonization, and fostering economic growth and international competitiveness in Brazil.

4 Governing Hydrogen: Policy at the Federal and State Level

In Brazil, hydrogen production, infrastructure, and usage have been promoted not only by the federal but also by state governments. This section retraces the policy developments related to hydrogen at both levels. While the federal government adopted subsidies and standards for low-carbon hydrogen in 2024, some states have pioneered the promotion of hydrogen even earlier, attracting considerable investments and building pilot projects. After illustrating the evolution of the federal policy landscape, we discuss the ambitions and strategies of state governments.

4.1 Governing Hydrogen at the Federal Level

From 2002 onwards, Brazil's federal government has progressively focused on the development of a hydrogen economy through multiple strategic policy documents and initiatives. Table 1 provides an overview of the most important documents and laws. Although no official national hydrogen strategy has been developed so far, the body of existing laws, programs, roadmaps, and official studies provide the basis for assessing Brazil's federal hydrogen policy.

Starting with the *Brazilian Hydrogen and Fuel Cell Systems Program* (PROCAC), which was later renamed the *Science, Technology and Innovation Program for the Hydrogen Economy* (PROH2), efforts have been made to enhance research and development (R&D) in hydrogen and fuel cell technologies (FCT) by fostering public–private partnerships and protecting intellectual property. In 2005, the Ministry of Mines and Energy (MME) together with the Ministry of Science, Technology, and Innovation (MCTI) developed the *Roadmap for the Structuring of the Hydrogen Economy in Brazil*, a comprehensive study to assess the prospects and challenges for creating a hydrogen market in Brazil. In consideration of the country's competitive advantages, it proposed to prioritize various technological pathways, including electrolysis but also ethanol, and natural gas reforming (EPE, 2021). In 2010, another study commissioned by the MCTI followed up with concrete policy recommendations for fostering hydrogen supply, demand, and infrastructure (CGEE, 2010). Although hydrogen was mentioned in the *Science, Technology and Innovation Plans* for Electricity and Biofuels published in 2017 and 2018, the federal government at that time did not seriously engage in creating a favorable policy environment for the development of a hydrogen market. The *National Energy Plan 2050*, launched in 2020 by the MME, addresses hydrogen as a key component for decarbonizing Brazil's economy, but without providing clear guidance on technology and sector prioritization (EPE & MME, 2020). The call for a "rainbow" (p. 26) strategy with no special emphasis on green hydrogen was reasserted by the MME in another report published one year later (EPE, 2021).

Table 1 Policy documents and federal laws related to hydrogen in Brazil

Policy document/law	Year	Description
Brazilian Hydrogen and Fuel Cell Systems Program (PROCAC/ PROH2)	2002	• Promotes the establishment of research networks and intellectual property protection for R&D in hydrogen and FCT
Roadmap for the Structuring of the Hydrogen Economy in Brazil	2005	• Elaborates on potentials and challenges for hydrogen market development in Brazil
Hydrogen Energy in Brazil—Support for Competitiveness Policies: 2010–2025	2010	• Outlines strategic guidelines for creating a hydrogen economy (incl. production, infrastructure, and usage) • Makes policy recommendations for all segments of a future Brazilian hydrogen economy
Strategic Agenda for Science, Technology, and Innovation in the Brazilian Electricity Sector	2017	• Details objectives for hydrogen and FCT research and innovation policy
Science, Technology, and Innovation Plan for Renewable Energy and Biofuels: 2018–2022	2018	• Encourages demonstration projects for hydrogen production
National Energy Plan 2050	2020	• Acknowledges the potential of hydrogen for the decarbonization of the economy • Discusses different technological pathways
Baseline to support the Brazilian Hydrogen Strategy (Technical Note)	2021	• Details main opportunities and challenges to the development of hydrogen production and use in Brazil
National Hydrogen Program: proposal for guidelines	2021	• Highlights domestic and international hydrogen prospects • Establishes objectives and principles for the National Hydrogen Program • Maps the governance structure of the National Hydrogen Program
PNH_2's three-year work plan (2023–2025)	2023	• Defines the main areas for political support • Proposes policy strategies and tax incentives (especially for low-carbon hydrogen) • Positions Brazil as a key player in the global energy transition
New Industry Brazil Program	2024	• Presents a green industrial policy strategy that includes hydrogen promotion as a priority for industrial decarbonization
Law 14948/24 (Hydrogen Act)	2024	• Establishes the legal framework for low-carbon hydrogen promotion • Defines low-carbon, renewable, and green hydrogen and creates a certification scheme • Establishes tax credits for low-carbon hydrogen
Law 14990/24 (Low Carbon Hydrogen Development Program)	2024	• Establishes a subsidy program to facilitate the production and usage of hydrogen in heavy industry and transport

Sources Authors' compilation based on CGEE (2010), CGEE (2017), MCTI (2018), MME (2020), GIZ (2021), EPE (2021), MME (2021), Brazil (2024c, 2024d)

Since 2021, hydrogen has become more central to energy and industrial policy in Brazil. In April of that year, the *National Council of Energy Policy* (CNPE) adopted a resolution for the creation of a *National Hydrogen Program* (PNH2). In response to this, the MME led the development of guidelines that specify objectives and principles for the program. Again, the government emphasizes its intention to promote hydrogen in accordance with the country's "national potential of energy resources" (p. 13), not precluding hydrogen production from non-renewable sources (EPE & MME, 2021). The PNH2's three-year working plan for 2023–2025, which was developed under the auspices of Lula's Minister of Mines and Energy, Alexandre Silveira de Oliveira, departs from this approach putting decarbonization and climate change mitigation at the center of hydrogen policy. The plan thus prioritizes low-carbon hydrogen and calls for the development of respective standards and certification schemes. It further tries to harmonize the policy efforts by establishing six main axes for the PNH2: (1) strengthening technological bases, (2) training human resources, (3) conducting energy planning, (4) creating regulatory frameworks and (5) fostering neo-industrialization and competitiveness as well as (6) international cooperation. The plan also presents a progression in terms of ambition, setting the goal of becoming the world's most competitive producer of low-carbon hydrogen worldwide by 2030 (MME, 2023).

The launching of the NIB Program in early 2024 has further clarified Brazil's ambitions for fostering hydrogen production and use. The program establishes a green industrial policy agenda combining the objectives of industrial development and decarbonization. Thereby, it seeks to promote the development of domestic industries targeting "the nationalization of production and equipment dealing with renewable energy generation" in the country (Brazil, 2024a). The promotion of low-carbon hydrogen is one of the policy priorities laid out in the program. In total, around USD 50 billion (BRL 300 billion) of funding from different sources will be made available until 2026 to support the objectives set by the NIB (Brazil, 2024b). Although it is unclear what share will be devoted to hydrogen, the development of "renewable energy capacities, particularly solar, wind and low-carbon hydrogen" is stated as one out of five priorities for financing with regards to decarbonization (Brazil, 2024a, p. 79).

Despite this multitude of studies and strategy documents, impactful policies promoting hydrogen investment at scale remained scarce. This changed with the adoption of the *Hydrogen Act* and the *Low Carbon Hydrogen Development Program* (PHBC) in 2024. Brazil's Hydrogen Act which became law on 6 August 2024 established a new regulatory framework for hydrogen development in the country. The framework is guided by five central principles (Brazil, 2024c):

- Respect for technological neutrality in the definition of incentives
- Competitive inclusion of low-carbon hydrogen in the energy mix for decarbonization
- Predictability in formulating regulations and granting incentives for market expansion
- Rational use of the existing infrastructure dedicated to energy supply

- Encouraging research and development for the use of low-carbon hydrogen.

Particularly the first is reflected in the way renewable and low-carbon hydrogen are standardized by the Hydrogen Act. Renewable hydrogen is defined as hydrogen "obtained from renewable sources, including hydrogen produced from biomass, ethanol, and other biofuels, as well as electrolytic hydrogen, produced by electrolysis of water, using renewable energies, such as solar, wind, hydraulic, biomass, ethanol, biogas, biomethane, landfill gas, geothermal and others to be defined by the government" (Brazil, 2024c). This standard interprets "renewable" broadly and leaves open the possibility for further extensions by the government. Low-carbon hydrogen is defined by the maximum amount of permittable lifecycle emissions. Initially, the bill foresaw low-carbon hydrogen to account for no more than 4 kg of CO_2-equivalent per kilogram of hydrogen produced (4 $kgCO_2eq/kgH_2$). In July 2024, however, the Brazilian Senate decided to raise the threshold to 7 $kgCO_2eq/kgH_2$, which was later adopted in the Hydrogen Act. This is currently the highest permittable emission level for low-carbon hydrogen apart from the unofficial standard suggested by the China Hydrogen Alliance (see Gong & Quitzow in this volume).[2] The controversial decision might have been motivated by the goal of making hydrogen produced from ethanol eligible for subsidy programs (Collins, 2024a).

The law also creates the country's own certification scheme, the *Brazilian System of Hydrogen Certification* (SBCH2), in which membership will be voluntary. Moreover, it includes subsidy programs: The *Special Incentive Regime for Low-Carbon Emission Hydrogen Production* (Rehidro) foresees tax breaks for companies using products made in Brazil in their hydrogen supply chain. The program is an extension of the *Special Regime of Incentives for Infrastructure Development* passed in 2007, allowing tax exemptions when acquiring or renting equipment for infrastructure development. The budget of the program is equally unclear. To benefit from the regime, firms need to comply with specific requirements, particularly a minimum share of domestic goods and services to be utilized, as well as a minimum investment in RD&I. Finally, there shall be a cap on the maximum share of hydrogen that can be exported after making use of this incentive. If passed, companies wishing to request the benefit will have five years to adapt to the requirements.

The PHBC, adopted shortly after the Hydrogen Act, will subsidize the promotion of low-carbon hydrogen in hard-to-abate sectors (including fertilizer, steel, cement, chemical, and petrochemical industries) and heavy transport. Most importantly, the PHBC grants a "tax credit on the sale of low-carbon hydrogen and its derivatives produced in the national territory" (Brazil, 2024d). Between 2028 and 2032, tax credits are expected to amount to over USD 3.3 billion (BRL 18 billion), which will be granted to producers and buyers of low-carbon hydrogen.

The funding shall generally be provided via budget allocations, donations from domestic or international bodies (either public or private), loans from domestic and

[2] For comparison, the EU's threshold is much lower, defining low-carbon hydrogen as hydrogen produced with lifecycle emissions not exceeding 3.38 $kgCO_2e/kgH_2$ (EU, 2023). Unlike the EU criteria for clean hydrogen, Brazil's Hydrogen Act foresees no additionality criteria.

international financial institutions, as well as the share of surplus profits of official financial development agencies from the previous financial year. Companies interested in producing low-carbon hydrogen take part in a competition with rules proposed by the PNH2 management committee. If the bid is successful, PHBC subsidies will be granted for ten years.

Another boost for the country's competitiveness could come from the recent approval of its Investment Plan for the *Renewable Energy Integration Program* to be funded by the Climate Investment Fund, one of the largest multilateral climate funds. The plan is expected to unlock additional resources amounting to USD 1.09 billion for industrial decarbonization and the creation of low-carbon hydrogen hubs (Collins, 2024b). A first call for project proposals was issued in October 2024 (MME, 2024).

These policy advances all take place in the context of broader discussions on the re-industrialization of the Brazilian economy. The current Lula administration has consistently linked this idea to the ambition of building a green economy, which might be interpreted as a response not only to civil society pressures for more sustainability but also to the desire for a new narrative for future development projects with both domestic and international appeal. In early 2023, the Ministry of Development, Industry, Trade and Services (MDIC) announced the creation of a new Secretariat for Green Economy, Decarbonization, and Bio-Industry, working alongside the Ministry of Environment (MMA), promoting the administration's green industrial policy agenda (Brazil, 2023d).

The government's focus on low-carbon over green hydrogen, defined in the Hydrogen Act as "produced by electrolysis of water, using renewable energy sources" (Brazil, 2024c), reflects its emphasis on aligning the country's hydrogen ambitions with the potentials of its energy mix. Brazil seeks to declare hydrogen from ethanol as sustainable, capitalizing on its large ethanol industry. Furthermore, the country has large natural gas reserves, which could be beneficial for producing blue hydrogen (Agora Industry et al, 2024). Interestingly, the preferred terminology also varies in official documents according to the actors concerned: subnational stakeholders aiming to produce and export hydrogen sourced through wind and solar often refer to "green hydrogen" in their programs, bills, and decrees.

The small but growing number of laws incentivizing particularly hydrogen production points to the acceleration of the policy discussion in Brazil between 2023 and 2024. Federal-level hydrogen policymaking has gained momentum, making the country's stance clearer for stakeholders and society. These plans and policies will be welcomed by partners and investors as they provide incentives and increase legal certainty for current and future hydrogen projects in the country. Generally, they signal that hydrogen has constituted a priority in Brazil's climate, energy, and industrial policy.

4.2 Governing Hydrogen at the State Level

While Brazil's main legislative framework for hydrogen governance is now established at the federal level, hydrogen policies have also been developed at the subnational level and ambition varies significantly from state to state. Ceará, for instance, is a trailblazer for green hydrogen development. The uneven distribution of state-level policies across the nation reflects different points of departure regarding energy mix, geographical location, pre-existing cooperation agreements, and political ambition. In the absence of a national hydrogen strategy, many states have, particularly since 2021, adopted hydrogen policies and programs to promote its production, transport, and usage. Table 2 in section 5 below provides an overview of hydrogen-related policy initiatives at the state level.

States from the Northeast have so far been the most ambitious in developing policies, focusing mostly on hydrogen export. They enjoy favorable conditions due to their existing renewable energy capacities and relative proximity to Europe. Being the most industrialized and logistically developed in the country, states in the South and Southeast have generally been less ambitious in adopting export-oriented hydrogen policies. The incentives for hydrogen exports are less pronounced, justifying why many of the projects in these regions have a stronger focus on domestic (or non-specified) markets. Rio de Janeiro is an exception, having developed a pilot project for hydrogen production and export at the Port of Açu. São Paulo state, the country's most industrialized and largest subnational economy, accounting for approximately 30% of the country's GDP (Exame, 2023), has not yet developed ambitious hydrogen policies. Western regions have also not shown the same ambition as the Northeast for crafting hydrogen markets. Overall, the state policy frameworks of northeastern states are the most extensive, relying on financial instruments such as tax breaks or low-interest loans to promote research and equipment acquisition, as well as hydrogen usage in transport and agriculture.

5 Investing in Green Hydrogen: Stakeholders, Partnerships, and Pilot Projects

This policy environment is giving rise to a still limited but growing low-carbon hydrogen market in Brazil. Firms have started to invest in hydrogen production and infrastructure, either on their own or in cooperation with other private or public entities. Important private stakeholders are, in the first place, those companies already engaged in the production and usage of hydrogen. As the Brazilian market is strongly dominated by Petrobras, hydrogen-producing firms are limited in number. Besides Petrobras, which is currently responsible for over 90% of hydrogen output in the country, other market participants are Messer, Air Liquide, Air Products, and Linde.[3]

[3] Linde was acquired by Messer in 2019. It is represented by White Martins in Brazil (GIZ, 2021).

Petrobras' role as Brazil's main hydrogen producer, now and possibly also in the future, cannot be overstated. The national oil company combines a strong tradition in energy and is considered a strategic asset for both investors and society at large and, although there are many controversies surrounding the state's role in its management, it has a reputation of being a frontrunner in new and risky energy enterprises. Petrobras also controls much of the country's long-distance pipeline network, which could theoretically be adjusted to accommodate hydrogen transport. Finally, the company has already gained much experience in sourcing hydrogen for fertilizer production, which could promptly synergize with the country's announced plans to revive the fertilizer industry. Although the Brazilian state is Petrobras' main shareholder[4] (Petrobras, 2023) the company is a publicly traded corporation and thus relies strongly on private investments. For Petrobras, the involvement in the production of low-carbon hydrogen and ammonia could provide a pathway for diversifying its portfolio, which is still heavily dependent on fossil fuels.

However, other private and public companies have also started to invest in hydrogen (see EPE, n.d for an overview). The fact that most of these firms are not based in Brazil legitimizes the government's current ambition to create favorable conditions for domestic companies along the hydrogen value chains (see Sect. 4.1). The geographical distribution of pilot projects largely reflects the different levels of ambition in state-level policymaking. Firms have often cooperated with local and state governments to realize hydrogen production or infrastructure projects. Most of the existing local initiatives are still in the stage of development, focusing on production, research, and in some cases international cooperation for export. In the following, we discuss some of the most important pilot projects and partnership agreements that have been pursued to realize the production and use of hydrogen in and beyond Brazil.

The first green hydrogen plant was launched in December 2021 in Itumbiara (Goiás state), where experiments were carried out to study the production and storage of hydrogen, as well as its re-conversion into electricity and its feeding into the country's power grid. The hydrogen has been generated from both a solar and a hydropower plant (Gontijo, 2023). In November 2023, EDP (with its Pecém project) and Eletrobras Furnas (in Itumbiara) received the first renewable hydrogen certificates in Brazil, following EU guidelines, being issued by the National Electricity Trade Chamber (CCEE, 2023; H2LAC, 2023).

In the state of Pernambuco, the Brazilian subsidiary of China's state-owned energy firm CTG collaborated with the state government to launch the *Green Hydrogen TechHub* at the Port of Suape, the most important in the country's Northeast. The aim is to foster research and development focusing on the production, transport, and storage of green hydrogen (Suape, 2022). This collaboration also involves the National Service for Industrial Training (SENAI), which has signed a Memorandum of Understanding (MoU) with CTG and the Government of Pernambuco in 2022.

[4] As of end of 2023, the Federal Government holds 50.26% of Petrobras' common shares (Petrobras, 2023).

In Rio de Janeiro state, multiple hydrogen projects are planned at the Port of Açu, which has an important oil and gas service infrastructure and, similar to other Brazilian ports, has shown interest in having a large offshore wind farm built in its area (Neder, 2022). If successful, this would allow large-scale hydrogen production facilities, be it for local consumption or exports. A first MoU was signed in May 2022 between the port's operator and Shell. It is expected that the pilot plant will become operational in 2025. The proposal envisions an electrolysis plant as well as a renewable ammonia plant and explicitly aims to integrate local firms along the supply chain, not having to rely only on exports (Porto do Açu, 2022). The Norwegian company Fuella is further planning to build a green ammonia plant at the port's site (Porto do Açu, 2024). Most recently, HIF Global signed a land reservation contract with the Port of Açu to realize a large e-methanol project that is expected to produce about 800,000 tons per year (HIF Global, 2024). Unlike the ports of Pecém and Suape, the Port of Açu is privately owned and is thus perhaps the most relevant case of an international private-private port partnership for the development of low-carbon hydrogen in the country.

In 2023, the state of Rio Grande do Sul signed an MoU with the Port of Rotterdam aiming at fostering the production of onshore and offshore renewable energy and green hydrogen in the vicinities of the Rio Grande Port. The signing took place during the World Hydrogen Summit in 2023 (Rio Grande do Sul, 2023b). Additionally, Neoenergia, controlled by the Spanish Iberdrola Group, signed an MoU with the Rio Grande do Sul state for the development of wind power projects and green hydrogen production (Neoenergia, 2022).

The state of Piauí announced two important projects for green hydrogen production in December 2023 (Brazil, 2023e). The recently inaugurated Piauí Port is planned to host green hydrogen facilities in the Export Processing Zone (EPZ) of Parnaíba. It is estimated that USD 35.7 billion (BRL 200 billion) will be invested in the project through public–private partnerships. The state of Piauí has developed strategic partnerships for the construction of one of the world's largest projects for green hydrogen and green ammonia production, which could make hydrogen one of the main products for the Parnaíba EPZ. It is expected that both plants (planned to be operational in 2035) will generate 20 GW of power. The companies *Green Energy Park* from Croatia, and *Solatio* from Spain, are the main private investors (Freire, 2023). Once operational, with construction set to begin in 2024, exports are to be directed to Europe, Asia, and the Middle East. Piauí state has partnered with the EU and is expected to receive around USD 10.7 billion (BRL 60 billion) of investments in green hydrogen production as part of Brazil's PNH2.

Apart from port-centered infrastructure, the Federal University of Santa Catarina (UFSC) opened its *Solar Energy and Green Hydrogen Research Laboratory* in August 2023, which includes a pilot plant producing nitrogen fertilizer from green hydrogen. The project resulted from Brazilian-German cooperation, receiving financial and technical support from the German government (UFSC, 2023). Germany also supports the development of a hydrogen research center at the Federal University of Itajubá. The facility includes an electrolyzer and a refueling station for facilitating research on the application of hydrogen in the transport sector (CH2V, n.d). The research center focuses on the application of hydrogen in the transport sector.

In the state of Paraná, the *Itaipu Technological Park* (PTI), located in the border city of Foz do Iguaçu, has advanced research in renewable hydrogen production over the past 12 years. The research center is operated by *Itaipu Binacional*, which also manages the Itaipu Hydroelectric Power Plant, the country's largest. PTI uses its own green hydrogen pilot plant to research the potential for producing and applying hydrogen in the transport and chemicals sector. In May 2023, the state government announced a USD 89.1 million (BRL 500 million) investment in green energy, which could incorporate green hydrogen. The know-how that has been developed at PTI, as well as the strategic location at a trinational border (Argentina, Brazil, and Paraguay) could contribute to the development of a regional hydrogen economy.

Finally, the largest project aimed at producing green hydrogen and ammonia is located in the state of Ceará. In 2021, the state government partnered with the Port of Pecém, the Federation of Industries of the State of Ceará, and the Federal University of Ceará to create a "Green Hydrogen Hub". As of late 2023, over 30 MoUs had been signed between the state government and other actors with the aim of producing and exporting green hydrogen and ammonia. The *Pecém Complex*, located in the city of São Gonçalo do Amarante, is a joint venture between the Ceará government and the Port of Rotterdam, officially launched in October 2018 (Ceará, 2018). As time progressed, the port's operations have developed projects with already existing renewable energy facilities in the state, stressing the potential for expansion in the area. Given the existing partnership with Rotterdam, Europe's largest port, the production and export of green hydrogen through Pecém was envisioned and kickstarted in 2021 and is an important flagship project of the state government.

As of late 2023, Ceará had 100 wind power farms (generating 2.5 GW), as well as 72 that had been commissioned (with a 2.8 GW capacity). Other 26 offshore projects (with an expected 64.9 GW capacity) were expecting environmental licensing from the Brazilian Institute of Environment and Renewable Natural Resources in early 2024. As for solar, 1.5 GW of installed capacity was spread among 35 initiatives across the state, whereas 419 solar plants were under construction with an estimated 16.7 GW capacity (Ceará, 2024). The existing and potential capacity for renewable energy production is an important asset for the development of a green hydrogen economy in the state.

As of January 2024, the current and expected investments in the Pecém Green Hydrogen Hub amounted to USD 30 billion, including signed pre-contracts amounting to USD 8 billion (Ceará, 2024). These numbers are likely to grow if international partners, such as several European countries, uphold their plans to upscale green hydrogen use. In December 2022, the Portuguese company EDP, one of Ceará's main partners for green hydrogen production, announced the creation of its first green hydrogen molecule produced in Brazil. This took place in Pecém's thermal power station in an existing pilot project for green hydrogen production. In January 2023, efforts were further intensified announcing the creation of a green power plant (EDP, 2023).

The focus of Ceará state on green hydrogen production and its relatively broad public–private partnerships in the field is a result of a longer-standing strategy by the state toward capitalizing global green hydrogen demand by making use of its existing renewable energy capacities, as well as its export facilities. These elements (large existing and expanding solar and wind projects, existing relations with foreign actors in international trade activities, as well as geographical proximity to Europe relative to other Brazilian regions) have contributed to a unique hydrogen profile. The adoption of the *State Policy for Green and Sustainable Hydrogen and its Products* (see Table 2) and the establishment of a green hydrogen council further facilitate these ambitions (Ceará, 2023).

The state of Ceará hence stands out as a pioneering subnational force in the green hydrogen economy. Through comprehensive planning and public–private collaboration, the state has attracted significant attention, pushing ahead with the production and exportation of green hydrogen. The strategic establishment of the Green Hydrogen Hub, bolstered by partnerships with entities like the Port of Rotterdam, has positioned Ceará as one of the leaders in renewable energy in Brazil. The state's plans to strengthen its green hydrogen infrastructure, reinforced by substantial investment and partnerships, highlight a promising model for leveraging local resources for the energy transition. However, as other states ramp up their investment in green hydrogen production through different pilot projects, they might also become potential frontrunners, depending in particular on their specific energy environment and trade capabilities.

6 International Hydrogen Cooperation

Since the return of Lula as president, Brazil has been heavily invested in demonstrating its renewed engagement in international cooperation, particularly with regard to environmental and climate politics. Under its presidency, it hosted the G20 Summit in 2024 under the slogan "Building a Just World and a Sustainable Planet" and will host the United Nations Climate Change Conference (COP) in 2025. Concerning green hydrogen in particular, the PNH2's Three-Year Plan considers the support for "cooperation at the regional and global level" as one out of six central elements for the promotion of hydrogen (MME, 2023). Generally, the federal government and subnational actors in Brazil have engaged in international cooperation at three levels: First, Brazil has been actively involved in multilateral hydrogen forums. It has, second, engaged in club cooperation across the region and within the BRICS. Third, Brazil has advanced several bilateral initiatives related to green hydrogen production and trade.

At a global level, Brazil has been involved in the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE) as one of its founding members. Its participation in the IPHE was the result of US-Brazil diplomatic talks in 2003 when Washington invited the country (at the time, under Lula da Silva's first administration) to be a member. This took place along with another invitation by the United States for

Table 2 State-level policy initiatives and programs for hydrogen in Brazil

State/federal district	Law
Alagoas	• Law 9360/2024 promotes the production, processing, and use of green hydrogen, aiming to modernize, diversify, and decarbonize the local industry • The law supports scientific and technological research and encourages the establishment of green hydrogen firms
Amazonas	• Law 6376/2023 declares climate emergencies and environmental racism a matter of state interest and cites RD&I, production, and usage of green hydrogen as a state priority • Bill 12/2024 outlines a framework for producing green hydrogen in the state, defining it as hydrogen produced via water electrolysis with zero carbon emissions • The bill encourages inter-institutional cooperation among government, research, and private sectors while promoting R&D through research centers and pilot plants
Bahia	• Decree 21200/2022 establishes the *State Plan for the Green Hydrogen Economy*, aiming to curb GHG emissions, attract investments, and foster scientific advancement in green hydrogen production and use • Further aims are forming partnerships, aligning policy with global initiatives, incentivizing projects, and establishing a business-friendly environment to develop and modernize the local green hydrogen industry • The decree encourages diverse economic sector engagement, particularly in industry, urban mobility, and transportation
Ceará	• Law 18459/2023 establishes the *State Policy for Green and Sustainable H2*, focusing on the diversification of the energy mix and GHG emission reduction • It governs the exploration, production, transportation, and storage of green hydrogen, emphasizing national interest, public utility, and sustainability as priorities • Objectives include increasing the state's green hydrogen share, fostering related research, and stimulating investment in the green hydrogen sector • The state government created the *State Council for the Governance and the Development of Green and Sustainable Hydrogen and its Products* to guide and develop the field
Espírito Santo	• *Program for Renewable Energy Generation within the Sustainable Chain* (2023) has the aim of fostering the production, storage, and use of sustainable hydrogen • It revolves around regional development policies, regulation, incentives, financing, and socio-economic benefits
Federal District	• Law 7.404/2024 establishes the *Federal District's Green Hydrogen Policy* to reduce carbon emissions and expand the Federal District's energy mix • It outlines several goals, such as reducing GHG emissions, supporting technological development, attracting investment, and promoting infrastructure for green hydrogen • It encourages tax credits and partnerships to enhance hydrogen and calls for the decarbonization of transport • The program is funded by specific budget allocations and includes a system for monitoring and evaluation

(continued)

Table 2 (continued)

State/federal district	Law
Goiás	• Law 21767/2023 establishes the *State Policy for Green Hydrogen*, tackling the promotion of green hydrogen, encompassing research, production, regulation, financing, investment, use, and collaborative partnerships
Maranhão	• The state government established the state policy for fostering green hydrogen production and use both for hydrogen and fertilizer production in 2023 • Included in the new *Policy of Ecological Taxation,* it promotes incentives for acquiring hydrogen-related equipment and facilities, focusing on partnerships (also in RD&I)
Mato Grosso	• Bill 1032/2021 proposes a public policy for green hydrogen in the state, aiming to enhance its contribution to the energy mix, particularly for agriculture • It stresses climate change mitigation and fostering the state's green hydrogen supply chain through incentives, legal frameworks, and infrastructural investment • Bill (1521/2024) seeks to establish the *State Policy for Renewable and Low-Carbon Hydrogen*, outlining a plan to develop a hydrogen economy • It encourages investment in research, production, and consumption of renewable and low-carbon hydrogen • It supports transitioning to a low-carbon economy by replacing fossil fuels and developing hydrogen infrastructure, including hubs • It promotes collaboration among various sectors and proposes incentives for hydrogen-related investments
Minas Gerais	• The state government and the Federation of Industries of Minas Gerais launched the program *Minas do Hidrogênio* in 2021 • It focuses on solar energy use for electrolysis-based hydrogen production, as well as biomethane and ethanol as sources • The stated goal of the project is to have the local industry use the hydrogen produced • State law 24940/2024 established the framework for the development and utilization of low-carbon and green hydrogen in the state • It aims to integrate hydrogen into the energy mix, reduce GHG emissions, and combat climate change • It promotes technological advancements, investments in infrastructure, and the development of a hydrogen value chain, focusing on applications in energy and agriculture • It provides fiscal instruments to encourage the production and acquisition of hydrogen-related equipment • It includes support for innovation and technological enterprises linked to hydrogen
Paraíba	• Law 12345/2022 established the state's public policy for green hydrogen aiming at GHG reduction, the diversification of the state's energy mix, fertilizer production, and the decarbonization of the transport sector • It regulates the development of hydrogen supply chains aiming to attract investment

(continued)

Table 2 (continued)

State/federal district	Law
Paraná	• Law 21454/2023 aimed at increasing the share of renewable hydrogen in the state's energy mix, stimulating renewable hydrogen use in energy and fertilizer production, reducing GHG emissions, fostering a renewable hydrogen production chain, and attracting investment
Pernambuco	• The *Green Hydrogen Policy,* established by state Law 17976/2022, aims to elevate the role of hydrogen within the energy mix, boost its diverse applications (including agriculture), reduce greenhouse gases, support the supply chain, improve economic, social, and environmental outcomes, promote technological advances, attract infrastructure investments, and enhance sector-specific professional development and training
Piauí	• The state's hydrogen-based energy policy aims to reduce emissions and boost energy production by integrating hydrogen into the state's energy mix • It encourages the use of hydrogen in various sectors like agriculture and supports the development of a local hydrogen industry • It seeks to attract investments in hydrogen infrastructure and develop training programs for the workforce
Rio de Janeiro	• Bill 1460/2023 seeks to establish the state's green hydrogen policy aiming to integrate green hydrogen into its energy mix, incentivize its use across sectors (including agriculture), enhance its supply chain, and attract investments while prioritizing greenhouse gas reduction and climate change mitigation • It stresses the need to pursue economic, social, and environmental sustainability, diversify the energy mix, and promote technological innovation and workforce development within the hydrogen sector
Rio Grande do Norte	• Bill 499/2023 established the state's *Legal Framework for Green Hydrogen and the Green Industry*, aiming to bolster investment by establishing a regime of tax benefits • It empowers state and local authorities to enact tax incentives, providing legal clarity to enhance sector growth
Rio Grande do Sul	• State decree 57173/2023 creates the *H2V-RS Program*, targeting the development of the local green hydrogen production chain for domestic use and export • It supports a low-carbon transition aligned with the UN's Sustainable Development Goals and aims to diversify the state's energy mix with an emphasis on renewables • It seeks to increase job creation, foster technological innovation, and uphold ESG principles to add value to regional products and services while encouraging sectoral dialogue and cooperation
Santa Catarina	• Bill 423/2021 aims to promote hydrogen with a focus on green fertilizer production and GHG emissions reduction • It strengthens the hydrogen value chain and aligns its use with environmental and social principles • It incentivizes infrastructure investment, sectoral workforce training, and technological advancements, supporting efficient and sustainable hydrogen applications
São Paulo	• Bills 308/2023 and 1510/2023 promote the use of hydrogen cars through tax reductions

(continued)

Table 2 (continued)

State/federal district	Law
Sergipe	• Bill 426/2023 promotes the use of hydrogen cars through tax reduction
Tocantins	• Bill 109/2023 establishes the *State Policy for Attention to Climate Emergencies and the Fight Against Environmental Racism* which proposes the creation of programs and the development of technologies for green hydrogen, as well as its use and production

Sources Authors' compilation based on Alagoas (2024), Amazonas (2023, 2024), Bahia (2022), Casarin (2021), Ceará (2023), Chiappini (2021), Espírito Santo (2023), Federal District (2024), Maranhão (2023), Mato Grosso (2021, 2024), Minas Gerais (2024), Paraíba (2022), Paraná (2023), Pernambuco (2022), Piauí (2024), Rio de Janeiro (2023), Rio Grande do Norte (2023), Rio Grande do Sul (2023a), Santa Catarina (2023), São Paulo (2023, 2024), Sergipe (2023), Tocantins (2023)

Brazil to be part of the Carbon Sequestration Leadership Forum (CSLF). Within the IPHE, Brazil took part in discussions related to research, testing, and the commercial use of hydrogen and fuel cells, as well as the elaboration of codes and common standards (Benevides, 2011).

Brazil has further taken part in Mission Innovation, the Hydrogen Initiative, the Clean Energy Marine Hubs, and the International Hydrogen Trade Forum, which all fall under the scope of the Clean Energy Ministerial, a multilateral forum formed to promote cooperation on matters related to the energy transition (MME, 2023). In 2024, Brazil hosted the organization's Ministerial Meeting to demonstrate its renewed commitment to the global energy transition (Clean Energy Ministerial, 2024).

A particular pressing issue for Brazil's future green hydrogen economy is standardization. The Brazilian National Standards Organization, which works closely with the federal and subnational governments, is a member of ISO TC-197, seeking standardization in the field of systems and devices for the production, storage, transport, measuring, and use of hydrogen (ISO, nd). However, Brazil's strong reliance on biomass and its decentralized energy market could complicate the certification of green hydrogen in accordance with strict standards such as those applied in the EU (Agora Industry et al, 2024). Therefore, recent government documents, particularly the PNH2's Three-Year Plan, have stressed the importance of harmonizing standards and quality infrastructure to remove potential investment barriers (MME, 2023). A globally accepted definition for renewable hydrogen could facilitate Brazil's hydrogen export ambitions if the level of permitted lifecycle emissions was higher than the level currently set by individual actors representing important export markets such as the EU.

Brazil is also engaged in hydrogen cooperation within the region. The PNH2's Three-Year Plan states "the aim of positioning Latin America within the global hydrogen arena" (MME, 2023), expressing its support for integrated regional economic development in the sector. This aligns with the ideological shift of Lula's administration, which is generally more prone to regional integration than his predecessor. The creation of a regional hydrogen economy represents an opportunity for Brazil and South America to become global players in energy through regional integration. Without collaborative consultation, however, there is a risk of contestation and unhealthy competition, as highlighted by the dispute surrounding the EU-Mercosur free trade agreement awaiting ratification (CFR, 2023).

Despite verbal endorsements, Brazil has so far taken an ambiguous stance toward regional cooperation. The country has actively participated in actions organized by the *Collaborative Platform for Green Hydrogen Development in Latin America and the Caribbean* (H2LAC) launched by the GIZ, the World Bank, the United Nations Economic Commission for Latin America and the Caribbean (CEPAL), and the EU's *Euroclima* + Program in 2020 (H2LAC, nd). Furthermore, the ABIHV joined the *LAC Green Hydrogen Action Alliance*, a platform for collaboration between private and public actors constituted at COP 26. However, when the Inter-American Development Bank (IDB) and the Latin American Energy Organization launched CertHiLAC at COP 28, an initiative to develop a common certification system for clean hydrogen in the region, Brazil did not sign the declaration (IDB, 2023). Its own certification scheme relies on very lenient sustainability criteria for defining clean hydrogen (see Sect. 4.1), which could have been called into question by joining CertHiLAC.

Hydrogen has also become an increasingly relevant topic for Brazil within the BRICS. The organization has repeatedly discussed and mentioned clean hydrogen in official documents. In a declaration adopted at the 15th BRICS Summit, member countries declare "hydrogen produced on the basis of zero and low emission technologies and processes" as a crucial element "for a just transition towards more flexible, resilient and sustainable energy systems" (BRICS, 2023).

The strongest emphasis of Brazil's international hydrogen politics has so far been on bilateral cooperation. As the future export of green hydrogen and its derivatives represents an important pillar of Brazil's hydrogen strategy, the federal government is particularly interested in securing trade partnerships and funding for production and transport infrastructure. In June 2023, it secured over USD 2 billion of funding from the European Union, which will be channeled through the EU's Global Gateway initiative to hydrogen production projects in Brazil (Parkes, 2023). In December 2023, Lula's government joined forces with the UK in founding the *Brazil-UK Hydrogen Hub,* which is supposed to serve as a bilateral platform for cooperation and the facilitation of access to finance in the development of a global hydrogen market (UK Department of Energy Security & Net Zero, 2023). Germany has also signaled an interest in cooperating for green hydrogen trade. In 2020, the *Brazil-Germany Alliance for Green Hydrogen* was created by the Chambers of Commerce and Industry of São Paulo and Rio de Janeiro (Hydrogen Europe, 2022).

Many of these initiatives are part of Lula's recent efforts to revive bilateral and multilateral relations in the context of climate and energy policy and to redefine Brazil as an environmental promoter. This new phase presents Brazil with a chance to regain its role as a key player in the global sustainability dialogue and at the same time capitalize on its high potential for building a green hydrogen economy. Brazil might continue to build on these efforts if it aligns this momentum with subnational actors' goals, consistent federal policy, and constructive international collaboration. Thus, by working with a wide range of partners to cooperate for production, export, and standards, hydrogen may increasingly find itself at the core of Brazil's energy transition.

7 Conclusion

Brazil has set itself the ambitious objective of becoming the "most competitive global producer of hydrogen" by 2030 (MME, 2023). Developing a low-carbon hydrogen economy promises growth and re-industrialization, economic and energy security, and industrial decarbonization across the country. Although the success of this endeavor is highly uncertain, the country generally enjoys favorable conditions for green hydrogen production, due to its large renewable energy sector, making it one of the most lucrative places for investment and future hydrogen trade. Still, becoming the world's leading producer of green hydrogen will be an enormous political challenge.

So far, Brazil lags behind global players, such as Germany, Japan, or Spain, and regional players, such as Chile, in terms of clean hydrogen projects. Although several projects have been initiated, most of them are still in the planning stage. For now, existing hydrogen production plants first and foremost produce grey hydrogen, which is primarily used in refineries. The political landscape, however, is rapidly changing. Developing a low-carbon hydrogen economy has evolved as a key policy priority, at least since the new Lula administration, and is strongly embedded in Brazil's recent turn to industrial policy. The Hydrogen Act establishes a new regulatory framework for hydrogen and creates a low-carbon hydrogen standard as well as financial incentives for hydrogen production. The tax credits provided by the PHBC will further boost the production and usage of hydrogen in the country.

Most hydrogen production pilot projects are realized at the state level. Some also aim at the production of green ammonia, underscoring the government's ambition to reduce its export dependency on fertilizer. These projects are typically governed by public–private partnerships and, in many cases, involve ports, signaling export ambitions.

On the international stage, President Lula has recently re-established Brazil's central role, particularly in the context of environmental and climate governance. The country has hosted the G20 Summit and the Mission Innovation and Clean Energy Ministerial Meeting in 2024 and will host the COP in 2025. International hydrogen cooperation has been advanced multilaterally, seeking to play an influential role in shaping international standards, but also across the region and within the BRICS. The primary mode of cooperation, however, has been the conclusion of bilateral agreements on hydrogen trade.

The advanced focus of the Brazilian government on low-carbon hydrogen in both its domestic and foreign politics can be understood as the consequence of three developments: First, a widespread awareness among policymakers and experts has developed for the potential of Brazil's extensive renewable energy capacities and resources, providing favorable conditions for low-carbon hydrogen production. Second, developing new competitive future-fit industries has evolved as a central quest for the country's recent turn to industrial policy. Third, the promise to contribute to a future global hydrogen economy serves to affirm the government's recent attempts to rebuild the country's image as a relevant global actor in environmental governance and beyond.

Although economic powerhouses like China, the United States, and the EU may be seen as the main actors aiming at leadership in the hydrogen sector, other countries, particularly those in the Global South, might also play an essential role in shaping a yet-to-be-formed global hydrogen economy. Internationally, Brazil's hydrogen ambitions have so far not been featured prominently in policy discourses. Yet, the country is developing an extensive policy framework supporting green hydrogen domestically and is increasingly engaged in bilateral and multilateral hydrogen cooperation. Thus, Brazil's role in the future might be much more central than it currently is.

Acknowledgements The publication of this chapter was financially supported by the German Federal Foreign Office within the framework of the project "Geopolitics of the Energy Transformation – Implications of an International Hydrogen Economy" (GET Hydrogen), funding reference number AA4521G125.

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The Emerging Geopolitics of Hydrogen: Navigating Uncertainty and Industrial Legacies Within the Net-Zero Transition

Rainer Quitzow and Yana Zabanova

Abstract This final chapter provides an overview of how hydrogen policies are taking shape in the major economies covered in this volume and discusses their implications. The chapter begins with a review of domestic hydrogen policies, highlighting key features and their similarities and differences across the countries. We discuss the different approaches to production technologies, priority uses of hydrogen, the focus and design of support schemes, and the role of industrial policy. We conclude this part of the chapter with a brief reflection on the changing geopolitical environment and how this has affected domestic hydrogen policies and politics. We then move on to contrast the main features of international hydrogen policy engagement, linking it to domestic strategies and interests. The chapter closes with a reflection on how hydrogen policy developments in the major economies that are presented in this book are likely to affect global decarbonization efforts and the related geopolitics.

1 Introduction

The contributions in this volume illustrate the important variation across countries in their pursuit of hydrogen as a new energy carrier. Each of the major economies covered in this volume is seeking to build a unique position within a future net-zero economy where the envisioned role of hydrogen differs based on the resources and assets that the country controls. Combined with the particular institutional legacies and the configuration of stakeholder interests, these variables are driving differing strategies for exploiting hydrogen as an energy carrier within a net-zero economy.

In this final chapter, we provide an overview of how hydrogen policies are taking shape in the major economies covered in this volume and discuss their implications. The chapter begins with a review of domestic hydrogen policies, highlighting key

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R. Quitzow and Y. Zabanova (eds.), *The Geopolitics of Hydrogen*, Studies in Energy, Resource and Environmental Economics, https://doi.org/10.1007/978-3-031-84022-7_9

features and their similarities and differences across the countries. We discuss the different approaches to production technologies, priority uses of hydrogen, the focus and design of support schemes, and the role of industrial policy. We conclude this part of the chapter with a brief reflection on the changing geopolitical environment and how this has affected domestic hydrogen policy and politics. We then move on to contrast the main features of international hydrogen policy engagement, linking it to domestic strategies and interests. The chapter closes with a reflection on how hydrogen policy developments in the major economies that are presented in this book are likely to affect global decarbonization efforts and the related geopolitics.

2 Hydrogen Policies in the Major Economies: Key Features and Their Domestic Underpinnings

2.1 Technology Pathways

One common theme emerging from the individual case studies is the diversity in the choice of hydrogen production pathways. Existing research in the geopolitics of the energy transition has focused primarily on the role and implications of future trade in renewable (or "green") hydrogen, which, unlike oil and gas, can be produced in many renewables-rich locations around the globe (van de Graaf et al, 2020; IRENA, 2022). Yet, a closer look at the hydrogen strategies and policies of key economies reveals a much wider range of preferences for possible hydrogen production pathways—albeit paired with persistent uncertainty about the future prospects of each particular pathway.

In line with its ambitious climate policy and its self-positioning as an international climate leader, the EU has put the strongest emphasis on promoting green - or renewable as it is referred to in EU legislation - hydrogen. It has introduced a stringent definition and binding mandates for green hydrogen use in industry and transport (including aviation and maritime shipping) from 2030 onwards. Production subsidies introduced in 2023 as part of the European Hydrogen Bank also target green hydrogen and its derivatives. That said, the clear priority given to green hydrogen at the EU-level has also seen challenges at the member state level. France and other countries with an important share of nuclear power have successfully pushed for exemptions in the strict EU policy framework for hydrogen produced with low-carbon nuclear power (Quitzow & Zabanova, 2024).

Similarly, blue hydrogen, produced from natural gas with carbon capture and storage (CCS), was not initially considered an important option for meeting EU hydrogen demand. Rather, green hydrogen has been framed as an important option for reducing dependency on Russian natural gas imports (Zabanova, 2024). By this logic, imported blue hydrogen was not viewed as a reasonable alternative. However, as green hydrogen projects have been slower to emerge than originally expected, blue hydrogen is now increasingly considered a viable transitional solution. Germany, the bloc's biggest proponent of a rapid ramp-up of green hydrogen, has grown increasingly open to the idea of importing blue and other types of low-carbon hydrogen. A definition of low-carbon hydrogen (including blue hydrogen and other types) is expected to be finalized in 2025, which would create the needed EU-policy framework. Nevertheless, investor confidence in the prospects of blue hydrogen remains mixed, and the scale of blue hydrogen use in the EU is difficult to predict.

The rest of the global frontrunners have largely chosen a technology agnostic approach from the outset. However, policy and regulatory choices reveal how the configuration of national interests permeates hydrogen strategy-making. Brazil, for instance, supports all pathways and has proposed one of the more lenient definitions of low-carbon hydrogen, with an emissions threshold of 7 kg of CO_2 equivalent/kg of hydrogen, more than double the EU's threshold of 3.38 kg. This is meant to enable the production of hydrogen from biomass, reflecting the country's bioenergy legacy.

Countries with a significant fossil-fuel industry, like the US, UK, and Australia, have also promoted technology-open approaches, despite criticism from national NGOs that have highlighted the risk of reinforcing fossil-fuel lock-ins. In the UK, the government has adopted a twin-track approach, as well as a stringent definition of low-carbon hydrogen. While the UK's key subsidy, the Hydrogen Allocation Round, targets electrolytic hydrogen, in October 2024 the government announced it would provide 22 billion GBP in funding over 25 years to develop two large-scale carbon capture clusters, which are expected to give a significant boost to blue hydrogen production (Collins, 2024a). In the US in particular—whether by design or by accident—the policy regime has initially strongly favored investment in blue hydrogen. The "45 V" hydrogen tax credit introduced in the Inflation Reduction Act (2022) links the amount of subsidy—up to the 3 USD/kg cap—to the total reduction in GHG emissions provided by clean hydrogen, irrespective of the production pathway. In addition, a separate tax credit for CCS, "45Q", rewards the amount of CO_2 that is captured and sequestered. Blue hydrogen projects may thus choose to apply for either tax credit. As of mid-2024, blue hydrogen projects have seen much greater progress in the US compared to green hydrogen ones, representing some 85 percent of total committed clean hydrogen production capacity (Hydrogen Council and McKinsey, 2024, p. 19). Trump's re-election in the US in 2024 and his combative stance vis-à-vis the Biden Administration's clean energy policies, however, cast uncertainty on the future of the US hydrogen tax credits.

In the Asia–Pacific, Australia, which is rich in renewable energy but is also a major coal and gas producer, has declared openness to various pathways, including, in one region, hydrogen made from coal. Nevertheless, Australia has started to shift toward a preference for green hydrogen, especially following the election of a new government in 2022, which introduced more stringent climate targets - a trend that is expected to continue under the Labor government elected in 2025. In China, the government targets primarily green hydrogen, which is consistent with the massive development of renewable energy nationally. However, at the sub-national level, a wide range of pathways are supported, with the tacit approval by the national government. A number of provincial governments have chosen to focus first on deploying new hydrogen technologies, regardless of the carbon footprint, and postponing the decarbonization of hydrogen production to a later stage. Finally, Japan, as a country planning to import most of its clean hydrogen and ammonia, is more preoccupied with developing robust and diversified international supply chains for these new energy carriers. It has established large demonstration projects focused on testing different transportation routes and modalities, regardless of the production route employed. Indeed, CO_2 emissions from imported hydrogen will not affect Japan's domestic GHG accounting, so that policymakers have chosen to largely ignore the emission profile of its hydrogen supply for now.

2.2 Priority Uses

Industrial legacies and domestic interests also play a key role in what hydrogen uses are prioritized. The EU, guided by its climate neutrality targets and eager to safeguard its energy-intensive industry within a net-zero future, was the first to strongly prioritize industrial decarbonization, especially in the steel and chemical sector. Yet, due to high costs of green hydrogen, investment in hydrogen-based industrial decarbonization has been sluggish at best. It is European refineries that are currently emerging as early adopters of green hydrogen, partly because of their ability to act simultaneously as producers and off-takers. Industrial end uses are beginning to attract attention outside of the EU as well. This includes large steel-producing countries like China, Japan, and the US but also Australia, where policymakers have shown increasing interest in developing a net-zero steel industry building on the combination of abundant renewable resources and domestic iron ore reserves.

Outside industry, transport is a prominent priority area for Asian economies such as Japan and China. Both have long legacies in the support of fuel-cell electric vehicles (FCEVs) (Gong et al, 2024; Haslam et al, 2012; Li et al, 2023; Trencher et al, 2020). In Japan, incumbent automakers like Toyota have made important investments in the technology, while the Chinese government has pursued FCEVs—alongside battery-electric vehicles—as an industrial policy strategy. Following the success of the battery-electric vehicle in the passenger car segment, support for FCEVs now primarily targets buses and heavy-duty commercial vehicles. Similarly in the US, the government continues to support the manufacturing and development of FCEVs alongside battery-electric vehicles with a focus on heavy-duty, commercial vehicles.

In the EU, there is a controversial debate on what role hydrogen may play in decarbonizing passenger mobility. While there is an emerging consensus that hydrogen-based e-fuels will likely play an important role in decarbonizing aviation and maritime shipping—despite limited progress to date—there is significant skepticism about the future of hydrogen in road transport. Nevertheless, the EU has adopted a target for e-fuel use in road transport and is promoting the development of refueling infrastructure in large urban centers. Brazil, with its developed expertise in biofuels (Rodrigues, 2021), is strongly targeting the e-fuel sector. Among other things, it is planning to produce hydrogen from ethanol.

As for power generation, Japan is the country with the strongest focus in this area. This has to do with the unique characteristics of Japan's power sector, where coal still plays an important role and where, in the wake of the 2011 earthquake, major nuclear power plants were shut down, eliminating the bulk of the country's low-emission generation. This has significantly deepened Japan's electricity sector's reliance on fossil fuels. While Japan has experienced a strong growth in renewable generation in recent years, the spatial constraints mean that renewables alone cannot fully decarbonize the power sector. In an effort to confront these challenges while protecting its legacy assets, Japan's industry has strongly promoted ammonia co-firing at thermal power plants. Bowing to these interests, the government has adopted this as a central approach for reducing its domestic carbon footprint in the short- to medium-term. Moreover, it is investing in R&D for related technologies and is supporting its industrial firms in promoting the technologies in other Asian countries. In China, the global leader in absolute volumes of renewable energy deployment, hydrogen is also viewed as an important element of its future electricity system, but for its storage and grid balancing functions and for reducing curtailment rates.

The UK stands out as one of the few countries that has also emphasized hydrogen as a major contribution to the decarbonization of residential heating, despite criticism from civil society and the country's Climate Change Committee. Overall, the UK government has taken a broad approach to hydrogen use and discussions are underway on the merits of introducing a separate support model for hydrogen use in the power sector.

2.3 Support Mechanisms

The countries featured in this volume have all developed schemes and support instruments for hydrogen development. Investment in R&D is the most established instrument, with each country targeting the technologies of particular interest to them. For instance, while the EU's Innovation Fund supports a wide range of clean technologies that have not yet reached market maturity, the US emphasizes large-scale domestic cleantech manufacturing of already market-ready technologies. China and Japan, in turn, have traditionally put an emphasis on developing FCEVs. Given its unique focus on ammonia co-firing, Japan has also supported technology development in this field. Brazil with its legacy in biofuels has a strong emphasis on the fuels sector.

In recent years, many jurisdictions have been experimenting with supply-side subsidies such as production premiums, contracts for difference, or tax credits. The specific choice often reflects existing policy legacies, institutional capacities, and political constraints. In the EU, the European Hydrogen Bank awards premiums for green hydrogen production as part of a competitive bidding process, aimed at ensuring a cost-effective allocation of subsidies. The level of subsidy requested by and awarded to the winning projects in the first round of auctions in 2024 ranged from 0.37 EUR to 0.48 EUR per kg, far below the 4.5 EUR/kg cap. In parallel, a growing number of EU member states are developing their national production subsidies as well. In the UK, on the other hand, production subsidies in the framework of the "Hydrogen Production Business Model" are designed as contracts for difference, mirroring its subsidy scheme in the renewable energy sector (Bunn & Yusupov, 2015). They provide revenue support to hydrogen producers by compensating the gap between the production costs of green hydrogen versus natural gas via 15-year contracts. The first Hydrogen Allocation Round held in 2023 resulted in probably the highest level of subsidy worldwide: in December 2023, the average strike price for the eleven winning green hydrogen projects stood at £9.49 ($12.44) per kilogram of hydrogen. However, even at this high level of subsidy, not all projects are likely to reach the crucial final investment decision stage (Martin, 2024).

Japan and Australia, despite being early to adopt hydrogen strategies, have lagged behind in developing more substantive financing schemes for domestic deployment. They have sought to close this gap by launching major funding schemes in 2024. The Japanese government passed the Hydrogen Society Promotion Act, which includes a contract-for-difference scheme that compensates the buyers of low-carbon hydrogen or its derivatives for the price gap to conventional fuels (Nishimura & Asahi, 2024). In Australia, the 2 billion AUD Headstart Programme provides ten-year production support contracts to large-scale hydrogen producers, seeking to compensate for the difference between the market price and the high costs of producing hydrogen.

A separate instrument in Australia—as well as in the US—are tax credits per kg of hydrogen produced in accordance with previously defined carbon thresholds. The US approach not only mirrors its long legacy of renewable energy support, via the so-called production tax credits (Barradale, 2010), but it is also considered the only politically feasible option in the context of a divided political system (McGlynn & Sparks, 2024). In Australia, there is a flat tax credit of 2 AUD per kg, while in the US the amount of tax credit is linked to the total carbon footprint of hydrogen and is capped at 3.5 USD/kg (and in addition, there is a separate tax credit for projects using carbon capture and sequestration). Brazil is planning to use tax incentives as well. The law adopted in September 2024 earmarked 18.3bn Brazilian reals ($3.36bn) in funding for companies producing or consuming "low-carbon" hydrogen in 2028–32, to be selected competitively, with projects featuring lower GHG emissions prioritized; other selection criteria are still to be determined (Argus Media, 2024).

Another prominent focus of support policies in leading jurisdictions are regional hydrogen hubs (also called clusters, or valleys). These are geographic areas where local hydrogen value chains are developed by bringing together hydrogen producers and consumers (and sometimes exporters) and bundling a variety of hydrogen uses in one place. Common examples include seaports such as Rotterdam, where hydrogen can both be produced on site from wind and solar power and imported by sea, and then distributed via a pipeline network to industries located nearby. Hubs can play a crucial role in jumpstarting a hydrogen economy, especially where little or no long-distance hydrogen transport infrastructure exists yet. The EU has been instrumental in promoting the idea of hydrogen valleys in Europe and globally, spearheading this work area in the framework of the global initiative by Mission Innovation.

The idea has been picked up by other global frontrunners as well. The US has dedicated a 7 billion USD budget line for funding regional hydrogen hubs through the Bipartisan Infrastructure Law (2021). The winners were selected in a competitive process and include seven regional hubs to be awarded federal funding, ranging between 750 million and 1.2 billion USD, with the first tranches disbursed in 2024. Trump's re-election, however, has cast uncertainty on the future of further funding, especially in the case of renewable and nuclear-based hydrogen hubs (Colman et al, 2025). Australia has allocated over 500 million AUD in federal funding, to be supplemented with a similar amount of funding from the subnational level, to support regional hub development, with five regions given the priority status. In China, so-called pilot cities have been launched for the development and deployment of FCEVs and the related infrastructure (Gong et al., 2024).

While hydrogen production has enjoyed large amounts of support around the globe, policies to promote the uptake of clean hydrogen in key demand sectors have been less commonplace. This reflects the general state of affairs in the hydrogen economy, where there is an abundance of investment in hydrogen production and supply yet sizable investment gaps exist when it comes to hydrogen end uses and infrastructure (Hydrogen Council and McKinsey, 2024). In the EU, Germany has led the way by launching a 50 billion EUR carbon contracts for difference (*Klimaschutzverträge*) scheme for industrial decarbonization. The scheme incentivizes the use of green production methods in industrial sectors (including renewable hydrogen) by compensating for the price differential between conventional and climate-friendly technologies. The EU in turn has launched targets and mandates for minimum shares of green hydrogen and green hydrogen derivatives in the industry and transport sectors, which will be binding from 2030 onward. However, reflecting the constraints on the EU as an industrial policy actor, they lack EU-level funding to ensure their implementation. Rather, responsibility largely rests with EU member states, despite highly diverging capacities and willingness to support the needed investments. The result may be a highly uneven investment landscape in the EU, further exacerbated by moves to relax the EU's restrictions on state aid. In the wake of the energy crisis, the European Commission has allowed member states additional leeway in providing subsidies to national industries, raising questions about the integrity of the European single market.

The US has also faced a lack of offtake contracts despite existing subsidies for hydrogen production, resulting in discussions on subsidies for users purchasing clean hydrogen from government-funded regional hydrogen hubs. With 1 billion USD in funding, the details of the scheme are expected to be disclosed by early 2025 and are likely to follow the contracts-for-difference logic as well (Collins, 2024b). In China, support for hydrogen end uses has largely taken the shape of consumer subsidies for the purchase of FCEVs.

2.4 Industrial Policy

Linking hydrogen development to green industrial policy has been a strong trend across all the countries. In particular, China's rise as a cleantech global superpower has been a major concern first and foremost for the US, but also increasingly for the EU. In the US, promoting local supply chains for clean energy has been an essential precondition for securing bipartisan support for major green investments, as outlined in the Inflation Reduction Act (2022). This is true for hydrogen as well. While the US does not mandate local content requirements for electrolyzers per se, it does incentivize the use of locally manufactured solar, wind, and battery technologies as well as the domestic sourcing of iron and steel and critical raw materials. In addition to promoting the "made in the USA" principle, the US explicitly excludes facilities relying on Chinese-made batteries and critical raw materials from receiving hydrogen subsidies. The newly elected Trump Administration has adopted a starkly protectionist stance in trade policy, further increasing tariffs on Chinese goods. Affected product categories include such key technologies as EVs, solar panels, and semiconductors (Abrahams, 2025).

In turn, the EU, which is home to many of the world's leading innovative electrolyzer manufacturers, has been highly apprehensive about losing technology competition to China, as was already the case with solar PV panels in the past. Although the EU has stopped short of mandating a certain percentage of local content in hydrogen projects, following lobbying by the electrolyzer industry, it has introduced a "resilience criterion" for European Hydrogen Bank auctions. The criterion requires bidders to ensure they source no more than 25% of electrolyzer stacks from China (Directorate-General for Climate Action, 2024). In addition, while the EU has traditionally focused on investing in technologies that have not yet reached market maturity, it is now increasingly beginning to promote EU-based manufacturing of clean technologies, through a combination of EU- and national-level funding.

China, for its own part, has a longstanding industrial policy aimed at promoting FCEV manufacturing, not only in China but also along the Belt and Road Initiative (BRI). The government encourages producers of FCEVs to export products, services, technologies, and standards by investing in foreign markets and supports the development of overseas automotive industrial parks. Typically, lead state-owned enterprises (SOEs) cooperate with other privately owned suppliers in spearheading such efforts. Another longstanding goal of Chinese industrial policy is the promotion of technology and innovation and the acquisition of foreign know-how to overcome remaining technology bottlenecks in China to ensure its strategic autonomy. Most recently, China has stepped up its efforts in promoting innovation in the hydrogen sector with the launch of the Central Enterprises Green Hydrogen Production, Storage, and Transportation Innovation Joint Venture. Initiated by SASAC and jointly led by CNPC and Sinopec, the initiative brings together major SOEs, technology providers, and academia in an effort to promote innovation and technology development in various areas of the hydrogen economy.

Japan has been strongly driven by industrial policy considerations as well. Japanese companies lead globally as patent holders for a number of hydrogen technologies along the value chain. This includes fuel cells, hydrogen and ammonia used in co-combustion in coal power plants, hydrogen use in steel, chemicals, and shipping as well as e-methane and e-fuels. The power sector and the transport sector are the two most important priority areas for Japanese industrial policy. In addition to planning hydrogen and ammonia imports, Japan is intent on promoting Japanese hydrogen know-how abroad and sees a major business opportunity in supplying co-combustion technologies to help decarbonize coal power plants in Southeast Asia. The government is also funding R&D for developing a 10+ MW hydrogen-ready turbine by Mitsubishi. The government's numerical targets are strongly linked to the automotive industry, with a target number of FCEVs on the road and hydrogen refueling stations, as well as to the electrolyzer industry, with a 15 GW target in global electrolyzer capacity operated by Japanese companies globally.

Other countries, especially potential hydrogen exporters, are increasingly considering the necessity to develop higher value-added industrial activities in the hydrogen sector. Guided by its policy priority of neo-industrialization, Brazil aims to create a domestic green fertilizer industry and plans the introduction of local content requirements. Australia, an established commodity exporter, envisions a leading role as a future hydrogen exporter but is also planning to promote domestic use of clean hydrogen, including a green steelmaking industry. The UK, by contrast, despite the ambition to become a "green energy superpower", has lacked strategic focus in its green industrial strategy. Partly, this is a reflection of the fractious domestic debate on the future role of hydrogen in the domestic economy. Although the government supports a wide range of uses, this also means resources are spread thinly and may be insufficient to make a substantive impact in any single area of application.

2.5 Domestic Hydrogen Politics in a Shifting Geopolitical Landscape

Over time, the hydrogen economy has picked up momentum, with an increasing number of countries jumping on the hydrogen bandwagon. At the same time, geopolitical developments—and their economic consequences—have begun to take their toll on the sector, calling into question some of the more ambitious goals, in particular in Europe. Rising energy prices and inflation have not only hampered the investment climate and slowed down—or even reversed—urgently needed price reductions. They have also translated into increasing skepticism toward the green transition among the public in the US and Europe. Moreover, increasing calls for resilience and national sovereignty have introduced new challenges for the design of green industrial policy measures. Finally, the election of Donald Trump in the US has introduced further uncertainty into the sector. That said, there are also countervailing trends with China, Japan, Australia, and Brazil all stepping up their hydrogen action. In Brazil and

Australia, this follows significant electoral shifts with left-wing forces taking over power from conservative parties.

In the EU, other priorities—such as the need to ensure access to low-cost energy to increase the competitiveness of European industry as well as hard security issues—have been competing for attention with the green transition. The EU's parliamentary elections in 2024 resulted in a clear shift to the right. Enthusiasm for hydrogen development has been weakening, discouraged by the slow progress and high costs and the resulting cancelation of a spate of hydrogen projects. The green backlash in many Member States as citizens and businesses grapple with the costs of the transition, compounded by the ongoing economic impact of the war in Ukraine and the loss of competitiveness of European companies, has presented a challenge to the Commission's green course. Forging a common path among Member States with very different starting points in their energy mixes as well as highly divergent attitudes to green industrial policy is a particular challenge (Quitzow & Zabanova, 2024).

In the US, President Biden's landmark Inflation Reduction Act (2022), complete with generous tax credits for hydrogen and investment incentives, catapulted the US to the position of the green tech frontrunner, sparking serious concern in the EU. Yet, Trump's re-election in November 2024 creates uncertainty for investors—not only for US firms but also for European companies that have considered moving their production facilities across the Atlantic in response to the IRA. At the same time, Republican-dominated US states have been some of the key beneficiaries of US hydrogen funding, making them interested in upholding this legislation.

Though the US and Europe remain central to an emerging international hydrogen economy, these challenges are not mirrored in the same way elsewhere. China saw important advances in 2024 with the passing of its Energy Law, which officially classifies hydrogen as an energy source rather than a hazardous chemical, as well as the launch of the Central Enterprises Green Hydrogen Production, Storage, and Transportation Innovation Joint Venture as a major new vehicle to promote innovation in the sector. Japan in turn passed the Hydrogen Society Promotion Act in May 2024, which introduces a major new subsidy scheme for hydrogen supply. Brazil, with its historical insistence on reducing hydrocarbon dependencies dating back to the oil crisis of the 1970s, has also seen hydrogen plans accepted across party lines. Lula's re-election as president in 2023 has further solidified the country's commitment to the sector and strengthened the link to decarbonization and green industrial development. The passing of the Hydrogen Act and the launch of the Low Carbon Hydrogen Development Program in 2024 represent critical steps forward in this regard and signal the country's ambition to assume a more active leadership role. In Australia, the commonwealth government elected in 2022 has pursued a more ambitious climate policy, including a stronger focus on promoting renewable hydrogen and developing domestic end-use sectors, a trend likely to continue under the new Labor government.

3 International Hydrogen Politics and Policies

As outlined in the preceding sections, hydrogen policies cannot be separated from domestic resources and assets and the pre-existing industrial legacies and stakeholder interests. Along with prevailing institutional legacies, these are shaping preferences regarding production pathways and preferred end-use sectors and are defining policy priorities across the countries considered in this volume. These domestic approaches and their political and economic underpinnings also translate into unique strategies for international engagement and cooperation (Quitzow et al, 2024). Each country is not only seeking to position itself within an emerging hydrogen policy landscape but also to influence and shape this landscape to match its priorities and needs.

3.1 The Question of Hydrogen Trade: Importers, Exporters and Prosumers

The European Union—led by its largest member state Germany—and Japan stand out in the international hydrogen landscape as the most important proponents of international hydrogen trade. With large industrialized economies and only limited renewable energy potential, both are strongly reliant on imported hydrogen to decarbonize their economies. Also, both the EU and Japan only have limited scope to scale-up nuclear energy. Although there has been growing openness to nuclear energy in the EU, and member states like France or Sweden remain committed to nuclear energy for domestic use, the future role of this technology in EU-level decarbonization efforts remains contested due to the high costs and continued political opposition in a number of member states, including Germany. In Japan, political establishment has remained open to nuclear energy, but its nuclear sector has not fully recovered from the Fukushima disaster, and its potential to play a major role in its net-zero future is highly uncertain. Hence, Japan, Germany, and the EU more broadly see their futures tied to an international hydrogen economy able to supply them with imports.

However, despite these similar starting points, their approaches to international engagement have differed markedly, reflecting the domestic political economy of hydrogen and their broader institutional legacies. As an international climate policy leader, the EU and Germany have focused strongly on the development of an international hydrogen market with a strong focus on green hydrogen. Both the German government and the European Commission are pursuing engagements around the world to promote green hydrogen as the energy carrier of the future and to support a favorable climate for hydrogen investment (Quitzow et al, 2024; Zabanova, 2024). While the prospect of hydrogen imports plays a major role in this regard, engagements from these two players have been characterized by their broad geographical scope and broad-based support for hydrogen policy development. Their international strategies are creating the political and institutional underpinnings of an international hydrogen market.

While the development of physical infrastructure and import corridors is a part of these efforts, it has not been the most prominent feature of their strategy. Partly, this is a result of internal EU politics (Quitzow & Zabanova, 2024). Not only has France been reluctant to assume its role as a potential transit country for hydrogen trade between Germany and the Iberian peninsula (Bouacida, 2024), but also Spain, with hydrogen export ambitions of its own, has been slow to support the continuation of a potential pipeline route to Morocco (Urbasos & Escribano, 2024). With the war in Ukraine precluding development of an Eastern route, a Southern corridor through Italy and a pipeline interconnection with Norway have emerged as the most tangible options for pipeline development. The latter, however, has seen setbacks, due to the uncertainty regarding the long-term viability of blue hydrogen within the EU regulatory framework. Shipping-based solutions are being pursued in parallel, though efforts are relatively hands-off. Germany's H2 Global, the most prominent initiative, takes a market-based approach, where supply chain development is clearly placed in the hands of private sector actors.

In contrast to this, the Japanese government has engaged in a number of large-scale, bilateral demonstration projects to pilot specific supply routes and transport technologies, while showing only limited concern for the mode of hydrogen production. Prominent examples include the Hydrogen Energy Supply Chain (HESC) project, in partnership with the state of Victoria in Australia, and a project to import hydrogen from Brunei. The former aims to advance technology for shipping liquid hydrogen, including its regasification in Japan. It involves the production of hydrogen via coal gasification, initially without CCS, though the consortium has signaled that this would change once production is scaled up. The partnership with Brunei involves the export of hydrogen produced from natural gas using a liquid-organic hydrogen carrier (LOHC). Complementing these larger-scale projects, Japan supports a number of smaller pilot projects via its Green Innovation Fund.

Australia as well as Brazil represent important counterparts to these activities launched by Japan, Germany, and the EU. Australia in particular has positioned itself as a major future exporter of hydrogen. Its legacy as a large fossil-fuel exporter, including coal and natural gas, predisposes it to this approach, with major incumbent firms as strong proponents. It has had little inclination to position itself strongly in favor of any particular production pathway, given its large endowments not only in renewable but also in fossil resources. However, following a change of government in 2022, it has shifted its emphasis more strongly to renewable hydrogen, proclaiming Australia a future hydrogen and renewable energy "superpower". It is now also exploring exports of downstream products, like hydrogen-based green iron, steel, and alumina.

Brazil has been slower to position itself in an international hydrogen economy. The national government has been supporting hydrogen as a complement to its strong biofuels sector, but did not feature among the frontrunners of hydrogen strategy development. Nevertheless, it aims to become "the most competitive producer of hydrogen" by 2030 (RadarH2, 2024). Moreover, subnational governments have formulated their own export ambitions. A number of regions in the northeast of Brazil have identified their strong renewable energy potential and relative proximity to European export markets as an asset in a future hydrogen market. At the national level, hydrogen received an important boost with the Lula government, where it now features as an important ingredient for industrial decarbonization and for safeguarding and further developing Brazil's position on European markets against the background of the EU's carbon border adjustment mechanism (CBAM). These developments exhibit important parallels to developments in the UK. While the national government has taken a more inward-looking approach overall, the Scottish government has pursued an export-oriented hydrogen policy, in line with its strong renewable energy potential and its pro-European outlook.

Neither the US nor China have a strong motivation to articulate a nuanced position on hydrogen trade. While they both represent important centers of future hydrogen demand, they also have the renewable potential to supply these needs. This is also clearly reflected in their international engagement, which does not include a strong component for the development of hydrogen trade. Similar to Brazil or the UK, this does not preclude subnational governments or firms from pursuing export opportunities. The ambition of the local government in Shanghai to position itself as a regional trading hub for hydrogen is a case in point. Similarly, developments along the Texas Gulf Coast indicate export-oriented ambitions.

3.2 Bilateral Hydrogen and Energy Diplomacy

As outlined in the previous section, securing hydrogen imports is a major driver behind the strong international engagement and leadership of Japan, Germany, and the European Union. This engagement is underpinned by broader climate, energy, and industrial policy goals as well as efforts to promote cooperation and knowledge exchange on hydrogen technologies and solutions. In the case of Japan, engagement on hydrogen supply is complemented by broader dialogue to facilitate investment and technology cooperation in the field of hydrogen and ammonia production as well as ammonia co-firing, bolstered by private sector interests in exporting related technologies.

EU-level activities are generally embedded in broader energy and climate policy initiatives and, in some cases, its Global Gateway strategy to support investments in infrastructure and connectivity. As such hydrogen is viewed as a promising field for cooperation, not only to supply the EU with hydrogen but also as an opportunity for investment and economic development in partner countries. Similarly, large member states, including Germany, France, and Italy, have added hydrogen to their broader cooperation on climate and energy. In both Germany and France, this offers important opportunities for supporting their domestic firms and technologies. In Italy, large state-owned energy firms, i.e., ENI and SNAM, have started integrating hydrogen into their existing energy relations in North Africa (Prontera, 2024). Germany in particular has seized on hydrogen as an important entry-point for engaging oil and gas-exporting countries in a dialogue on the opportunities of decarbonization, as emphasized in its H_2diplo initiative (Quitzow et al., 2024).

The UK has also begun addressing hydrogen-related issues within its existing energy cooperation initiatives, with a primary focus on the US and its European neighbors. It has incorporated hydrogen in its strategic energy dialogue with the US, and it is increasing its engagement on hydrogen with a number of European countries. In particular, it engages with Norway and other North Sea countries on cross-border energy projects, including hydrogen. Technology cooperation has not featured as an explicit priority so far.

The Australian government has launched cooperation with a series of partner countries to promote technology cooperation and supply chain development. Complementing the cooperation between the state of Victoria and Japan on hydrogen trade, it has launched the Japan-Australia Partnership on Decarbonization through Technology to facilitate collaboration on a number of decarbonization technologies, including clean hydrogen and ammonia. Similar agreements exist with Germany, South Korea, and Singapore. The Brazilian government has engaged primarily with the EU and Germany so far, successfully securing financial support to promote its domestic hydrogen sector. This includes USD 2 billion in funding, which is being channeled through the EU's Global Gateway initiative to finance hydrogen-related infrastructure. It has also launched the Brazil-UK Hydrogen Hub to support investment in the hydrogen sector.

Though China and the US have not made hydrogen a priority of their energy diplomacy, it is being integrated into existing initiatives. The US engages with partners for the promotion of the hydrogen sector within the context of established formats for international collaboration and finance in the energy sector, like the Strategic Clean Energy Partnership with India or the Partnership for Accelerating Clean Energy with the United Arab Emirates. Similarly, China has integrated hydrogen within existing energy cooperation with strategic partners like Pakistan, Egypt, Saudi Arabia, or Brazil, aiming to position China as a supplier of hydrogen technologies in these countries and around the world. Moreover, the government has supported overseas investment in FCEV manufacturing along the BRI as part of its industrial policy for the automotive sector. Finally, an important element of international cooperation is aimed at facilitating knowledge and technology transfer to China to close what are perceived as central technology bottlenecks in its domestic hydrogen sector (Gong et al., 2023).

3.3 Multilateral Cooperation

All the major economies highlighted in this volume have engaged in multilateral hydrogen cooperation. This cooperation includes knowledge exchange and technology cooperation as well as engagement in standard-setting. Multilateral hydrogen cooperation to date includes both hydrogen-specific initiatives, many of them focused on green hydrogen, as well as initiatives launched as part of existing institutions, like the International Energy Agency (IEA), the International Renewable Energy Agency (IRENA) or UN bodies like United Nations Industrial Development Organization (UNIDO). The latter largely focuses on the broader hydrogen sector, with the notable exception of IRENA (Lentschig et al., 2024).

These multilateral initiatives generally focus on knowledge exchange on best practices, joint generation of research and analysis as well as the development and harmonization of standards and certifications. Prominent initiatives are the Clean Energy Ministerial's (CEM) Hydrogen Initiative, the Clean Hydrogen Mission under the auspices of Mission Innovation, the Hydrogen Breakthrough Agenda as well as the longstanding Hydrogen Technology Cooperation Program (TCP) of the IEA and the International Partnership on the Hydrogen Economy (IPHE). In addition, the G7 and the G20 have launched hydrogen-related initiatives to jointly advance the hydrogen economy. Except for Brazil, all the major economies presented in this volume are active in all the initiatives (with the exception of the G7 Hydrogen Action Pact, which is limited to G7 member countries). So far Brazil is only involved in the CEM initiative and the IPHE, signaling a lower level of engagement on hydrogen-related cooperation so far.

3.4 International Cooperation on Hydrogen Standards

Most of the countries assign particular importance to the development of standards and certifications as an enabler for hydrogen trade. This was underlined by a joint declaration signed at COP 28 on "Mutual Recognition of Certification Schemes for Renewable and Low-Carbon Hydrogen and Hydrogen Derivatives". Furthermore, the Hydrogen Breakthrough Agenda has initiated a report that outlines the main features of standardization and certification schemes as the basis for promoting mutual recognition and interoperability. The report was jointly developed with participation by the IEA TCP, IRENA, and IPHE, signaling the high level of importance attributed to it (Breakthrough Agenda et al., 2023). Another important activity has been the development of a methodology by the IPHE for determining the greenhouse gas emissions associated with the production of hydrogen. This was led by representatives of the EU and the US with participation of most of the other IPHE member countries. Notably, China and Brazil were not represented during the development process, however. So far China has focused most of its attention on the development of technical standards, notably in the sphere of fuel cells. Brazil has begun to engage more actively in hydrogen-related standardization. However, the relatively high emissions threshold in its own *Brazilian System of Hydrogen Certification* is out of step with initiatives like CertifHy in the EU and may complicate efforts to harmonize its approach with other schemes. Brazil has also refrained from joining CertiLAC, a regional initiative to create a harmonized certification system.

The relatively strict standards in the EU for renewable hydrogen, referred to as renewable fuels of non-biological origin (RFNBOs), have been considered an important barrier to a more rapid ramp-up of hydrogen, not only in the Union but also in potential exporting countries. In the latter, electricity market rules that do not match those in the EU may complicate verification processes. Nevertheless, there are signs that EU regulatory power is shaping rulemaking in other jurisdictions. The US has proposed a similar set of rules for renewable hydrogen projects to benefit from the Hydrogen Production Tax Credits under the IRA.

4 The Emerging Geopolitics of Hydrogen and Decarbonization

The case studies in this book illustrate how the different political and economic conditions and legacies are shaping a wide variety of hydrogen strategies. The three dominant economic blocs—the EU, China, and the US—not only depart from very different starting points and different climate and energy regimes but their relative resource endowments and capacities also imply different types of challenges. Crucially, the renewable resource potential in the US and China will allow them to pursue a future green hydrogen economy without relying significantly on imports. The EU—like Japan—on the other hand will not have this luxury.

Nevertheless, the EU has emerged as a central champion of a hydrogen economy based on renewable power. It has built on its strength as a regulatory state (Bradford, 2019; Kennis & Liu, 2024) to develop a stringent set of rules aimed at ensuring a hydrogen ramp-up that is compliant with its net-zero goals. However, this approach has faced serious challenges, as the EU has seen itself confronted with a changing geopolitical and geoeconomic landscape (Prontera & Quitzow, 2021). The EU's regulatory model, centered on a combination of its emissions trading system and sector-based regulations, has to confront the fact that costly investments in decarbonization technologies, including hydrogen, may also harm short-term competitiveness. Specifically, hydrogen-based steel and chemical production could face serious challenges if exposed to competition from imported products from traditional producers. While the EU's carbon border adjustment mechanism (CBAM) seeks to address this challenge, it remains unclear whether this will suffice in protecting EU industries. This is further compounded by the energy price shock in the wake of the Ukraine war, which has driven up energy prices in the EU.

Another key question that emerges from the EU's focus on green hydrogen is how it will secure its green energy needs, and, closely related to this, how much of its existing energy-intensive industry it will be able to retain in the future (Eicke & De Blasio, 2022). Led by Germany, its largest member state, it is pursuing ambitious import targets via an increasing number of hydrogen partnerships (Quitzow et al., 2024). While these efforts are driven by its vulnerability in the field of energy supply, it also places the EU at the forefront of an international hydrogen economy. It positions the EU as an important partner for countries seeking to reap the gains of their renewable energy assets in a future net-zero economy. It also places it at the center of political negotiation processes over the configuration of net-zero industries and supply chains (Quitzow & Zabanova, 2024).

At the same time, the EU needs to grapple with China's increasing dominance in the field of green technologies and its ability to rapidly scale up and reduce the costs in emerging green sectors (Lema et al., 2020). On the one hand, low-cost Chinese technologies could play a key role in accelerating hydrogen ramp-up. On the other hand, it raises fears of technological dependencies at a moment where the US has embarked on a path toward increasing decoupling from Chinese supply chains. Conversely, for China, this means that it may have to rely more strongly on domestic demand for hydrogen and hydrogen technologies if it wants to compete in the race for technological leadership in the hydrogen economy. For now, the national government has not yet taken a strong stance in support of green hydrogen deployment. Rather it is pursuing a strong policy to close perceived gaps in its domestic know-how, while relying on industrial ambitions in a number of provinces. These include provinces with strong chemical industries as well as abundant renewable resource endowments. This allows the Chinese government to experiment with different approaches and technologies, while developments take shape internationally. Clearly, its 2060 carbon-neutrality target—ten years later than the EU and the US—also plays in favor of this approach (Gong et al., 2024).

With the IRA, the US government under President Biden has arguably provided the strongest fiscal stimulus to the hydrogen economy so far, propelling the US into the spotlight of hydrogen investment. However, this comes against the backdrop of a deeply divided US political system. The election of the new Trump administration has introduced substantial uncertainty into the US policy landscape, weakening its role as a leader of a global net-zero economy. This raises the question to what extent state-level initiatives will fill an emerging gap in US policy support. Though driven by a different set of political framework conditions, the EU faces a similar dilemma. Due to limited fiscal capacities at the EU-level, it has to rely heavily on financing by its member states to support the hydrogen ramp-up. As it has moved toward loosening its strict competition rules to allow member states to fill a widening financing gap, this has raised important questions regarding the integrity of the EU's single market, a key geoeconomic asset in its own right.

Beyond the three leading economic blocs, the other case studies in this book also reveal how the interplay of political developments, resource endowments, and industrial legacies are shaping their positioning within an emerging hydrogen economy. While developments in Australia are influenced by its past as an exporter of carbon-intensive energy commodities, changes in the political leadership have marked a shift toward a strategy that emphasizes its renewable potential and its potential for downstream value creation. Similarly, a new government in Brazil has not only increased the profile of its national hydrogen ambitions, but also emphasized its role within a new strategy for industrialization. Japan's resource constraints have placed it at the forefront of the global hydrogen economy, with a strategy strongly shaped by its traditionally close relationship between government and the national business community. In the UK, the hydrogen strategy epitomizes how the country's increasing shift toward a more active industrial policy in the hydrogen sector is complicated by its lack of clarity on priority applications and infrastructure.

These developments in the hydrogen sector are testimony to the growing confluence of geopolitics and markets in the context of global decarbonization processes. Efforts aimed at decarbonizing industries and stimulating new sectors are deeply intertwined with processes of policy development and the political negotiations underlying and shaping these. The choice and design of policy interventions have far-reaching implications for the competitiveness of technologies and economic actors and the resulting geographic configuration of a future net-zero economy (Quitzow and Zabanova 2025). The previously held belief in a liberal market governed by principles of efficiency and aimed at the optimal allocation of economic resources is giving way to a messy transition to a net-zero economy shaped in large part by regulatory choices and fiscal incentives (Goldthau, 2021).

It also reveals the intense challenges of developing the appropriate mix of policies that can help unlock the investment to unleash the needed economies of scale to bring down technology costs. Market uncertainties are compounded by regulatory, and underpinning this, political uncertainties. Compared to renewable electricity, hydrogen technologies suffer from a dual uncertainty. Not only is their uncertainty regarding the supply of hydrogen and the related costs, but future demand for hydrogen, i.e., the end-use sectors and technologies that will act as the hydrogen off-takers, is arguably even more uncertain (Lentschig et al., 2024).

Against this background, the central challenge of policymakers is to provide sufficient clarity and certainty to investors, while leaving options for adapting policy to international developments in market and technology. Historically, China has resolved this with strategic ambiguity and experimentation, combining this with the willingness to accept significant degrees of overcapacity. The US, with the IRA, has shown willingness to accept a degree of overinvestment and possibly stranded assets in its effort to catalyze new renewable and low-carbon technology pathways. The EU, on the other hand, remains committed to market-based incentives and mechanisms, including auctions and CO_2 pricing, while coupling this with a stringent regulatory landscape to avoid the misallocation of capital to unsustainable technologies. At the same time, with its Clean Industrial Strategy proposed in February 2025, the new European Commission formed in 2024 has pledged to focus on raising the competitiveness of European industry, closing the innovation gap with other major economies, and reducing strategic dependencies. This raises fundamental questions regarding the relationship between the EU, its member states, and the rules of its single market. It remains uncertain at this stage which approach will prove the most effective in the long run and how the green transition will affect geoeconomics more broadly. From a climate policy perspective, the central question is how the interplay of these industrial policy approaches can enable the needed acceleration of investment to fuel a sustainable ramp-up of the hydrogen economy.

Acknowledgements Research for this chapter was financially supported by the German Federal Foreign Office within the framework of the project "Geopolitics of the Energy Transformation – Implications of an International Hydrogen Economy" (GET Hydrogen), funding reference number AA4521G125.

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