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Jacopo Maria Pepe, Dawud Ansari, and Rosa Melissa Gehrung

The Geopolitics of Hydrogen

Technologies, Actors, and Scenarios until 2040

Stiftung Wissenschaft und Politik
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- The transition to a hydrogen-based economy is gaining momentum in both Germany and the European Union (EU). Used as an energy carrier, hydrogen holds the promise of freeing hard-to-decarbonise sectors like heavy industry, aviation, and maritime trade from their emissions. At the same time, policymakers hope that hydrogen will promote Europe's energy independence, push sustainable development, and strengthen value-based trade.
- This study presents three plausible yet disruptive scenarios for the geopolitics of hydrogen up to the year 2040 (developed with a team of experts in a multi-stage foresight process). "Hydrogen Realignment" considers the possibility of an eastward shift of industry, power, and technological leadership; "Hydrogen (In)Dependence" depicts a future, in which Europe pursues hydrogen self-sufficiency but becomes dependent on raw material supply; and "Hydrogen Imperialism" delves into the dystopian scenario of a hydrogen transition dominated by hegemons and despots.
- The transition to hydrogen is likely to shift and complicate Europe's external dependence rather than eliminate it; the role of supply chains will become more important. Moreover, the potential of hydrogen trade for global sustainable development is limited and requires targeted efforts.
- Resource distribution, production potential, current geopolitical power dynamics, and their interplay will influence hydrogen policy and decision-making along the entire value chain, with actors often giving priority to socioeconomic, geopolitical, and technopolitical considerations.
- Germany and the EU must pursue a proactive hydrogen strategy, acknowledge the preferences of external actors, and form pragmatic partnerships to keep sight of climate goals, retain industry, and avoid losing global influence.
- In addition to promoting targeted technologies, decision-makers must manage dependencies across sectors and do so in an anticipatory way. Pursuing diversification is indispensable, and instituting targeted diplomacy and development assistance would be helpful. The new hydrogen sector also needs governing institutions – for example a "Hydrogen Alliance" – to mitigate geopolitical risks and allocate investments correctly.

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The Geopolitics of Hydrogen: Technologies, Actors, and Scenarios until 2040

Governments around the world are throwing their weight behind the new "hydrogen economy"— particularly in Germany and the EU. Clean hydrogen could ultimately help decarbonise such economic sectors as heavy industry, aviation, and maritime trade, thereby mitigating climate change. However, recent geopolitical events such as the Russian invasion of Ukraine have cemented the previously latent shift in the EU's narrative of the energy transition — from climate action and justice towards strategic autonomy and industrial policy. Policymakers are thus eyeing hydrogen as a way to achieve long-term energy independence. At the same time, Germany and the EU will have to rely on hydrogen imports — a fact that throws a spotlight on the international dimension of hydrogen. As that dimension evolves within a maelstrom of surging (technological, industrial, and systemic) competition, security tensions, and the fragmentation of global supply chains, it is ever more important to consider the *geopolitics of hydrogen*.

Studies on the dynamic interactions of market factors, geopolitical path-dependency, and national motives vis-à-vis the hydrogen economy are absent so far. The current discourse in Germany and Europe has yet to consider anything but domestic technological, regulatory, and political preferences; the intentions of other actors are practically absent. Yet the preferences of foreign actors are diverse, dynamic, and reflect the geopolitical environment. Simultaneously, policymakers formulate a growing number of (sometimes inconsistent) expectations for the hydrogen transition — ranging from global sustainable development to restricting trade to narrow "value-alliances" to energy independence. Since conflicts, dependencies, and market setups can and might be reshaped for decades to come, it is essential for Germany and Europe to identify and strategize relations, trade-offs, risks, and interdependence.

This study provides a first overview of the geopolitics of hydrogen. In addition to presenting technology choices and preferences emerging in the hydrogen economy, we present three novel, interdisciplinary scenarios — "Hydrogen Realignment", "Hydrogen (In)Dependence", and "Hydrogen Imperialism" — for the hydrogen world up to 2040. These scenarios offer disruptive yet plausible futures that highlight conflicts, risks, opportunities, and potential for action.

"Hydrogen Realignment" envisions the combined effects of ambitious Chinese hydrogen governance and European deindustrialisation — foretelling a shift in energy flows, industry, and geopolitical power towards the Gulf and Asia. New power dynamics and supply chains emerge within Afro-Eurasia, while Europe meets its climate goals but loses its geopolitical influence.

"Hydrogen (In)Dependence" pictures a more fragmented world in which only Europe commits to the hydrogen transition — as part of its quest for energy autarky. However, previously ignored dependencies on raw material supply from foreign actors ultimately threaten the EU's security autonomy, forcing it back into the energy trade.

"Hydrogen Imperialism" explores the dystopian vision of a hydrogen-powered throwback to the era of historical protectorates. A unified push for hydrogen kicks off a race to divvy up value chains and exporters, but things go south when security incidents force large importers to become more assertive — and the original premise of "international development" becomes a pretext for supporting hydrogen dictatorships.

The study demonstrates that while hydrogen has the potential to significantly disrupt present energy geopolitics, it cannot overturn its basic premises. Under certain conditions, the degree of foreign energy dependence may indeed weaken. However, as value and supply chains grow more intricate and dispersed, dependencies may also end up becoming more complex and difficult to monitor. Even an economy that does not import hydrogen or its derivatives can still depend on other parties for raw materials, hydrogen technology, and components. Moreover, the hydrogen market may not necessarily develop in alignment with established structures and the goals European policymakers expect. Most governments prioritise socioeconomic, geopolitical, and industrial factors over climate policy; a fact that could result in growing asymmetries and incongruities between European consumers and global producers.

Despite ambiguities, challenges, and a persistent degree of foreign energy dependence, Germany and the EU should continue to consider hydrogen as essential for their energy transition efforts. Hydrogen will enable Europe to achieve climate targets while preserving its industries — and even establishing new ones; meaning the "old world" can make use of its geopolitical potential in an era of heightened competition for key industries. This will require four essential steps from Germany and the EU to proactively help the hydrogen landscape.

1) They must understand the preferences of non-European actors and acknowledge realities. In dealing with external actors and selecting partners, they should take a pragmatic, compromise-oriented, and ambitious approach, as narrowly Eurocentric visions of the hydrogen economy do not reflect reality. If they do not, Europe risks not only missing its climate targets but also losing out in the global competition to acquire technology, set standards, and maintain influence.

2) They should promote technologies and industries in a targeted way. While it is generally advisable to support industry's adaptation to hydrogen as well as versatile technologies like carbon capture and storage (CCS), Europe should also ensure that the technology portfolio it promotes be closely aligned with future geopolitical developments and energy sector dynamics.

3) They must actively manage dependencies connected to the hydrogen economy. Complex value chains call for comprehensive cross-sector dependency management, including managing raw material chains. Here, diversifying technology, raw material sourcing, and energy imports are crucial, regardless of the trading partner. Accompanying development policy and diplomacy that considers the interests of partner countries can help mitigate risk.

4) They must work to establish global hydrogen governance. A governance structure can help allocate investments correctly, mitigate the drawbacks of purely bilateral trade structures, and reduce geopolitical risks. One such format could be a "Hydrogen Alliance", a multilateral, two-tiered trade club. Without suitable governance mechanisms to consider all potential market actors and acknowledge their agency, hydrogen's potential to ease geopolitical tensions and promote collaboration will remain limited in the face of an increasingly uncooperative and fragmented world order.

Geopolitics, hydrogen, and scenarios for the future

The establishment of a hydrogen economy is widely considered an essential component of a sustainable energy system, particularly for decarbonising key industrial sectors that would otherwise be difficult to decarbonise. However — not least with the resurgent rivalry between the United States and China and Russia's aggression against Ukraine — energy supply security, energy autonomy and resilience, and the struggle for technological leadership have remerged as central paradigms of both energy policy and foreign policy more generally.

While scholars have investigated how these factors interact for conventional energy sources, the geopolitics of hydrogen is still uncharted. Most studies of the hydrogen economy focus on the technologies, costs, resources, and infrastructure; they then extrapolate implications for the future geopolitical and market landscape from these aspects.[1] Literature on the geopolitics of the energy transition meanwhile has yet to give adequate attention to the impact of existing (geo-)political dynamics overall and the individual preferences of potential market actors in particular. Energy scenarios for their part have yet to address the nexus of geopolitics and hydrogen.[2]

Examining the geopolitical implications of hydrogen requires identifying and mapping prospective actors, conflicts of interest, risks, and potential dependence relationships. Here the tools of strategic foresight prove useful.

1 An example of a more nuanced approach to the geopolitics of hydrogen is found, for instance, in International Renewable Energy Agency (IRENA), *Geopolitics of the energy transformation: The hydrogen factor* (Abu Dhabi, 2022).

2 Geopolitical and security considerations feature prominently in the latest Shell energy security scenarios but do not focus specifically on hydrogen. See Shell, *The energy security scenarios* (2023), https://go.shell.com/3u8PvlP.

The geopolitics of hydrogen: Resources, technology, power, and the world order

Geopolitics refers to the interaction of geographical factors (location, space, and resources) with political processes. The geopolitics of energy traditionally examines the impact on interstate power dynamics of concentrated (fossil) energy resources, including their transportation and trade.[3] The interrelationship of geopolitics and energy markets is of course complex and anything but unidirectional.

The geographical concentration of fossil-fuels (coal, oil, and gas) has influenced patterns of power and prosperity ever since the Industrial Revolution. Energy resources have long served as a currency of power, a strategic asset, or a source of conflict. Technology, together with the distribution and concentration of resources, is key to the geopolitics of energy. New technologies can unleash major changes in extraction, production, transport, and distribution, thus triggering tectonic shifts in the geopolitical power balance. For instance, technological innovations influence the strategic importance of individual energy sources and promote new value chains, supply chains, and trade routes. This in turn may affect infrastructural and trade-related interdependence, redrawing economic and energy landscapes.

It is important to recall, however, that neither resource distribution nor technology are inherently "geopolitical". Rather, they gain geopolitical significance only when they are "deployed in a political direction."[4]

Market mechanisms and certain market configurations can minimise dependence risks, defuse conflicts, and depoliticise interdependence. However,

3 Michael Bradshaw, "The geopolitics of global energy security", *Geography Compass* 3, no. 5 (2009): 1920–37.

4 Otto Maull, *Politische Geographie* (Berlin: Safari-Verlag, 1956), 30.

existing geopolitical power constellations influence the political preferences of state and non-state actors and ultimately affect market mechanisms. This in turn influences energy relations, flows, and markets.

This reciprocal relationship between geopolitics and energy markets extends to the global order.[5] On the one hand, energy relations have the potential to shape the global framework. (Arabia's political integration in the world system in the 20th century is one example; Soviet/Russian gas exports into Eastern European economies before 2022 is another.) On the other hand, the global framework shapes the conditions for energy relations. A multilateral world order with well-functioning global institutions and global governance mechanisms is more conducive to the unimpeded flow of energy, open and liberalised markets, and fair competition than an environment with weak global governance institutions, competing powers, and a lack of cooperation among states. For example, the gradual liberalisation of energy markets and the pursuit of global energy governance (with the Energy Charter Treaty of 1991) occurred in a period of growing acceptance of a liberal, multilateral world order largely shaped by the West at the end of the Cold War.

The "new" energy world is even more dominated by technology, raw materials, and the desire to set regulatory and technological standards.

The ongoing transformation of the energy system, much like the current system based on fossil fuels, has its unique geopolitics. But the "new" energy world is even more dominated by technology, (critical) raw materials, and the desire to set regulatory and technological standards and maintain industrial leadership.[6] Renewable energy resources are generally less concentrated (fig. 1). However, value chains and supply chains are longer, more convoluted, and spatially more dispersed; they are also more interconnected than in the case of fossil energy sources. Such factors craft and shift dependencies at different stages of value and supply chains along with their geography, making them potentially more complex. States, public entities, and private companies are competing for access to resources and transport routes as well as for key markets, components, production processes, industries, and their maintenance, and even investment flows and financing.

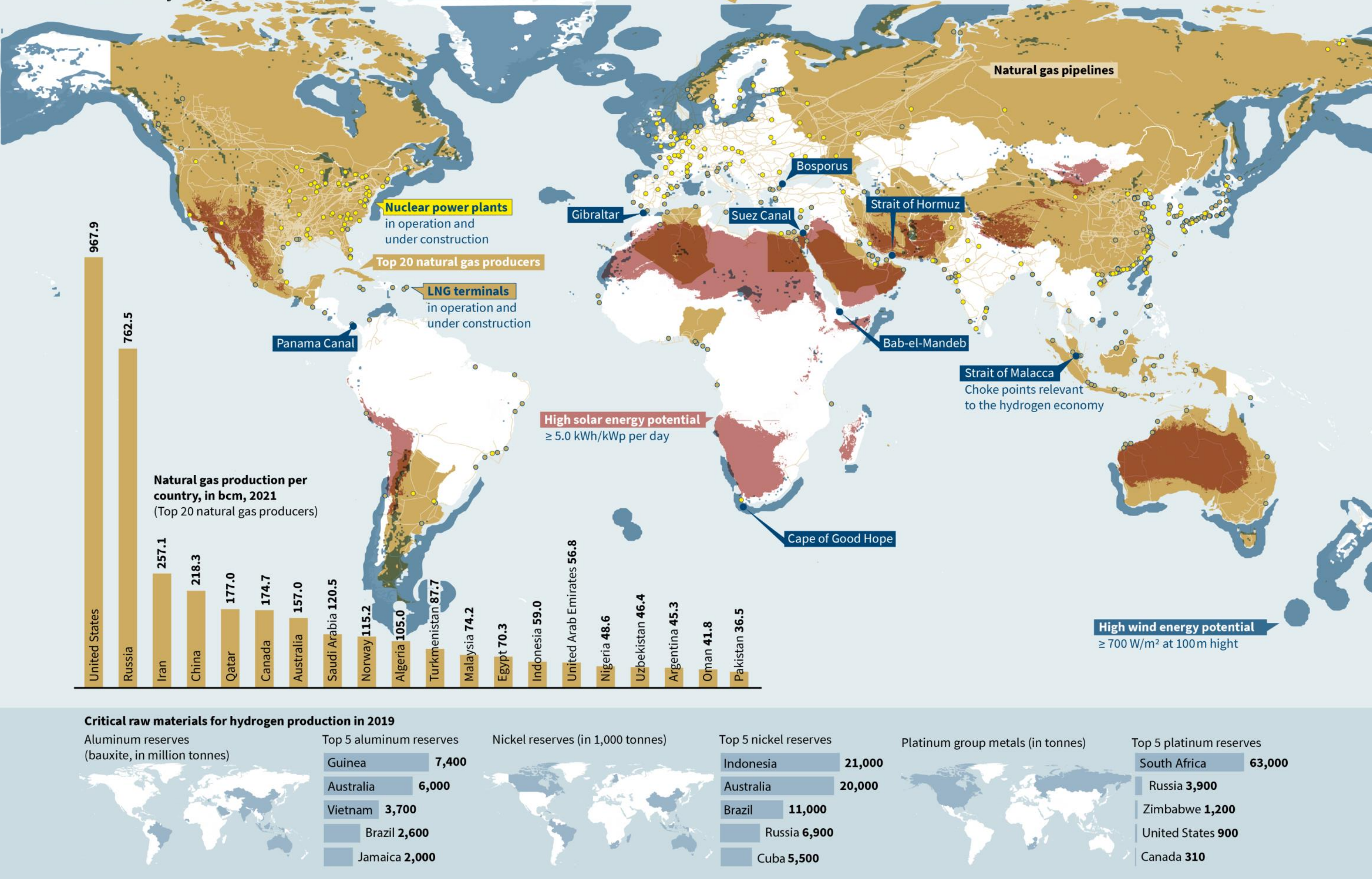
The geopolitics of hydrogen will presumably follow — and exacerbate — these trends. Depending on production technology, certification path, transport option, and final products, distinct value chains, supply chains, and production networks arise. Exporters of technology, hydrogen, and raw material therefore have a vested interest in establishing and proactively shaping dependence relationships, be it through technological and market leadership or through path-dependencies that favour specific technologies in production, transportation, or application.

Hydrogen's resource, technology, and transportation landscape is indeed diverse (fig. 1). The new hydrogen world could well alter the role of concentrated resources as a determinant of the geopolitics of energy. For example, natural gas (one possible source material for hydrogen) is relatively concentrated, but other resources for hydrogen production such as solar and wind energy (as well as nuclear power plants) are more evenly distributed. Diversification could reduce the risk of geographic concentration. At the same time, critical raw materials (like nickel and platinum), their extraction, and their processing are crucial for hydrogen production. Like natural gas, these materials are rather concentrated, although they involve different owners. Transportation is yet another crucial issue. Building up new or/and upgrading existing infrastructure (especially ports, freighters, and pipeline networks) will tie-up major resources, and investment decisions will thus forge long-term interdependence and greatly influence the topographies of actors and power in the hydrogen sector.

5 These include the configuration (bipolar, multipolar, unipolar); the governance mechanisms (regional, global); and the nature of relations between states (cooperative, confrontational, multilateral, bilateral) and their foreign policy ambitions.

6 Jason Bordoff and Meghan L. O'Sullivan, "Green upheaval: The new geopolitics of energy", *Foreign Affairs* (online), (January/February 2022), https://www.foreignaffairs.com/articles/world/2021-11-30/geopolitics-energy-green-upheaval; Daniel Scholten et al., "The geopolitics of renewables: New board, new game", *Energy Policy* 138 (2020); Kirsten Westphal, Maria Pastukhova, and Jacopo Maria Pepe, *Geopolitics of electricity: grids, space and (political) power*, SWP Research Paper 14/2021 (Berlin: Stiftung Wissenschaft und Politik, September 2021).

The new hydrogen world: Raw materials, infrastructure, resources



Sources: data based on World Bank, DERA, BGR, and Global Energy Monitor, collected and supplemented by SWP team “Data and Statistics”; https://doi.org/10.18449/2023RPxx#Map_Sources
The map is for illustrative purposes only and does not represent a position on claims under international law. For optimal readability, we recommend viewing in colour.

In addition to technologies, resources, and transportation routes, political decisions (heavily influenced by competing connectivity, industry, and energy policy preferences) are crucial in shaping markets and geopolitical developments.[7] Current power dynamics — particularly increasing fragmentation, the erosion of the liberal order, and geopolitical competition as reflected in (re)militarisation of global affairs — may thus have a direct impact on the nascent hydrogen economy and significantly shape future hydrogen geopolitics. For instance, in addition to the US-China rivalry and the ongoing tensions between the EU and Russia, various actors are realigning their priorities and preferences — including emerging powers like India and regions with new geopolitical weight like the Gulf States. Even within the traditionally strong and value-driven transatlantic relationship, fault lines are emerging.

Although it is far from clear who the winners and losers of the emerging hydrogen economy will be, a more precise exploration of hydrogen's geopolitical implications is indispensable, not least in aiding the EU and Germany as they develop coherent courses of action.

Using strategic foresight to envision hydrogen geopolitics

The geopolitics of hydrogen is emblematic of the "VUCA world" — it is developing in an environment characterized by **v**olatility, **u**ncertainty, **c**omplexity, and **a**mbiguity.[8] Such an environment renders reliable predictions of future developments infeasible, which is why we turn to strategic foresight and scenario generation.

Scenarios are hypothetical sequences of events that lead from the present to an endpoint in the future (see fig. 2).[9] Their purpose is to explore and anticipate uncertain developments, unknown factors, and emerging opportunities and risks. Scenarios differ from predictions in both conceptual and practical terms. Predictions rest on the *probability* of an envisioned future and strive for precision, typically operating in a short-term framework. Scenarios, on the other hand, seek to generate new insights and create preparedness, and their main criterion is *plausibility*, meaning that they demand internal consistency and credibility. They may even deliberately target visionary or improbable futures in an attempt to give bounds to the range of possibilities[10] (see again fig. 2). The scenario-generating process draws on structured qualitative analysis, heterogeneous and interdisciplinary expertise, and participatory frameworks.

Scenarios eschew rigidity, formality, and reductionism and instead aim at evoking a "memory of the future" with the audience.

The hybrid and fluid nature of scenarios, which occupy the intersection of logic and intuition, is their strength compared to more linear and "sterile" approaches. Scenarios eschew rigidity, formality, and reductionism and instead aim — in a somewhat artistic process — at evoking a "memory of the future" with the audience. Ideally, this enables decision-makers to anticipate previously unforeseen consequences and

7 Regarding policy preferences for strategic imports, see Dawud Ansari and Jacopo Maria Pepe, *Toward a hydrogen import strategy for Germany and the EU: Priorities, countries, and multilateral frameworks*, SWP Working Paper, Research Division "Global Issues", 01/2023 (Berlin: Stiftung Wissenschaft und Politik, June 2023).

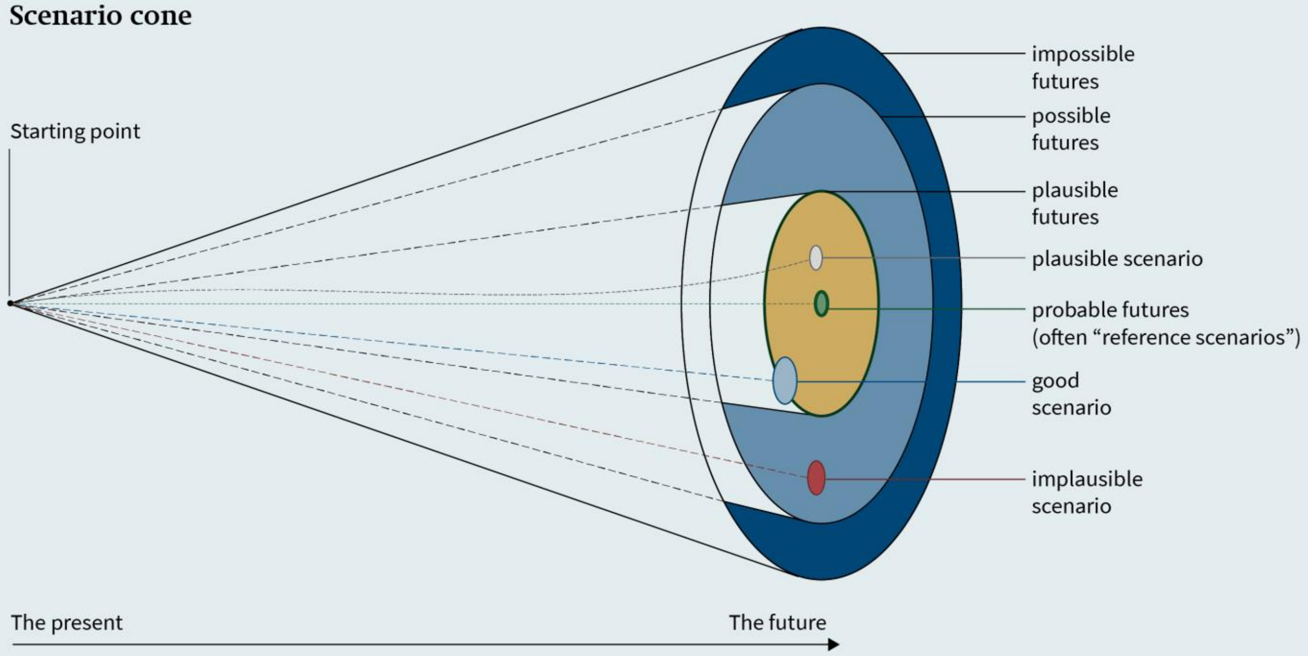
8 Nicholas W. Townsend and Judith Stiehm, *The U.S. Army War College: Military education in a democracy* (Philadelphia, PA: Temple University Press, 2002), 64—65; Mathew J. Burrows and Oliver Gnad, "Between 'muddling through' and 'grand design': Regaining political initiatives — the role of strategic foresight", *Futures* 97 (2018): 6—17.

9 Herman Kahn and Anthony J. Wiener, *The Year 2000* (London: Macmillan, 1967), 6; Dawud Ansari et al., "Energy outlooks compared: Global and regional insights", *Economics of Energy & Environmental Policy* 9, no. 1 (2020): 21—42.

10 The continuous interaction of uncertain influencing factors ensures that uncertainty about the future steadily increases as the time horizon extends, forming a "cone of uncertainty." The centre of this cone contains the most *probable* future as a linear continuation of current trends — while the futures situated at increasing distance from its centre represent more improbable visions, up to the *implausible* and even the *impossible*. In order to cover a broad spectrum of possible developments, scenario development should (i) move along the edge of plausibility and (ii) choose, as far as possible, to explore contrasting futures. See Paul J. H. Schoemaker, "Scenario planning: A tool for strategic thinking", *Sloan Management Review* 36, no. 2 (1995): 25—40; Ansari et al., "Energy outlooks compared" (see note 9).

Figure 2

Scenario cone



Source: Based on Dawud Ansari et al., "Energy Outlooks Compared: Global and Regional Insights" *Economics of Energy and Environmental Policy* 9, no. 1 (2020): 21–42

risks and develop preparedness through strategic options.[11]

This study presents the first scenarios at the nexus of hydrogen and geopolitics. While scenario foresight has become a centrepiece of the energy sector, geopolitical aspects or security policy are rare — even though the method calls explicitly for interdisciplinary expertise. However, scenarios are arguably the best method of approximating the complex and ambivalent chains of cause and effect in the geopolitics of hydrogen — and assessing them strategically. Before presenting the scenarios, we first map out the technological and technopolitical aspects of hydrogen production and transport and provide an overview of the hydrogen ambitions in different regions and their geopolitical context.

11 In the context of sensing and experiencing an imagined future in which uncertain events have already occurred — a "memory of the future" — decision-makers are supposed to experience an "aha moment" that reveals new risks and options or challenges underlying assumptions. See Pierre Wack, "Scenarios: Shooting the rapids," *Harvard Business Review* (1985): 139—50; Peter Schwartz, *The art of the long view: Planning for the future in an uncertain world* (New York: Doubleday, 1996), 205.

Technology pathways, modes of transportation, and regional preferences: An overview

Currently, there is neither a global nor a regional market for (clean) hydrogen as an energy carrier, and both supply and demand need to be established.[12] The range of conceivable production methods, technologies, products, transportation routes, and applications for hydrogen is wide. The paths actors choose to take in the future will be determined, on the one hand, by their political preferences and, on the other, by existing market and power structures. Different requirements for raw materials, components, and know-how will in turn create different energy (market) structures, new relationships of interdependence, and — potentially — new centres of power. Here, an overview of the world's potential hydrogen actors helps place their respective preferences in geopolitical context.

Technologies, resources, and dependencies: Hydrogen production

Most hydrogen produced today (>99 per cent) is derived from fossil fuels without methods to reduce accompanying carbon dioxide (CO_2) emissions.[13] Steam methane reforming (SMR), by far the most common production technique, uses heat and water (steam) to extract hydrogen from natural gas; the process emits large quantities of carbon dioxide and carbon monoxide. In 2021, about 12 to 13 tonnes of CO_2 equivalents were emitted for every tonne of hydrogen produced, aggregating to about two per cent of global greenhouse gas emissions.[14] Such hydrogen extracted from fossil gas via SMR is often referred to as "grey" hydrogen (fig. 3).[15]

For hydrogen to become a low-carbon or even carbon-free energy carrier, its production must be decarbonised. The carbon capture and storage (CCS) approach separates the emissions generated during the SMR process and stores them, typically underground.[16] The captured CO_2 could also find productive use, for example in enhanced oil recovery or potentially as raw materials; the process is then labelled Carbon Capture, Utilisation, and Storage (CCUS).

While this "blue" hydrogen yields fewer carbon emissions, the process is not entirely carbon-free. The residual emissions depend on the efficiency of the CCS/CCUS plant involved. Compared to renewable energy sources — which have received extensive research and government support over the past decades

12 While hydrogen has long been an essential raw material in sectors like agriculture (ammonia production) and the chemical industry more generally, it is not yet traded in large quantities. Current production methods remain emission intensive. The use of hydrogen as an energy carrier is not presently widespread.

13 IEA, *Hydrogen* (website), https://www.iea.org/energy-system/low-emission-fuels/hydrogen.

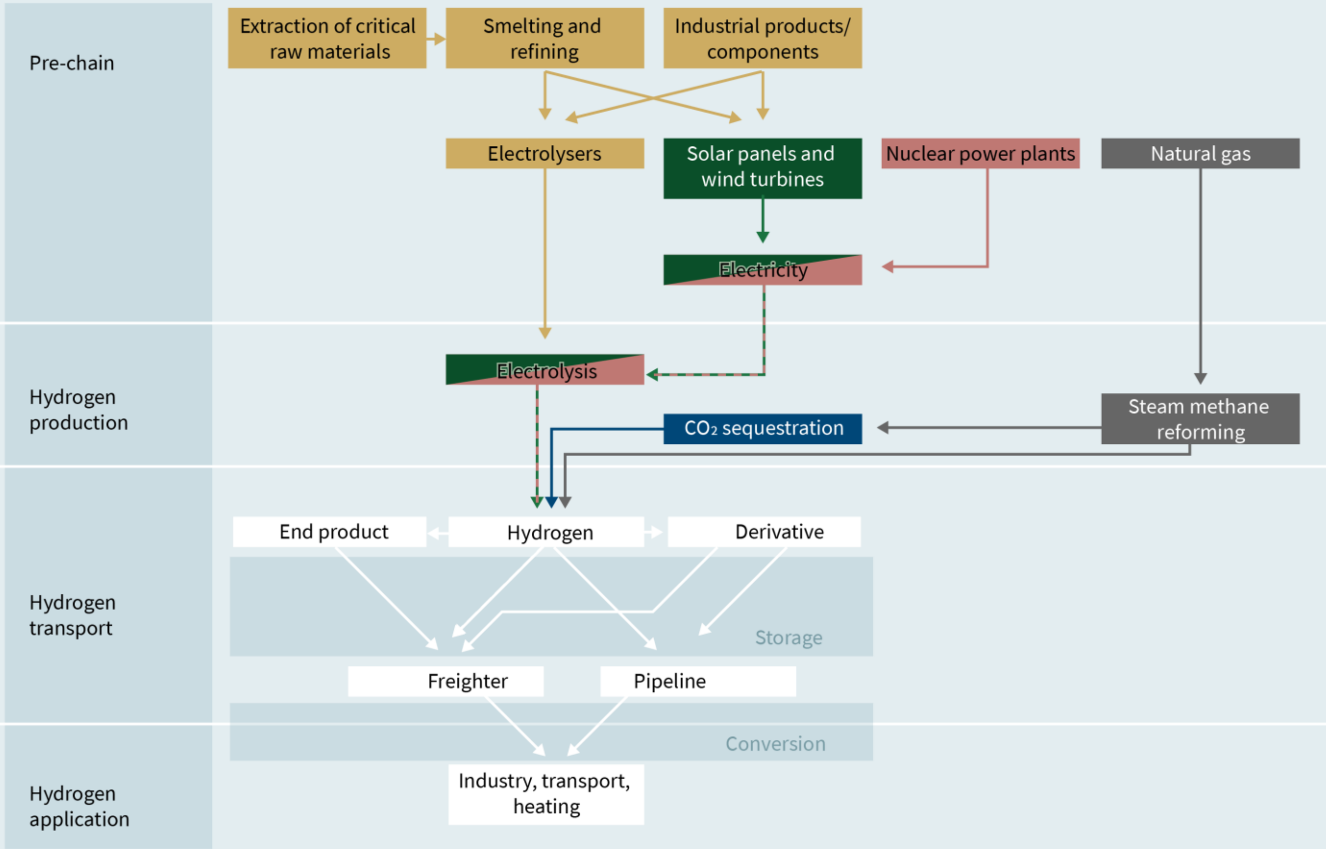
14 IEA, *Towards hydrogen definitions based on their emissions intensity* (2023), 8.

15 Several experts consider the current practice of ascribing different "colours" to different types of hydrogen (to denote the different manufacturing technology used to produce it) confusing and inconsistent. For a complete review of the "colour spectrum" and respective degrees of emissions, see Amela Ajanovic et al., "The economics and the environmental benignity of different colors of hydrogen", *International Journal of Hydrogen Energy* 47 (2022); Julian Grinschgl et al., *A new hydrogen world: Geotechnological, geoeconomic, and geopolitical implications for Europe*, SWP Comment 78/2021 (Berlin: Stiftung Wissenschaft und Politik, December 2021).

16 Felix Schenuit et al., *"Carbon management": Opportunities and risks for ambitious climate policy*, SWP Comment 30/2023 (Berlin: Stiftung Wissenschaft und Politik, May 2023).

Figure 3

Hydrogen value chain (simplified and selective)



Source: Based on Julian Grinschgl et al., *A New Hydrogen World: Geotechnological, Economic, and Political Implications for Europe*, SWP Comment 58/2021 (Berlin: Stiftung Wissenschaft und Politik, December 2021)

— CCS and CCUS technologies are still largely immature and can at present only capture a portion of total emissions. Estimates of future emission reductions vary widely; moreover, it is necessary to stop methane leaks in the natural gas supply chain.[17]

The cost of producing hydrogen using SMR depends significantly on the price of natural gas. From a European perspective, this increased notably with the onset of the 2022 energy crisis — at times reaching approximately 5 to 8 euros per kilogram.[18]

From a geopolitical perspective, low-carbon hydrogen from natural gas could consolidate and prolong the power of natural gas producers, who could continue to export gas via established trade relationships. The race to bring CCS to the market (along with the extent of natural gas reserves) will determine the degree to which fossil fuel exporters gain a foothold in renewable energy markets. Completed and planned commercial facilities are mainly located in North America, Australia, northern Europe, the Gulf States, China, and Southeast Asia, with capacity expansion planned, particularly in Europe and the Asia-Pacific region, to take place by 2030.[19]

17 See for example Christian Bauer et al., “On the climate impacts of blue hydrogen production”, *Sustainable Energy Fuels* 6 (2022): 66–75; Julian Schippert et al., “Greenhouse gas footprint of blue hydrogen with different production technologies and logistics options”, *Social Science Research Network* (2022).

18 IEA, *Towards Hydrogen Definitions* (see note 14), 22. In 2019, the per kilogram price ranged from roughly 0.70 to 1.50 euros per kilogram, see IEA, *Global average levelised cost of hydrogen production by energy source and technology, 2019 and 2050* (website), 24 September 2020, https://www.iea.org/data-and-statistics/charts/global-average-levelised-cost-of-hydrogen-production-by-energy-source-and-technology-2019-and-2050.

19 Global CCS Institute, *Facilities Database* (website), https://co2re.co/FacilityData; IEA, *CCUS Projects Explorer* (website), However, Germany and the EU are focussing their hydrogen ambitions on producing hydrogen through water electrolysis powered by renewable electricity — so-called green hydrogen.[20] Electrolysis involves using an electrolyser to split water (H_2O) — or potentially other liquids — into oxygen (O) and hydrogen (H_2). Hydrogen from electrolysis will be carbon-free, if the electricity has been generated without emissions (for example, from solar-, wind-, or nuclear power).

With current costs ranging from 4.60 to 7.30 euros per kilogram, green hydrogen is rather expensive.[21] These costs, which will decrease over time, generally depend on the cost of developing renewable energies (and, thus, on geographical and meteorological factors). For example, estimates for 2030 see production costs for green hydrogen at around 1.90 euros per kilogram in sub-Saharan Africa and approximately 1.50 to 2 euros in the Gulf States.[22]

Electrolysers and the raw materials needed to manufacture them (see again fig. 1) are critical to scaling the market for green hydrogen.[23] Two types of electrolysers currently prevail: alkaline electrolysers and polymer electrolyte membrane electrolysers (PEM).

Alkaline electrolysers are the oldest, most cost-effective, and most widely used technology, accounting for 61 per cent of globally installed capacity. They require nickel and (nickel-plated) steel. Nickel processing takes place primarily in Indonesia, China, and Japan.[24] As some countries (like Indonesia) strive to prevent the export of unrefined nickel, China is securing on-site smelting capacities in these mining countries through strategic investments. This gives China the ability not only to produce most of the world's alkaline electrolysers but also to offer them at a cost of approximately 190 euros per kilowatt (kW) — one-sixth of the European price.[25]

PEM electrolysers are slightly better suited to the fluctuating supply of renewable energies, but their technology is less mature, and they are more expensive than alkaline electrolysers. Their current global market share is just under 31 per cent, with costs ranging from 1,300 to 1,960 euros per kW.[26] Europe currently holds an advantage in terms of PEM patents and production. Platinum and iridium are required for production, and their distribution (and potential supply chains) is highly concentrated. South Africa holds the world's largest reserves of platinum group metals (approximately 91 per cent), including iridium, followed by Russia (about 6 per cent) and Zimbabwe (about 2 per cent).[27] In contrast to alkaline electrolysers, the supply of components for PEM electrolysers tends to be concentrated among individual manufacturers in the EU, the US, the UK, and Japan.

Hydrogen from renewable electricity could well lead to the emergence of a new class of exporters along new and more diffuse value chains in comparison to those of fossil fuels; dependencies in such chains will also be more diffuse. Competition for resources may diminish, but competition for components, expertise, and modes of transportation remains relevant.

Pipelines, shipping, and choke points: Geopolitical transport challenges

Large-scale hydrogen transport can in principle take place in gas or liquid form: either through pipelines (in gaseous form) or shipping (either as liquid hydrogen, through Liquid Organic Hydrogen Carriers, or as hydrogen-derived products like ammonia, see again fig. 3).

24 March 2023, https://www.iea.org/data-and-statistics/data-tools/ccus-projects-explorer.

20 European Commission, *Hydrogen* (website), https://energy.ec.europa.eu/topics/energy-systems-integration/hydrogen_en; German Federal Ministry of Education and Research (BMBF), *Nationale Wasserstoffstrategie: Grüner Wasserstoff als Energieträger der Zukunft* (website), 26 March2023, https://www.bmbf.de/bmbf/de/forschung/energiewende-und-nachhaltiges-wirtschaften/nationale-wasserstoffstrategie/nationale-wasserstoffstrategie_node.html.

21 IEA, *Indicative Production Costs for Hydrogen via Electrolysis in Selected Regions Compared to Current References* (website), 12 January 2023, https://www.iea.org/data-and-statistics/charts/indicative-production-costs-for-hydrogen-via-electrolysis-in-selected-regions-compared-to-current-references-2.

22 IEA, *African Energy Outlook (*Abu Dhabi, 2022), 157; Dutch Ministry of Foreign Affairs, *Hydrogen in the GCC* (The Hague, 2020), 2.

23 Dawud Ansari et al., *Electrolysers for the hydrogen revolution: Challenges, dependencies, and solutions*, SWP Comment 58/2022 (Berlin: Stiftung Wissenschaft und Politik, September 2022).

24 IRENA, *Geopolitics of the energy transition: Critical materials* (Abu Dhabi, 2023), 40.

25 Xiaohan Gong et al., *China's emerging hydrogen economy: Policies, institutions, actors* (Potsdam: Research Institute for Sustainability — Helmholtz Centre Potsdam, 2023).

26 Aliaksei Patonia and Rahmatallah Poudineh, *Cost-competitive green hydrogen: How to lower the cost of electrolysers?* (Oxford: The Oxford Institute for Energy Studies, 2022).

27 Deutsche Rohstoffagentur (DERA), *ROSYS – Rohstoffinformationssystem* (website), https://rosys.dera.bgr.de.

Most attention is currently given to liquid ammonia shipping and pipeline transport of gaseous hydrogen; this is because both would be able to benefit from existing infrastructure, tested production methods, and established supply chains and markets.

Existing natural gas pipelines can be repurposed for hydrogen, or new pipelines can be constructed. Estimates consider pipeline transport to be a cost-effective solution in the long term for distances of up to 4000 km for new pipelines and up to 8000 km for converted pipelines, provided projects carry sufficient volume.[28] Repurposing pipelines for hydrogen depends on a steady decline in demand for natural gas, going hand in hand with the extensive transformation of national and (inter)regional natural gas pipeline networks. New pipelines require not only high initial investment, intense diplomatic effort, and years (or even decades) to complete, but also create path-dependence due to infrastructure rigidity. Moreover, their inherent limitations are not conducive to inter-regional trade. In the case of onshore pipelines, risks of third-party dependence increase with distance and the number of countries such pipelines cross.

Compared to pipelines, ships could be more competitive, especially over long distances. This mode of transport depends less on network infrastructure, which favours global trade — also as distance has only a moderate effect on transportation costs. Although liquid ammonia is a promising candidate for shipping, its transportation technology is still immature. The crucial factors here are port infrastructure, freighter design, and the processing technology for deriving ammonia from hydrogen and vice versa. Moreover, especially for derivatives like ammonia, investment security and economic viability depend on coordination and integrated network planning between buyer and seller countries[29] — measures that tend to solidify long-term interdependency. Ultimately, maritime transport requires complex supply chain risk management, as demonstrated by choke points, global bottlenecks (for example in Suez, Malacca, and Panama), and potential threats to sea routes.

28 See IRENA, *Global hydrogen trade to meet the 1.5°C climate goal: Part II – Technology review of hydrogen carriers* (Abu Dhabi, 2022), 125–26.

29 Kirsten Westphal et al., *Commercial interfaces as a challenge for the build-up of hydrogen supply chains* (Hamburg: H2Global, 2023).

Regional incongruities and geopolitical divergences

Early decisions over technology and transport routes as well as the market setup underline the degree of political competition among potential future hydrogen actors — which results from their diverging preferences.[30] In addition to resource availability, meteorological conditions, and existing infrastructure (see again fig. 1), the following subsections outline the respective strategies of these actors as well as broader regional geopolitical contexts.

Europe on the edge: Between wishful thinking and (geopolitical) reality

The EU has positioned itself as the largest demand centre for low-carbon hydrogen, and it aims to take a leading role in establishing a hydrogen market. As the EU's technological-industrial competition with both the US and China appears to increase, initiatives such as the EU Green Deal, the REPowerEU plan, the Clean Hydrogen Partnership, and the European Hydrogen Bank are intended to accelerate the development of the hydrogen market in the EU.[31] The goals are to solidify the EU's technological and regulatory leadership, help the EU achieve climate neutrality (or establish a post-fossil energy system), and enhance the region's supply autonomy.[32]

When the war in Ukraine broke out, the EU set the target of installing electrolysis capacity of over 120 gigawatts (GW) by 2030 for domestic hydrogen production. It aims to produce 10 million tonnes of hydrogen annually. Although the Net-Zero Industry Act of March 2023 also promotes CSS, its focus is on electrolysis powered by renewables.[33] Areas in the

30 The order of the regions or the selection of the presented (example) countries in the following subchapters does not express any valuation by the authors.

31 *Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee, and the Committee of the Regions, REPowerEU Plan*, 18 May 2022, COM(2022) 230 final, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2022%3A230%3AFIN &qid=1653033742483.

32 Jacopo Maria Pepe, *Geopolitik und Energiesicherheit in Europa* (Brussels: Competence Centre for Climate and Social Justice und FES Just Climate, 2023).

33 European Commission, *Net Zero Industry Act: Kommission will bessere Bedingungen und mehr Investitionen für saubere Technologien in Europa* (website), 16 March 2023, https://germany.

EU with climates favourable to producing renewable hydrogen through electrolysis are limited, however; current industrial policy and access to resources and technology are moreover insufficient for a rapid scale-up of domestic production. The REPowerEU plan therefore also envisions importing 10 million tonnes of hydrogen to the EU annually, despite differing views among member states. Having ruled out the EU's eastern neighbourhood — which could build on proximity and existing infrastructure — for security reasons, in the short and medium term, the EU has only a few suitable potential trading partners that can enable a swift ramp-up of hydrogen trade; these are mainly located in North Africa and the Gulf States. (See the subsection on Africa and the Middle East.)

Continental Eurasia in transition: Geopolitical impacts on hydrogen potential and priorities

The current security situation notwithstanding, Russia, Ukraine, and countries in Central Asia offer significant long-term potential for hydrogen production. Proximity to both European and Asian markets could make continental Eurasia a natural swing producer. However, the geopolitical and security environment has significantly shifted priorities and opportunities in the future hydrogen market.

In 2021 Russia's export plans[34] envisioned delivering 2 million tonnes of hydrogen per year by 2035, with the goal of maintaining the country's leading role as a global energy exporter.[35] Now that Europe is no longer a viable market (for security reasons), Russia is focusing on cooperation with India and China, although neither of these countries is currently positioning itself as major demand and import centre. Ukraine for its part could still play an important role in the EU's hydrogen import plans but is unlikely to become a player in the hydrogen economy until after 2035 at the earliest.

The war in Ukraine has created an opportunity for the countries of Central Asia to position themselves as an alternative to Russia and Ukraine for the European market.[36] They are interested in increasing the resilience of their own (carbon-intensive) economies and integrating into "green value chains" of other key players, including China, the EU, the United Arab Emirates (UAE), and Russia. Now that Russia has ceased to be a primary transit country to Europe, westward exports will depend on complex logistics along the intermodal corridor connecting the Caspian Sea to the Black Sea via the Caucasus. Central Asia's hydrogen future is thus more likely to lie in the Asia-Pacific region, at least in the short and medium term.

Africa and the Middle East: Great opportunities meet great expectations

Oman, Saudi Arabia, and the UAE are probably closest to realising a hydrogen (export) economy.[37] In addition to the Arabian Peninsula's abundant resources (land, sun, wind, natural gas), these states can draw on extensive expertise in energy exports, the petrochemical industry, CO_2 management, substantial financing capabilities, and agile decision-making.

The hydrogen economy could potentially stabilise current social and governmental power structures in the long term.

These Gulf States aim to establish a hydrogen export sector that compliments rather than substitutes the oil and gas business. Moreover, they seek to onshore value chains and increase domestic value-adds — for instance, using hydrogen applications (such as green steel). The hydrogen economy could potentially stabilise current social and governmental power structures in the long term and advance the region's geopolitical ambitions. Potential buyers include Europe and countries in East Asia (especially Korea and

representation.ec.europa.eu/news/net-zero-industry-act-kommission-will-bessere-bedingungen-und-mehr-investitionen-fur-saubere-2023-03-16_de.

34 See also Yana Zabanova and Kirsten Westphal, *Russia in the global hydrogen race: Advancing German-Russian hydrogen cooperation in a strained political climate*, SWP Comment 34/2021 (Berlin: Stiftung Wissenschaft und Politik, May 2021).

35 Government of the Russian Federation, *Pravitel'stvo Rossiyskoy Federacii [Decision]*, Moscow, August 2021, http://static.government.ru/media/files/5JFns1CDAKqYKzZ0mnRADAw2NqcVsexl.pdf.

36 Yana Zabanova, "Towards a geoeconomics of energy transition in Central Asia's hydrocarbon-producing countries", in *Climate Change in Central Asia*, ed. Rahat Sabyrbekov et al. (Cham: Springer Nature Switzerland, 2023), 106.

37 See Dawud Ansari, *The hydrogen ambitions of the Gulf States*, SWP Comment 43/2022 (Berlin: Stiftung Wissenschaft und Politik, July 2022); Dawud Ansari, *Omani hydrogen for Germany and the EU*, SWP Comment 18/2023 (Berlin: Stiftung Wissenschaft und Politik, March 2023).

Japan). Recent project awards and delegation visits suggest, however, that the scales are currently tipping from Europe towards East Asia.

Regional escalations of the Israeli-Palestinian conflict could potentially affect hydrogen flows to Europe — depending on the port of origin, hydrogen freighters must pass two choke points (see also fig. 1). Such escalations could also affect hydrogen policy in the Levant. To date, Israel sees itself a hydrogen importer, and Jordan considers hydrogen exports via and to the former.

North Africa on the other hand is a hotspot. This is driven by both supply (excellent renewable resources and — in the cases of Algeria and Egypt — natural gas reserves) and demand (EU's hydrogen plans).[38] The region as a whole has an ambivalent relationship with the EU, however. On the one hand, it desires economic integration; on the other it deliberately seeks to display differentiation (e.g., with respect to regulatory requirements for hydrogen). Overall, the region envisions itself as a hydrogen exporter. It gives precedence to economic and political considerations and only marginally associates hydrogen with local climate policy. While Egypt stands out for its geography and infrastructure, financial risks stemming from its debt crisis are a barrier.[39] The states of the Maghreb benefit from an existing network of gas pipelines. Morocco, which already collaborates with the EU in different sectors, sees itself as a major exporter of renewable hydrogen to the EU.[40] However, diplomatic differences with the EU and recent incidents overshadow this promising potential partnership. Algeria for its part seems less involved in the (renewable) hydrogen transition, both for institutional reasons and due to its focus on the existing gas industry. Further complicating the Maghreb's emerging hydrogen economy is the ongoing conflict between Morocco and Algeria, which also involves Tunisia and Libya.

South of the Sahara, several countries are considering hydrogen exports mainly for economic reasons and often in response to EU hydrogen diplomacy. Examples include Namibia, Senegal, Nigeria, Kenya, and South Africa.[41] With the exception of South Africa and Nigeria, these parties are relatively inexperienced when it comes to energy. They face significant financing and infrastructure constraints, making capacity expansion uncertain and reliant on substantial direct investments. Moreover, these countries are also looking towards East Asia. For example, Namibia's hydrogen strategy notes that it intends to target export volumes to Japan, South Korea, and China in addition to the EU.[42]

The Indo-Pacific in flux: Hydrogen politics between global and middle powers

In the vast Indo-Pacific,[43] different resource endowments, actor preferences, and energy policy orientations intersect.

China's hydrogen ambitions are grounded in considerations of energy security and energy independence as well as in its sustainability aspirations and industrial policy. By 2025, the country aims to produce between 0.1 and 0.2 million tonnes of hydrogen annually from renewable energy, which will position it as both a self-sufficient producer and a hub.[44] Its strategic competition with the US fuels the race for technological and market leadership. China already leads in the production of alkaline electrolysers, as a refiner of many raw materials, and as a manufacturer of such products as solar panels and, to a lesser extent, wind turbines.

India is also pursuing a protectionist approach to industry and value chains. The country aims for self-sufficiency by 2047 and seeks to export hydrogen and technology in addition to meeting domestic demand.[45] It already envisions producing five million metric

38 Laurent Ruseckas, *Europe and the eastern Mediterranean: The potential for hydrogen partnership*, SWP Comment 50/2022 (Berlin: Stiftung Wissenschaft und Politik, August 2022).

39 Stephan Roll, *Kredite für den Präsidenten: Auslandsverschuldung und Herrschaftssicherung in Ägypten*, SWP-Studie 10/2022 (Berlin: Stiftung Wissenschaft und Politik, September 2022).

40 Moroccan Ministry of Energy, Mines, and Environment, *Feuille de Route de l'Hydrogene Vert* (January 2021), https://www.mem.gov.ma/Lists/Lst_rapports/Attachments/36/Feuille%20de%20route%20de%20hydrog%C3%A8ne%20vert.pdf.

41 European Commission, *Global gateway 2023 flagship projects: infographics* (website), 2 October 2023, https://international-partnerships.ec.europa.eu/publications/global-gateway-2023-flagship-projects-infographics_en.

42 Namibian Ministry of Mines and Energy, *Namibia: Green hydrogen and derivatives strategy*, (Windhoek, November 2022), https://www.ensafrica.com/uploads/newsarticles/0_namibia-gh2-strategy-rev2.pdf.

43 In this context, the term Indo-Pacific includes India and refers to a purely geographic rather than a political concept.

44 Gong et al., *China's emerging hydrogen economy* (see note 25).

45 Government of India, *National green hydrogen mission* (website), https://www.india.gov.in/spotlight/national-green-hydrogen-mission.

tonnes of hydrogen annually by 2030, primarily from electrolysis.[46] Among the factors complicating India's ability to meet this target, however, are high capital requirements; competing national priorities; India's deep trade relations with both the West and China; and its reliance on Russian arms exports.

For their part, Japan and South Korea are focusing their hydrogen efforts to decarbonise their economies, build competitive domestic industries, and establish energy security and strategic autonomy.[47] Both see territorial disputes with China as posing a fundamental risk to energy supply, further driving diversification efforts. With limited natural resources (including land), both countries prioritise imports. They plan to import green hydrogen from Oman and blue hydrogen from sources like the UAE and Australia.

Australia meanwhile aims to establish itself as a renewable energy superpower by leveraging its experience in energy exports, current domestic hydrogen production, and access to capital.[48] Although trade with the EU would seem to be a logical outcome of strategic partnership, Europe will have to compete for Australian hydrogen exports with (geographically closer) Japan and South Korea.

Australia, Japan, and South Korea meanwhile all have extensive economic ties with China, driven not only by the three countries' shared interests in regional peace and stability but also by the desire to counteract China's regional influence. Increasing military-industrial cooperation between these three countries and the US is another factor in the security and geopolitical landscape.

In Southeast Asia — which includes traditional regional exporters of natural gas like Brunei, Indonesia, and Malaysia, as well as long-standing importers like Singapore and Thailand — the implementation of hydrogen ambitions remains limited, with the exception of Singapore.[49] While some countries have substantial raw material resources (such as nickel in Indonesia or natural gas in the countries just mentioned), they lack technology, capital, and renewable energy infrastructure. China is of paramount importance to the region, not least because it is making development-oriented investments. However, countries in the region actively suffer from the ongoing systemic conflict, making peace and stability top priorities.

All in and all out: The United States as a strong prosumer alongside emerging exporters in Latin America

In the Americas, the US plays a special role as a potentially influential "prosumer" (both a producer and consumer) in the future hydrogen world.

The US takes a largely agnostic approach to hydrogen technology. Protectionist legislation such as the Inflation Reduction Act (IRA) of 2022 targets the production of both blue hydrogen and green hydrogen (through electrolysis powered by both renewable and nuclear energy).[50] The US hydrogen strategy, released this year, envisions domestic production of 10 million tonnes of clean hydrogen annually by 2030, increasing to 50 million tonnes annually by 2050.[51] This could not only meet almost the entire long-term domestic demand but also leave room for the US to export to allies.

The US push for clean hydrogen is driven not only by concerns about climate change but also by its systemic rivalry with China.

The US push for clean hydrogen is driven not only by concerns about climate change but also by its systemic rivalry with China. Other motives include the growing industrial-technological competition with

46 Ibid.

47 Japanese Ministerial Council on Renewable Energy, Hydrogen, and Related Issues, *Basic hydrogen strategy* (website), (June 2023), https://www.meti.go.jp/shingikai/enecho/shoene_shinene/suiso_seisaku/pdf/20230606_5.pdf; Ministry of Trade, Industry and Energy, "Segye Choegosujunui Susogyeongje Seondogukgaro Doyak" *[Taking a leading role in the hydrogen economy], press release,* 17 January 2019, http://www.motie.go.kr/motie/ne/presse/press2/bbs/bbsView.do?bbs_cd_n=81&cate_n=1&bbs_seq_n=161262.

48 Australian Department of Climate Change, Energy, the Environment, and Water, *Growing Australia's hydrogen industry* (website), 26 September 2023, https://www.dcceew.gov.au/energy/hydrogen.

49 Singapore Ministry of Trade and Industry, *Singapore's national hydrogen strategy* (website), https://www.mti.gov.sg/Industries/Hydrogen.

50 US Congress, *H.R.5376 – Inflation Reduction Act of 2022* (website), 16 August 2022, https://www.congress.gov/bill/117th-congress/house-bill/5376/text.

51 US Department of Energy, *U.S. national clean hydrogen strategy and roadmap* (June 2023), https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/us-national-clean-hydrogen-strategy-roadmap.pdf.

both China and Europe (seen as a threat to US technological and economic leadership) and the pursuit of resilience and supply independence in critical raw materials and industrial components.

In Latin America, hydrogen is slowly entering the energy policy spotlight. Potential and interest are not evenly distributed, however. The countries aim for energy independence and decarbonisation through hydrogen development, while also seeking opportunities to export regionally and overseas. Chile and Brazil are prominent examples. Chile in particular stands out thanks to its favourable geographical and climate conditions. Brazil has particularly relevant experience in commodity trading, fossil fuel exports, and a petrochemical industry that already uses conventional hydrogen.

Chile's production potential is estimated at 160 million tonnes of green hydrogen per year by 2050.[52] It already plans to export green hydrogen and derivatives to Japan, South Korea, and Germany. Despite its highly advantageous access to both the Pacific and Atlantic Oceans, however, Chile lacks regulatory frameworks, infrastructure, and electrolyser technologies, which is hindering the initiation of exports. Chile's export preferences and future trade configurations could well be influenced by its growing dependence on exporting resources to China and accepting Chinese investments in resource extraction and infrastructure. In Brazil, climate ambitions may take a back seat to competing priorities like alleviating poverty. Though the country stresses its willingness to increase cooperation with the EU on energy and climate issues, its position and role within BRICS, as well as its changing geopolitical preferences, might eventually influence the country's choice of partners.

52 Chilean Ministry of Energy, *National green hydrogen strategy* (2023), https://energia.gob.cl/sites/default/files/national_green_hydrogen_strategy_-_chile.pdf.

Three scenarios for the geopolitics of hydrogen

With diverse technologies, intertwined global value chains, and incompatible preferences embedded in geopolitics and path dependence, the emerging hydrogen economy is anything but simple. Here we present three global scenarios for how it will develop up to the year 2040: **Hydrogen Realignment**, **Hydrogen (In)Dependence**, and **Hydrogen Imperialism** (fig. 4). Recounted in the dramatic present tense, they sketch possible developments, risks, and options.

The scenarios were developed during a multi-stage process with the input of an interdisciplinary group of international experts.[53] Five motifs guided the scenario development process: raw materials, technological leadership, autonomy, system conflict (especially the US-China rivalry), and global order. The scenarios offer a European but not a Eurocentric perspective by emphasising global dynamics and the diverging preferences of various global actors.[54] All three rest on the (significant) assumptions that 1) European and global climate policies will remain high-priority, 2) governments will remain the dominant actors in the hydrogen sector, and 3) global access to capital will remain in effect.

Hydrogen Realignment pictures a world in which the EU's hydrogen ambitions dissipate, while the hydrogen economy, energy-intensive industries, and the world order shifts towards the East. **Hydrogen (In)Dependence** envisions a future in which Europe commits to the global hydrogen transition in order to promote its strategic autonomy; its latent dependence on supply chains for raw materials, however, ultimately diminishes its ability to respond to global power shifts. **Hydrogen Imperialism** presents a dystopian future: a global hydrogen economy in which hegemonic powers divvy up the value chain (and export countries) among themselves, while development projects become a pretext for propping up "hydrogen dictators" and authoritarian client states.

Those three futures explore the breadth of the "cone of uncertainty" (see again fig. 2). They are deliberately not *probable* but *plausible*; and by exploring three contrasting narratives, the scenarios allow us to navigate the broad spectrum of possible futures. Together, they encircle a "reference scenario" (rudimentarily sketched in Table 2 of the Appendix) that is the "most likely" future.

Hydrogen Realignment

Europe on ice

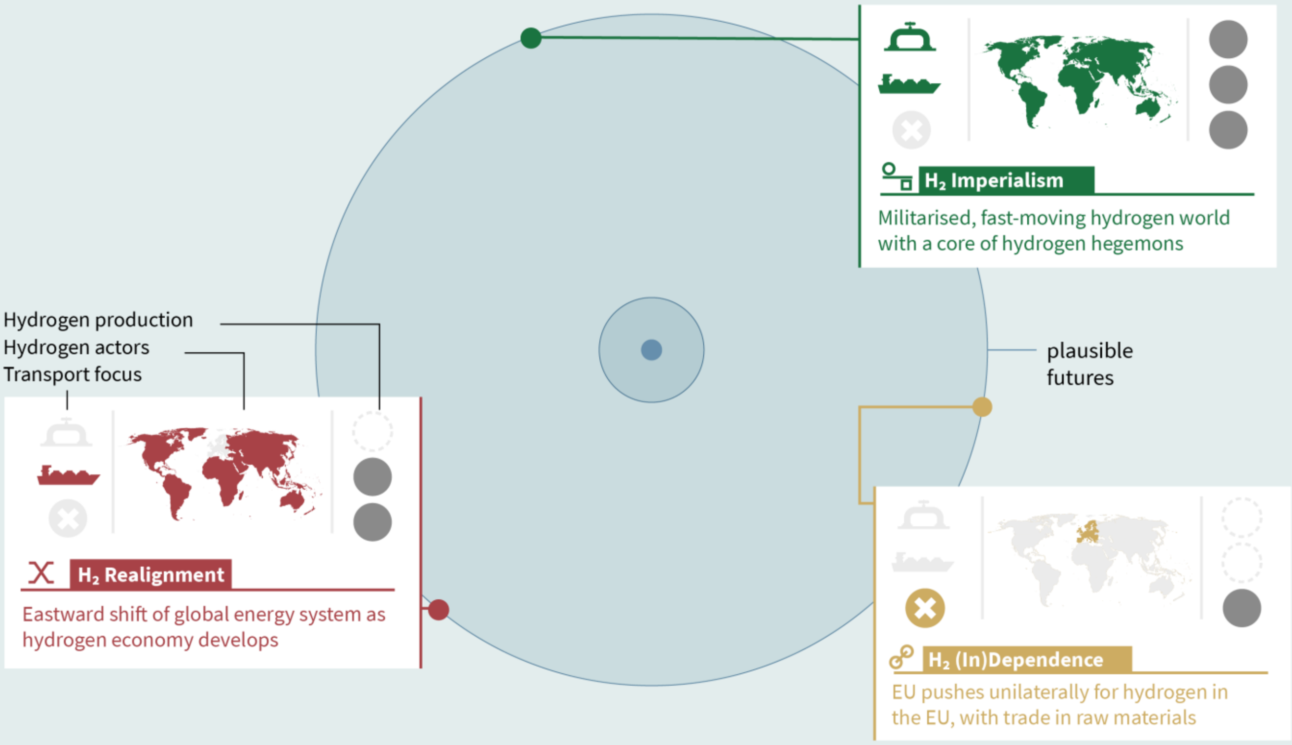
In early 2024, meteorologists confirm that Europe's current winter will be long and tough. After a period of deceptive calm, electricity and gas prices start to roar; this haunts the economy and feeds the far-right, which vies for political power with a still-strong environmentalist camp. Elections on all levels result in disarray. Political polarisation across the EU and within its member states produces enduring policy deadlock. (Rudimentary policies to shield low-income households are put in place, but political paralysis hinders thorough reform, infrastructure investment, and support for European industry — not least because the EU is still consumed by Russia's ongoing war in the Ukraine.) Hydrogen remains a large part of the energy debate, but hardly any binding agreements or investment decisions follow. This is because deadlock has spread to institutions, which discourages the private sector from making commitments. EU states continue to grant a narrow majority to those favour-

53 The appendix describes the process, its methodology, participants, and scenario indicators.

54 The method nonetheless results in some analytical imbalances. Although the scenarios provide a consistent and plausible picture for the globe at large, the global focus required a certain abstraction from national and even regional processes. For example, the scenarios largely leave out the inter-European dimension and instead views the EU as a bloc.

Figure 4

Scenario overview



Source: Scenarios "The Geopolitics of Hydrogen"

ing ambitious climate action — in early 2025 the European Commission's president gives a powerful speech declaring Europe "the green continent" — but there is complete disagreement on how (or even whether) to manage those multiple crises. This stymies support for new technology and industry of all kinds.

This intensifies Europe's (hitherto weak) deindustrialisation, bringing fundamental changes to Europe's economy. In 2026, for example, BASF opts to close its biggest plant, in Ludwigshafen, Germany, and drastically scales back operations at its "Verbund site" in Antwerp, Belgium. The EU meanwhile finds itself needing to import more and more energy-intensive products from regions with lower energy prices, and significant sectors of European industry relocate to these places. They include various locations in Asia (where multinationals expand already existing clusters) and the Gulf States (where abundant natural gas and hydrogen meet abundant financial resources for developing prospective new industries). In 2028 — after a two-year delay — the EU finally implements its Carbon Border Adjustment Mechanism (CBAM) in an attempt to stem deindustrialisation. This yields little more than spiking import prices, however, since affordable clean energy allows the (new) industrial hotspots to decarbonise some of their exports to Europe.

Elsewhere, the US has managed (after the 2024 presidential election) to overcome its political stalemate of the early 2020s with a broad compromise that simultaneously supports domestic industry and combats climate change. This new US deal sustains trends initially launched with the IRA and consolidated during ongoing trade rows with China (manifest in an increasingly toothless WTO). Washington's aggressive new green mercantilism prioritises technological autarky over openness because it sees low-carbon technologies as a prime way of decoupling from China and competing with it. In 2027, the US president proudly announces offshore wind power ("freedom power") as a core component of its clean and self-reliant future. The US adopts significant financial support schemes and removes most red tape for wind projects in a nationwide movement ("A Strong and Clean America") that strategically expands to hydrogen. With time, polymer electrolyte membrane (PEM) electrolysers become a top US industry.

Building on its hydrogen ambitions of the early 2020s, China decides in 2024 to ramp up its hydrogen ambitions.

While most US-made PEM electrolysers target the domestic market and selected outlets (such as Canada, Chile, Australia, and Brazil), Chinese alkaline electrolysers dominate the rest of the globe. Building on its hydrogen ambitions of the early 2020s, China decides in 2024 to ramp up its hydrogen ambitions. The holistic technology ecosystem it strives for rests on three pillars: 1) control over its own energy sector; 2) a prosperous emerging export industry with geopolitical leverage; 3) and the ability to quickly dominate the global climate agenda. China throws its weight behind hydrogen-affiliated technologies, especially alkaline electrolysers, which appear to be more efficient for large-scale applications and easier to scale up than PEMs. For its part, the US government is relying on targeted innovation funding, the presence on its soil of former European PEM champions (manufacturers who relocated to the US when it became clear that the EU's own hydrogen transformation had stalled), and a freshly brokered exclusive US-South African partnership for necessary raw material supply chains. By 2028, however, Chinese manufacturers have managed to drive prices below 100 US dollars per kW in 2028. China's growing hydrogen market push gains even more momentum with the influx of ex-EU energy-intensive industries into China. This motivates the Communist Party to formally adopt the dual policy of net-zero industrial leadership in 2029. And it builds significantly on China's domestic use of hydrogen — also in reaction to the EU's CBAM tariff system.

The age of the dragon

As the US and Europe become more introverted, global power shifts towards the Indo-Pacific accelerate a transition that began in the early 21st century. A Gulf-China axis now becomes the region's most significant trade and power corridor. Not only do the Gulf States share with China a pragmatic approach to politics, but both actors are zealous about expanding their (geo-)economic reach. In addition to (informal) multilateral agreements that govern how these nations distribute their ever-growing presence in East Africa and the Middle East, in 2028 China and the Gulf States form an accord on the preferential supply of Chinese electrolysers in exchange for hydrogen, minerals, and petrochemicals. The Gulf has become an emerging hub for services, raw materials, and heavy industry — alongside its continued (albeit slightly lower) hydrocarbon exports to the Indo-Pacific region. Notably, in 2031, Saudi Arabia inaugurates the world's largest "green steel" facility in Neom, which is powered by green hydrogen initially earmarked for EU export. Similarly, a broad industry-research consortium of Omani and UAE actors announces that their two countries have successfully developed the ports of Jabal Ali and Duqm into the world's most influential hubs for clean marine fuel.

Meanwhile in East Asia, in 2030, Japan and Korea introduce a structure similar resembling the EU's CBAM to push decarbonisation. While they manage to maintain most of their domestic industries, they begin to draw hydrogen supplies (or LNG to be converted to hydrogen) from the Gulf, Australia, and closer neighbours such as Thailand and Chile.

China's trade corridor with Africa has gained importance, with China trading infrastructural support (including energy) for raw materials from the continent. These are needed for a range of elements like batteries in China's low-carbon tech sector. In 2031, the African Union and China finally inaugurate the China-Africa Cooperation Organisation. Within two years, the hundredth country signs on to China's Dragon Accord. Signatories benefit from cheap electrolysers financed with affordable Chinese loans, while (partially) subscribing to China's regulatory framework for hydrogen; poorer parties to the accord in particular expect Chinese infrastructure investment and deepening trade relations in return. Such investments enable Kenya and Tanzania for instance to leapfrog straight to hydrogen for their industrialisation and then benefit from selling both hydrogen to China and green industrial products to the EU. Meanwhile, Southeast Asian nations, by producing hydrogen domestically, gain the ability to substitute some of their oil and gas deliveries from the Gulf; the latter has developed into the second-largest supplier to the EU of goods, including not only raw materials but also steel and even cars.

Russia for its part, whose relationship with China is built on cautious pragmatism, has also become a supplier of critical mineral resources like nickel for China's new industries. Its broader economic ties with China have not however compensated for its continued isolation from the West. Moscow's attempts to create an integrated energy market and foster a Eurasian Hydrogen Union fails to attract Central Asia. Vladimir Putin's exit from office in 2032 (for health reasons) furthermore increases political instability and economic stagnation, which extends to the region. But this ultimately only deepens Russia's ties to the Gulf States and China. Both players have invested significantly in Central Asia to acquire an aspiring new target market (and tourism destination), gain critical raw materials, and expand their reach into a region they believe to be more relevant as new power dynamics unfold. Two years later, Russia, Kazakhstan, and Uzbekistan sign on to China's "Low-Carbon Hydrogen Standards" and begin to provide additional supply bases for critical mineral resources and energy production.

Ultimately, in 2034, China concludes the "Hydrogen and Raw Minerals Alliance" with Indonesia, the Philippines, and Australia as part of enhanced regional trade agreements. Within this new, transregional global order, China's influence in Europe and the US has diminished considerably. Both are less dependent on Chinese goods than they were in 2023 — except that the EU still relies on Chinese solar panels as well as some other energy-intensive imports. In 2036, the Chinese mining and chemical giant Sinopec buys BASF and Norilsk Nickel. A year later Sinopec rebrands as SinoHy after producing 500 GW of electrolysers for international markets.

Throughout this time, India has pursued a more agnostic approach to climate issues, balancing carbon-intensive growth with clean tech. Some first hydrogen applications exist, but India is more of a cautious "fast follower" — hence not (yet) a major player in this geoeconomic landscape. It is not willing to enter into deeper agreements with China (or the US) but instead keeps a certain distance from all but the GCC countries. By 2035, India and its immediate neighbours have long since outpaced China as the primary importer of oil and gas from the Gulf. (India's relations with the GCC, though imbalanced, have deepened substantially after major Gulf investments in India combined with a codification of the "right-to-stay" for Indian expats in the UAE, Qatar, and Saudi Arabia.) An Indian-Russian oil and gas pipeline is still on the table, but GCC influence in the region has kept it at bay. The use of pipelines for the transport of hydrogen is rare, with shipping — mostly methanol and ammonia — dominating the sector.

In 2040, hydrogen accounts for more than 25 per cent of China's energy mix; other East Asian nations also have large shares of hydrogen in their systems. In addition to Chinese aviation and shipping, where hydrogen is becoming the standard, Chinese research is giving new momentum to hydrogen-powered vehicles, especially trucks. (Passenger cars and other small vehicles are by now mainly electric.) China's leadership in clean technology — indeed, China sets the technological standards everywhere but Europe and the US — allows it to expand its reach far beyond its borders, making it the de facto arbiter of all disagreements in the eastern hemisphere.

The GCC has an implicit power sharing agreement with China and exercises hegemony from Pakistan to Libya.

The GCC — now a source of energy exports, manufacturing, and the world's highest paying services industry — has an implicit power sharing agreement with China and exercises hegemony from Pakistan to Libya. Türkiye and parts of Europe are increasingly coming under its sway as well. The latter continues to host a carbon-free services industry, but its overall economic power has contracted by nearly 20 per cent since 2024 (especially after the financial industry followed Europe's manufacturing sector in moving abroad). Even major research institutions have relocated eastwards, with universities from China, India, and the Gulf together accounting for 14 of the world's 20 top-ranked schools in the QS World University Rankings. Only Europe's tourism sector continues to thrive and has grown over the past decade, driven by demand within the expanding middle class in China and the Middle East.

There is a silver lining to the EU's economic and geopolitical weakening, however: in December 2040, as the continent's first facilities for direct air capture of carbon dioxide go online, the president of the European Commission announces that the EU has managed to reach its net-zero goal, 10 years ahead of target.

Hydrogen (In)Dependence

Fortress Europe

In 2024, a wave of droughts and storms sweeps Europe, inflicting more than 20 billion euros in economic damages and causing substantial loss of life.

One such event is the flooding of villages along the river Danube in northern Austria, a catastrophe, in which nearly 3,500 people die, and the industrial port of Linz is destroyed. From this point on, no political party can afford to downplay climate change. But the war in Ukraine is still raging, and Russian troops are en route to Kiev; refugees to the EU receive a cooler welcome than in previous years. Across Europe, security, autonomy, and nationalist sentiment are cemented as major themes.

The resulting landscape pushes green nationalism and political bargains that demand both a "strong Europe" and decisive climate action.

These supposedly conflicting trends fuel support for both green and right-wing parties in 2024's EU parliamentary and member state elections. The resulting landscape pushes green nationalism and political bargains that demand both a "strong Europe" and decisive climate action. Analysts point out what this will mean in the years to come: curbing migration; strategizing trade; and relying on homegrown renewable energy, with hydrogen the king. The clean gas emerges as the smallest common denominator — as something on which both greens and nationalists can agree, provided it is sourced within Europe.

Across the Atlantic, the 2024 US presidential elections bring a Republican hard-liner to power, yet another voice calling for "America First". The president works to decouple the US from China and pushes mercantilist policies. The global (economic) order starts to erode at a faster pace, and trust in global governance and cooperation wanes broadly and quickly. In a push for "friendshoring" — i.e., focussing trade on (presumed) allies — the US begins to negotiate a free trade agreement with the EU, but this is stymied by bickering over the US approach to climate issues, its industrial investments, and the EU's focus on (energy) sovereignty (even at the expense of US LNG and hydrogen).

By 2025, it is apparent that "Fortress Europe" has become operational. In addition to new agreements with Morocco, Tunisia, Libya, and Türkiye to secure Europe's borders through policing and refugee internment camps, the EU agenda seeks to disassociate itself from any "undesired" (i.e., non-Western or democratic) trade partners. It also pushes energy from hydrogen and renewables. The EU streamlines the permitting process for renewable energy and passes strategic regulations on hydrogen, including the launch of the European Hydrogen Union. It aims to facilitate domestic hydrogen production and make European industry "H_2-ready." The EU does not officially outlaw hydrogen imports, but its Hydrogen Union features CBAM along with draconic non-tariff barriers, which effectively make hydrogen exports to the EU (deemed hostile to energy self-sufficiency) uncompetitive. The European Commission commits to its electrolyser industry with broad support policies, including an innovation fund and direct subsidies. Action focusses almost entirely on PEM electrolysers (with some research grants for less mature technologies as well), since the Commission considers the battle for alkaline electrolysers lost. The necessary raw materials are sourced from democratic South Africa. By now, the US and Canada have both banned exports of their own supplies of platinum group metals; this makes South Africa the EU's only significant choice, but the EU deems it a "safe" trading partner. In 2026, the European Commission proudly announces the Democracy Trade Channel, a formalised agreement giving it preferential access to (and guaranteed purchase of) platinum group metals and other critical raw materials from South Africa. EU decision-makers hope to extend the agreement to other (democratic) countries later, creating a secure trade union among allies.

Elsewhere, the momentum for hydrogen seems to have largely dissipated. The year 2026 finds Korea and Japan still running a few pilot projects they had commissioned earlier in the Gulf States, but there are virtually no new initiatives. Decision-makers in the Asia-Pacific region and elsewhere consider hydrogen to be impractical: expensive to produce and complicated to transport or handle. (Fresh research on the direct use of ammonia as an energy carrier yields dismal results.) China's electrolyser industry continues to grow, albeit at a slower pace and without industrial policy support for any significant scaling up. Instead, investment in clean technologies diversifies. In 2027, Japan, Korea, China, Singapore, and the GCC states found the "Global Carbon Alliance" to bundle and fast-track research and development in CC(U)S technology, which numerous countries increasingly consider "the way forward". In this context, hydrogen is eventually used, but in the form of LNG that is converted locally, for instance in Singapore and Japan. In the US, too, natural gas is the main answer to climate concerns; a renewed commitment to the domestic oil and gas industry bridges the national political divide, along with a moratorium on phasing out coal.

False friends

In spite (or because) of these developments, the EU reinforces its lonely commitment to hydrogen. By 2028, the first large-scale electrolysers in Spain are operational and supply local industry clusters; 25,000 km of the "Hydrogen Backbone" are completed. That same year the European Hydrogen Bank is finally established and receives the first tranche of 3 billion euros to finance "Cost of Difference Schemes" to establish lead markets around steel and petrochemicals. The EU announces a plan to implement in steps a renewable hydrogen use quota in steel and chemical industries and to reach 80 per cent by 2038. Investments (mostly private) into hydrogen transport infrastructure increase, and hydrogen clusters also develop in northwest Europe.

The fast-tracked transition is entirely domestic. It targets self-reliance but hungers for foreign solar panels (the EU had briefly invested in reviving its domestic PV industry, but the project was ultimately deemed too expensive, and tensions with China were considered sufficiently "balanced") and critical raw materials. It particularly needs electrolysers, the manufacturing of which becomes the lynchpin of the EU's industrial policy.

Meanwhile in South Africa, the country's political system has been fairly stable since the mid 2020s. Smaller regional parties have settled within the country's political landscape, and the "experiment" of coalition governments did an unexpectedly good job enriching, stabilising, and reviving the country's democracy. Even while it maintains positive relations with Europe, however, South Africa's government is increasingly seeing its role within BRICS, which is becoming increasingly institutionalised; that said, it still retains flexible forms of collaboration. While the idea of a common BRICS currency never materialised, in 2027 the bloc founded its own payment infrastructure (as an alternative to the US-backed SWIFT) in cooperation with the Eurasian Economic Union. The BRICS summit has evolved into a semi-institutionalised cooperation body that is widely considered a crucial power beyond the West and a de-facto element of global governance in a fragmented order.

By 2032, clashes in Ukraine have for years been levelling off, although major parts of the country are occupied by Russia. The EU sticks to its stance of "interference without confrontation" by integrating Ukraine economically and militarily. (Along with Türkiye and the UK, Ukraine is now part of the European Hydrogen Alliance and supplies hydrogen from its nuclear power plants to the European grid.) The cornerstone of the EU's activity is a vast air defence shield set to be installed in 2034 in non-occupied areas of Ukraine. In reaction, Russia proposes a BRICS "Customs and Security Union" (CSU) that builds on existing economic ties and military relations between some of the countries. In China in particular, the idea finds resonance for its political value.

South Africa is only peripherally interested in trade with Russia, but existing security ties between the two countries are long-standing and valued by the ANC. The proposal also fits with quiet but growing anti-EU sentiment within South African society; the EU's Democracy Trade Channel's strict regulations (especially its high social and environmental standards) have increased the cost of mining, leading companies to replace workers with machines; this in turn fuels the narrative of "white European neocolonialism". Meanwhile, demand for South African platinum group metals continues to grow both inside and outside BRICS, which clashes with South Africa's previous policy of giving preferential access to the EU. As a result, the ANC-led government — and indeed society as a whole — begins to distance itself from Europe in order to exercise more power (and enjoy renewed loyalty) within BRICS. In 2034, China, Russia, Brazil, and South Africa sign the framework agreement. (India, demonstrating autonomy from China, chooses not to join and instead deepens its partnership with the US.) In this new geopolitical configuration, plans for South African mining projects designed for EU export are put on hold. The government makes further extraction rights indirectly but unequivocally conditional on the EU dropping its aforementioned plans for an air defence system over parts of Ukraine.

These developments roil an EU energy and trade doctrine that had previously sought to evade exactly such situations.

These developments roil an EU energy and trade doctrine that had previously sought to evade exactly such situations. A cut-off from critical South African materials would certainly cripple EU green industry, most notably electrolyser manufacturing. While the

EU is undoubtedly committed to protecting Ukraine, worries about halting the energy transition — or sliding into energy shortages — gain the upper hand. The EU drops its plans for the missile shield. Once again European authorities scramble to diversify, but the stakes have been raised. Major parts of European industry have already switched over (or are in the process of switching) to hydrogen, and no other producers can come to the EU's aid. Efforts such as repurposing gas pipelines from North Africa or building domestic CCS facilities for producing hydrogen from natural gas are launched, but it will be years before they are finished.

Building on these experiences, in 2037, China seizes the opportunity and seeks to annex Taiwan by military force. The EU faces a dilemma: accept China's actions or risk economic and military escalation with the entire CSU (that most BRICS members had signed a few years before). In only a few short years, this union has become a counterweight to NATO. The US, whose administration had already significantly reduced trade with China in the 2020s, condemns the aggression against Taiwan, breaks off diplomatic relations with China, and urges Europe to join it in taking decisive action. However, the EU ultimately chooses to be only "deeply concerned" about the situation. Not only is the military risk too great; the EU's dependence on solar panels and raw materials from the CSU countries is too deep. Other regional powers, such as the Gulf States, Chile, and rapidly industrialising Kenya officially stay neutral, but their sympathies have long been closer with the BRICS than with the EU.

In 2040, a newly built CCS facility in Norway and a repurposed Maghreb—Europe pipeline feed hydrogen from natural gas into the by-now completed Hydrogen Backbone. Europe breathes a sigh of relief, but it also faces a permanently altered landscape. Its desire to use hydrogen to decrease other forms of energy dependence put the continent at the mercy of outside suppliers of material and equipment; this merely shifted dependence and geopolitical complexities. At the same time, Europe has cut its emissions significantly without losing many of its industries. As its long-time approach of overregulating technologies, standards, and trade routes collapses — and as the first supply of "blue" hydrogen arrives from North Africa — new geopolitical challenges as well as new opportunities emerge.

Hydrogen Imperialism

Harder, better, faster, stronger

2024's COP29 concludes with powerful momentum: the EU, the US, Japan, South Korea, and China agree to mandate that most energy-intensive industries achieve (almost) net-zero emissions by 2033. All signatories see hydrogen as key to this transformation. Four parallel developments lead up to this milestone. First, weather extremes — a staccato of wildfires, droughts, floods, cold snaps, and heat-waves — had again pummelled the globe, making climate change a dominant theme in nearly all the major economies. Second, the G7 reaffirmed at its summit in Italy the commitment to decrease dependence on China; at the same time it commits to rebuilding constructive relations with Beijing to prevent a new Cold War. By now the countries of the G7 view hydrogen with a certain ambivalence: on one hand it supports global collaboration (because it requires it); on the other it could be the key to one country or region's sustained industrial dominance. Third, political efforts notwithstanding, the global geopolitical divide has deepened further. (The lack of reaction to Russia's ongoing invasion of Ukraine has shown Europe how much its position, diplomatic ties, and leverage have eroded over the years.) The fourth development is that peaking energy prices and the aftermath of Covid-19 have led to a mild yet noticeable global recession; meaning that economic slowdown requires fiscal stimuli, while budgets still allow for this.

Therefore, signatory countries to COP29's hydrogen milestone want three things from the hydrogen transition: that it happen as fast as possible; that it build bridges while allowing each country to demonstrate autonomy; and that it boost their respective economies (meaning that the price tag hardly matters). Looking at previous green stimulus packages like the IRA in the US and the European Green Deal, governments now begin putting forward comprehensive support packages to advance their own hydrogen economies. They grant vast financial support to mandated key industries — to incentivise offtake and make them "H_2-ready" by 2033. And they set up massive financing mechanisms to push research and development in hydrogen and scale up its production and transport.

Following the geopolitical doctrine of balancing collaboration with autonomy, countries set out on diverse innovation pathways.

Following the geopolitical doctrine of balancing collaboration with autonomy, countries set out on diverse innovation pathways. Hydrogen players begin to specialise in individual niches along the value chain that will make them indispensable; this leads to quick advances in development and production as well as significant cost reductions in each individual technology. Japan and Korea expand their focus on freighters for hydrogen derivatives and start supplying shipping companies in 2027. In addition to manufacturing pipelines and PEM electrolysers, the EU focusses on hydrogen-powered trains and airplanes and successfully demonstrates the first hydrogen-powered transatlantic flight in 2029. Boeing in the US has similar ambitions; the US also makes advances in end-use products and methane pyrolysis. China for its part engages primarily with alkaline electrolysers with solar and fuel cell technology and develops novel applications in the private sector as well as in heavy transport. The GCC countries continue their advances in CC(U)S technology, but their stake in hydrogen is fading, apart from straight export. (Because they did sign the milestone COP29 agreement, signatory governments now tend to keep them out of the loop.) The globalised hydrogen value chain that results from this overall process has no single hydrogen technology leader; rather it is characterised by "distributed leadership". By 2030, with no one country able to dominate hydrogen geoeconomically, the global order is stable for the moment.

This is not to say that the geopolitical climate is not tense, however. Quarrels surrounding patents and alleged abuses of market power erupt frequently. Imports are an even more obvious locus of rivalry. By now, all signatory countries to the COP29 milestone have realised that their plans require a substantial share of imported hydrogen, and most governments actually care very little about what "colour" that hydrogen has. Throughout the 2020s, importers expand into key regions: Japan and South Korea deepen their ties with the GCC (which continues to provide fossil fuels to the hungry markets of India and developing Asia); the US, taking its first imports from Latin America, prepares for a future spike in demand for hydrogen that it is not willing to supply on its own; China piggybacks on its existing relations with East Africa and Central Asia to set up its own hydrogen imports; and the EU invests heavily in North Africa. But tensions are already growing by 2030. For instance, when Japan and Korea approach Kenya and Chile respectively in order to diversify import sources, trade rows flare up with both the US and China.

Meanwhile China has substantially ramped up investments and loans that push its infrastructure-industrial complex further into central Africa. This is not just to acquire hydrogen and critical minerals but also to expand its geopolitical power. EU decision-makers have also made Africa the focus of their hydrogen import strategy and broadly expand energy and climate partnerships across the continent. For one thing, Europe wants to circumvent the (already) tight market for hydrogen freighters with a focus on pipeline-based trade instead. For another, it sees its hydrogen channel with Africa as a ground-breaking tool for promoting sustainable development. For instance, the EU guarantees excellent offtake conditions and infrastructural support to Mauretania and Senegal in exchange for forfeiting further development of their oil and gas industries. While China and the EU are not (yet) directly confronting each other in Africa, both actors know that their competition for the continent's most lucrative locations and government contracts is about to intensify. For their part, most African governments welcome the new investments and export opportunities; they provide stable inflows of foreign currency and help develop infrastructure and the labour force.

(Hydro-)Apocalypse Now

In 2030, tensions escalate around local communities displaced by hydrogen projects in Morocco. This exacerbates existing social conflicts there, leading to an uprising. The country has long been considered an agile hydrogen front-runner at the centre of the EU's hydrogen ambitions due to its efficiency and promising baseline conditions. It has attracted electrolysers, mega-scale solar farms, and pipelines to the south. Much of this was carried out on utilised land so that existing settlements, local tribes, or traditional lifestyles were displaced. After scattered protests in previous years, a new wave of land concessions to European companies in 2030 causes tensions to escalate. Insurgents enter and occupy construction sites and workers' compounds, kidnap European staff, and threaten to kill hostages and sabotage pipelines.

The events instantaneously upend the European news cycle — at a time when the EU's deep engagement in "African hydrogen" is already under public scrutiny. (Mostly for the vast costs involved; EU member states have already ploughed more than 40 billion euros into Morocco alone.) EU governments fear that cutting off the African hydrogen supply could deal a death blow to the hydrogen transition. They also fear financial repercussions and, most importantly, a drop in public approval. To prevent further disruptions and free European hostages — in a show of strength to its constituents — the EU formally asks Morocco for the right to swiftly intervene and support the measures Morocco is taking to contain the insurgency. The offer is welcomed, as Morocco is eager to preserve economic relations with the EU. EU member states thus dispatch "military training missions" to the area; France and Spain provide weapons such as drones and light armoured vehicles.

NGOs worldwide condemn the militarisation of hydrogen and what they call the "authoritarian hydrogen bargain".

The insurgency ends rapidly, but the flare-up sets the stage for the next decade. Despite the quick reaction, opposition leaders and members of civil society across Europe call EU energy policy into question. (The discourse mirrors 2022's outcry about European dependence on Russian gas and, like it, demands drastic measures to increase the security of energy supply.) Since vast investments have already been made, Europe's leaders see no alternative to doubling down on the existing import structure; they must secure it at all costs. In an erratic move, the EU pressures the governments of exporting countries with civil leadership to allow a permanent presence of EU forces on their soil — to secure hydrogen infrastructure. In exporting countries run by military dictators (and such where the military is similarly dominant), the EU agrees to adopt a new "development policy" instrument, which is essentially a lump-sum transfer to despots. The condition: that the country in question give unlimited protection to hydrogen production and transport infrastructure — no questions asked. NGOs worldwide condemn the militarisation of hydrogen and what they call the "authoritarian hydrogen bargain": supporting repression and dictatorship abroad in exchange for a secure hydrogen supply. But EU politicians see no way out.

The discourse on hydrogen supply security echoes beyond Europe and adds to tensions among the large importers. The events in northwest Africa have provided a stark reminder that countries depend on their importers and a warning — given the diversity of the hydrogen value chain — that problems may ultimately affect everyone. At the same time, actors know that continuing their quarrels and expanding without regulation will ultimately lead to increased conflict far beyond the hydrogen sector. Talks about formalising the collaboration and the geographical distribution of technologies and imports start in 2031. They culminate in 2034, when the original signatories to the COP29 milestone celebrate the agreement's tenth anniversary by founding the "Organisation of Hydrogen Importing Countries" (OHIC). The organisation is officially a discussion forum but in fact serves to smooth tensions and lower import prices. Its provisions suggest an oligopsony mechanism (much like the oil market under the reign of the "Seven Sisters" in the 20th century) that sets and fixes import tariff "recommendations" (and conditions such as concession fees) for all members. Moreover, the organisation agrees to divvy up exporting countries, to set regulations for access to critical mineral resources needed for hydrogen and renewables, and to share technology (or offer goods competitively) along the value chain.

Of course, the OHIC members see the new framework as an opportunity to cement their place in the world order beyond hydrogen. The US, China, and the EU form hegemonic relations with their respective hydrogen suppliers that resemble the EU's earlier experiences in Africa: client states trade hydrogen in exchange for money and regime survival. The importers have a major interest in stability along the hydrogen supply chain and are willing to assist export governments both militarily and economically — as long as they keep hydrogen flowing at the fixed prices. In many exporting countries, this bargain strengthens autocrats and armies, who are the primary recipients of hydrogen revenue and use "export security" as an excuse to crack down on the opposition. As importing countries divide the hydrogen production map among themselves, producers depend on particular markets, which allows the importers to dictate the price of hydrogen.

Even though Russia retreated from Ukraine (which has by now entered the European Economic Area) well before 2030, it never managed to rebuild its energy trade with the West. It sought instead to increase exports of fossil fuels (particularly oil) to India and developing Asia but had to compete with the Gulf for market share. Indeed, since the global demand for oil has dropped (and, with it, prices — to below US$40 per barrel), the Russian oil industry is barely viable. In 2034, the president of Kazakhstan announces that the region's future lies to the south and east — meaning that the nation (like its neighbours) wants little to do with Russia. It favours economic (and hydrogen) integration with South Asia and East Asia. Japan seizes the moment and strongarms Russia, left with little choice, into building hydrogen production and export facilities in Siberia for supplying Japan — a move that the other OHIC members welcome, since it broadens the geographic divergence among members.

In 2037, the EU's own installed hydrogen capacity exceeds 60 GW, while the installed hydrogen capacity among importers to the EU amounts to roughly 200 GW. Building on the OHIC's distribution of importers, Europe extends its pipeline networks further into North and West Africa as well as to its eastern neighbourhood, most prominently Ukraine. Despite the EU's focus on hydrogen imports, persistent concerns about energy security — especially in the context of delays in infrastructure construction — motivate it to continue developing domestic hydrogen production as well; demand is still growing. The US, China, Japan, Korea are also on track with decarbonisation and have increased both their domestic hydrogen capacities and their imports. As countries move away from fossil fuels (and because hydrogen development in the Gulf has stagnated), the region is increasingly isolated. It shifts (back) to using its domestic oil and gas reserves. In 2038, Saudi Arabia formally drops its net-zero target, and Kuwait proudly inaugurates a new oil-fired power plant.

By 2040, hydrogen supply clusters have formed, and hydrogen trade further intensifies. Hydrogen and its primary derivatives are transported via both pipelines and shipping. While the hydrogen trade primarily runs along a North-South line between the hegemons and their respective suppliers, Central Asia's hydrogen market serves different Asian economies (Japan, Korea, and China). Russia is further isolated from the West and is also cut off from the hydrogen trade on continental Asia. Progress towards global climate action has advanced significantly, though certain nations have actually increased their carbon footprint. Hydrogen is still considered a tool for international development, but reality says something else: the list of the world's hydrogen exporters overlaps considerably with the list of countries marked by corruption and poverty.

Analysis and evaluation of the scenarios

The three scenarios depict disruptive developments that reflect various (and conflicting) risks and opportunities already apparent in hydrogen policy and the global order. A closer examination of the scenarios and the chains of effects within them allows us to gain insight into the geopolitics of hydrogen, sketch out conflicting objectives, and identify strategies for mitigating risk.

Ambivalent futures: Climate and development

Table 1 shows the fundamentally ambivalent nature of hydrogen by comparing how each scenario would affect possible goals of German and European hydrogen policy.[55]

Although all three scenarios assume robust progress on curbing carbon emissions, there are distinctions. Only in the “Hydrogen Imperialism” narrative is climate action achieved solely through the switch to hydrogen energy; in the other two scenarios, (regional) deindustrialisation and carbon management technologies also contribute to emissions reduction.

The scenarios all suggest that regional commitments to reducing harmful emissions will depend on what path(s) the hydrogen transformation ends up taking. The Gulf States, for example, may choose between decarbonisation and increasing their carbon footprint depending on their level of integration into the global energy transition and openness towards various technologies.

The cross-sectional comparison shows, moreover, that Europe’s role as a (climate) technology leader is not a given, or even realistic; and it can only come from deliberate and proactive political action. Finally, Table 1 offers a sobering assessment of the potential to link the hydrogen trade to sustainable development. None of the scenarios envisions the shift to hydrogen bringing positive sociopolitical developments; rather, the hydrogen trade is likely to create or at least reinforce international and domestic power imbalances. Economic development could be possible, but it is hard to escape the zero-sum game of industrial relocation. In the scenarios, significant growth outside Europe goes hand-in-hand with an exodus of industry from the EU. Only the “Hydrogen Imperialism” narrative hints (weakly) at a possible economic win-win — but development in export economies would largely materialise in infrastructure-led growth or in sectors adjunct to exports. Negative consequences of trade in raw materials to the exporters’ political economy — the “resource curse” — are therefore possible and indeed already reflected in negative sociopolitical development.[56] Hydrogen’s potential contribution to development is far from guaranteed, and this has serious implications.

55 We evaluated the scenarios, contexts, and options for action from a German and European perspective, drawing the goals listed here (climate action, technology leadership, strategic autonomy, public costs, hydrogen supply costs, global and European economic development, socio-political development, and value-based trade) from current political discourse. These were initially identified by the participants during the foresight process. For a discussion of possible hydrogen import targets and their trade-offs, see Ansari and Pepe, *Toward a Hydrogen Import Strategy* (see note 7).

56 The Resource Curse is a term from development economics describing the phenomenon in which resource revenues are accompanied by negative (political) economic consequences for a country, often as resources weaken institutions. See also Frederick van der Ploeg, “Natural resources: Curse or blessing?” *Journal of Economic Literature* 49, no. 2 (2011): 366—420; Alycia Leonard et al., “Renewable energy in Morocco: Assessing risks to avoid a resource curse”, *Social Science Research Network* (2022).

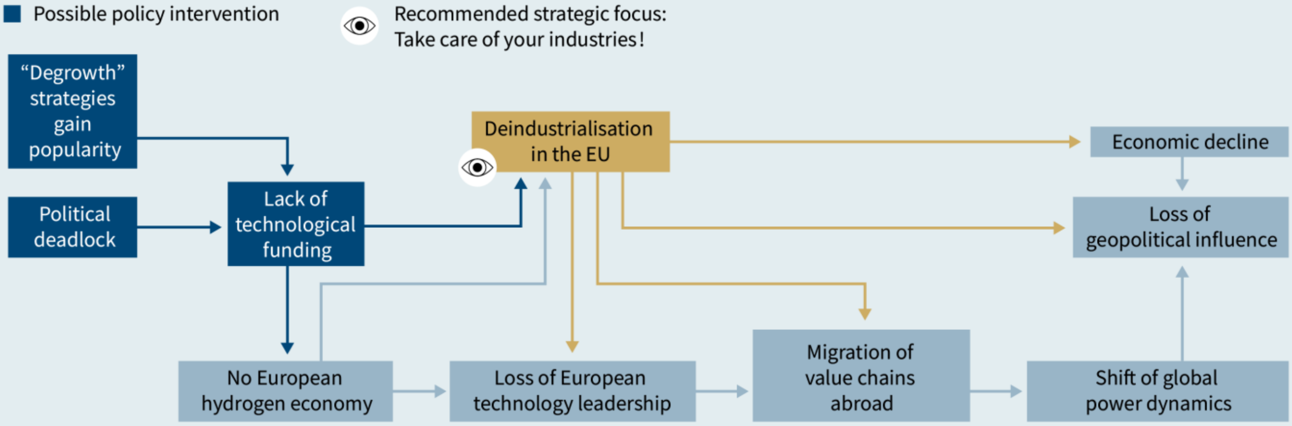
Table 1: Comparison of geopolitical scenarios for the hydrogen transition

↑ Positive effect → No significant effect ↓ Worsening effect

Scenarios	H_2 Realignment	H_2 (In)Dependence	H_2 Imperialism
Scenario core	Geoeconomic focus shifts eastward with EU deindustrialisation, degrowth, and loss of significance	EU solo venture in hydrogen concentrates dependence on supply chains upstream; despite friendshoring, this limits European autonomy	Rapid ramp-up of hydrogen, high global demand, and lack of governance structures lead to "eco-colonialism" and regional supply clusters
Remarks	• The EU exceeds its climate targets • The EU grows less dependent on China • The formation and strengthening of an Afro-Eurasia corridor supports economic growth but degrades pluralism	• Lack of coordination, myopic friendshoring, and failure to monitor supply chains create hidden dependencies • EU hydrogen governance does little in the absence of global governance • The EU preserves its infrastructure and development	• Development, infrastructure expansion, and selective industrialisation in the Global South serve as a pretext for "eco-colonialism" • Hydrogen consolidates power relations • The globalised energy system disintegrates into regional energy silos • Low hydrogen prices
Recommended strategic action	Take care of your industries	Take care of your value chains	Take care of your infrastructure
Possible effects on aspects of European hydrogen policy			
Climate action	↑	↑	↑
Technology leadership	↓	↑	→
Strategic autonomy	↓	→	↑
Public cost	↓	→	↑
Supply costs	n/a	↑	↓
Global economic development	↑	→	→
EU economic development	↓	→	↑
Sociopolitical development	→	→	↓
Value-based trade	→	↑	↓

Figure 5

Impact chain for "Hydrogen Realignment" scenario: Strategic focus on industry



Source: Scenarios "The Geopolitics of Hydrogen"

In line with the "imperialism" scenario, decision-makers and experts are at risk of internalising and promoting narratives traditionally used by authoritarian regimes: idealising infrastructure development and partial industrial relocation instead of supporting agency, sophisticated value chains, and social development in export countries.

The individual scenarios also demonstrate the ambivalent effects of a hydrogen economy and explore early courses of action.

Hydrogen Realignment: Hydrogen between Eurocentrism and eastward shifts

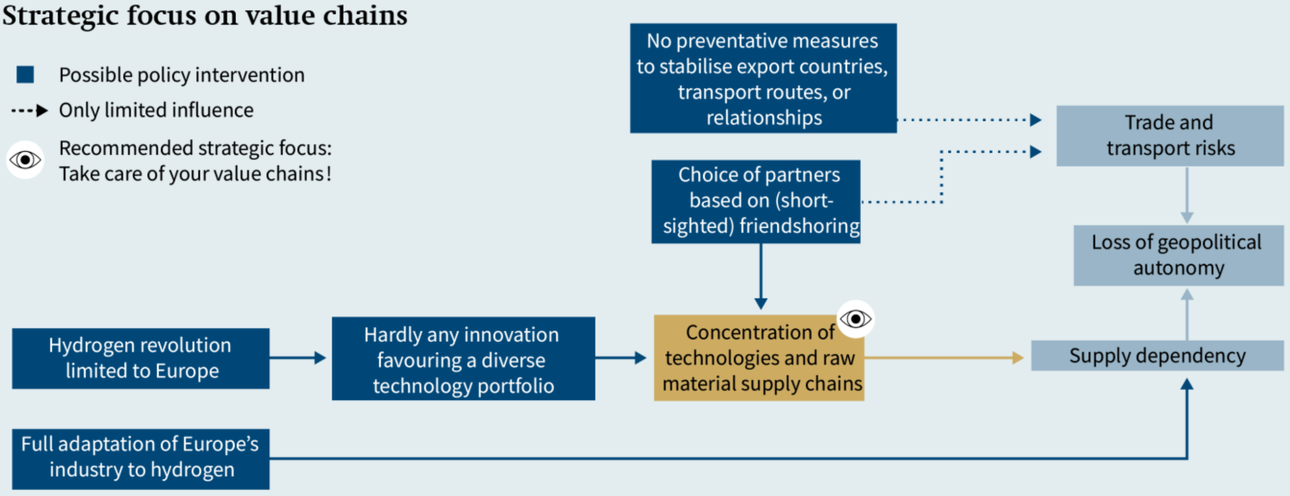
The "realignment" scenario depicts a world in which Europe can no longer shape events but also no longer needs to. Global development and climate change mitigation progress without European involvement — perhaps even at a faster rate than would be the case in other scenarios (Table 1). EU innovation and industrial support suffer as political deadlock and competing preferences cause the EU to fall behind in building its hydrogen economy (fig. 5). The result is widespread deindustrialisation, causing a draining away of European technological leadership, the withdrawal of value chains from Europe, and thus a shift in geoeconomic focus to Afro-Eurasia. EU (in)action decreases the opportunity costs of low-emission sectors (such as information technology), but ultimately, the magnetism of capital, influence, and industry prevails (pulling sectors like finance and education to the eastern hemisphere as well). The Europe-less hydrogen transition catalyses geoeconomic and geopolitical trends. Over time, the development of an energy corridor between the Gulf and China translates into a zone of geopolitical power that goes far beyond energy. In this context, the role of resource-rich middle powers like Indonesia in the Indo-Pacific gains significance.

This vision illustrates that Europe can hardly afford to be Eurocentric. Decision-makers should understand this as a warning: Europe's energy position and place in the global order is fragile indeed. Only a capable Europe can implement its own goals or philanthropic and idealistic ambitions. The Hydrogen Realignment scenario pictures the EU ultimately leaving the field to new hegemons — as its own diplomatic and industrial capability progressively erodes. The scenario also illustrates the close imbrication of technological leadership, economic strength, autonomy, and energy.

The given scenario underscores the critical need for Europe to adopt a strategic focus on its key industries. A strong, diversified industrial sector will allow the EU to maintain its geopolitical influence and prevent a loss of living standards. The scenario shows how difficult it is to halt deindustrialisation once it has begun; once irreversible investment decisions have been made and know-how has migrated elsewhere, there is no turning back. Political interventions should therefore start as early as possible in the chain. Aside from preventing political deadlocks and critically examin-

Figure 6

Impact chain for "Hydrogen (In)Dependence" scenario: Strategic focus on value chains



Source: Scenarios "The Geopolitics of Hydrogen"

ing preferences for degrowth — two areas beyond the scope of this study — industrial policy stands out (particularly measures such as subsidies for the hydrogen economy, corresponding technologies, and the industry as a whole).

Hydrogen (In)Dependence: Friendshoring is no substitute for diversification

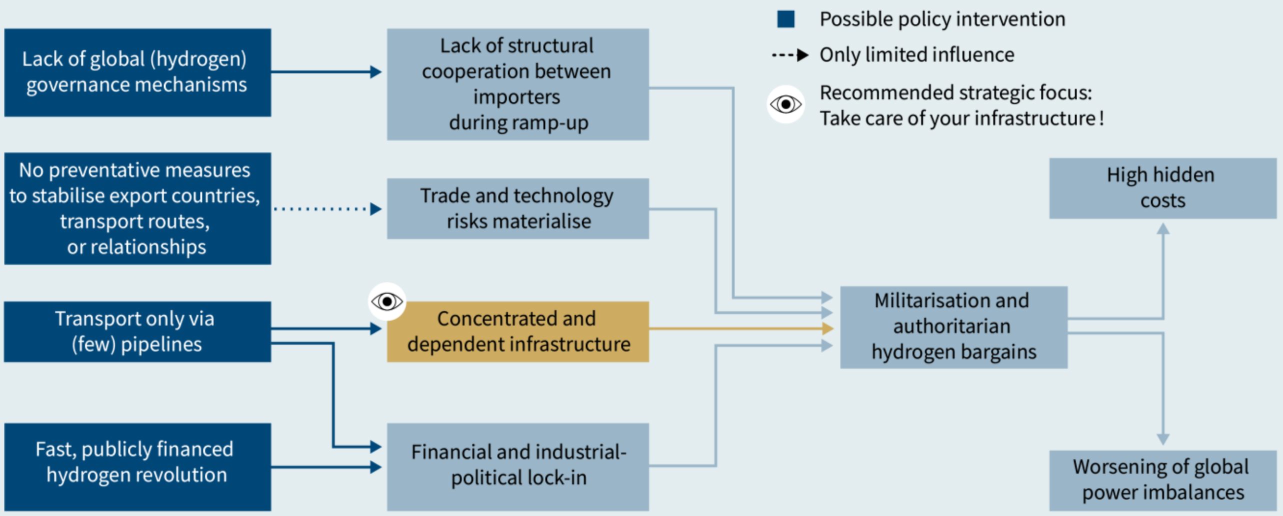
This scenario illustrates the central role of value and supply chains in green technologies and the complexity of dependence involved. Although the EU deliberately aims for a self-sufficient energy supply (thus maximising its autonomy), failure to diversify its technologies and supply chains ultimately leads to the loss of geopolitical autonomy (fig. 6). Europe must map, diversify, and mitigate these risks. However, it is imperative to acknowledge that it cannot avoid dependence, especially if it shifts solely to green technologies.

Trade is inevitable, indeed essential, especially where raw materials are concerned. An insular EU would help fragment the world order and constrict and restrict Europe's capacity in other areas. This leads to the second insight of the scenario: myopic policies revolving around shared values and supposed autonomy may mask significant pitfalls and blind spots in policy design. Value-based trade is hardly an effective way to reduce risk or promote geopolitical objectives. Democratic states are not inherently more stable than non-democratic ones, nor do they necessarily make better trading partners. Simultaneously, a deliberate push to align trade with narrow alliances based on common "values" accelerate the erosion of the world order — with dangerous consequences. In any case, the scenario vividly demonstrates that "friendshoring" is by no means a substitute for pragmatic concerns like diversification and stabilisation.

Again, the strategic focus here must lie with value chains. Measures to diversify the supply risks are the priority. Accompanying measures — particularly diplomacy or development assistance in raw material or hydrogen exporters — can help reduce (though never completely rule out) the risk of entering into harmful new situations of dependence. Alternatively, the EU must address the issue of supply dependence itself. One way it could do so is by promoting demand-side diversification, i.e., using natural gas and electrification in parallel to forestall a hydrogen lock-in. While this might promote autonomy, it would significantly raise system costs and dampen the focus of technological progress in hydrogen. This lever should be handled with care within the context of a hydrogen transition. An alternative could be promoting different value chains for hydrogen (for example, competing electrolyser technologies) or supporting the hydrogen transition on a global scale. The latter would broaden value chains and support the development of competing technologies, which would in turn reduce concentrations of dependence. This could involve various possible instruments — from energy and cli-

Figure 7

Impact chain for "Hydrogen Imperialism" scenario: Strategic focus on infrastructure



Source: Scenarios "The Geopolitics of Hydrogen"

mate partnerships to global hydrogen governance concepts — that promote research, trade, and investment.

Hydrogen Imperialism: Tension and mismanagement are unleashed on the Global South

In the "imperialism" scenario, the EU manages to expand its influence, advance climate action, promote economic development, and create a thriving hydrogen market. Remarkably, the distribution of technological leadership has enabled significant learning curve effects in favour of globally affordable hydrogen. However, the scenario also highlights substantial challenges, which show some overlap to those of the previous scenario (fig. 7).

The initially tense geopolitical climate, coupled with a lack of (hydrogen) governance mechanisms, discourages cooperation and militarises hydrogen relations. This imperialist dystopia not only costs exporting countries their agency (exacerbating global power imbalances) but brings high costs for importers (e.g., military expenditures) that are not reflected in the price of hydrogen.

The establishment of the "hydrogen oligopsony" proves that inconsistencies between energy and geopolitics cannot coexist in the long term: a system that cooperates on energy must end in a framework that cooperates on geopolitics as well or risk falling apart. Introducing governance structures in the hydrogen market early on could counteract this constellation (which is only moderately stable) and help it avoid structures that later motivate militarisation. Furthermore, accompanying measures of diplomacy and development assistance could help mitigate the risk of incidents in the supply chain.

These measures ultimately have only limited potential to break the chain of events leading up to the dystopia, however; for the core of the problem is concentrated infrastructure. The industry's rapid transformation paired with the decision to rely solely on a limited number of pipelines led to severe dependence. In this context, the industry and infrastructure being locked into hydrogen again cements dependency, so slowing down the hydrogen transition or diversifying the demand side poses a remedy. Yet this comes with the same massive constraints mentioned earlier. The strategic focus here therefore lies on infrastructure. In the coming decade, it will hardly be possible to build a diversified network of pipelines, so relying on the few existing ones will pose significant risks in the interim. Establishing alternative transportation methods for hydrogen — particularly shipping — is thus the primary available option.

Recommendations for a proactive hydrogen policy

Our scenarios and their analysis confirm that the same trends apparent in the geopolitics of the energy transition more generally also apply specifically to hydrogen — and that the interplay of resources, technology, power, and the world order is still crucial. Compared to fossil-based energy systems, a hydrogen-powered energy architecture shifts power from concentrated energy resources to technology, standards, (critical) raw materials, and industrial leadership. This aligns with the general paradigms of other new forms of energy, but the hydrogen world is likely to prove even more ambivalent and complex. Multi-tiered supply chains, technology-specific value chains, and a diverse topography of actors will create complex power structures. And actors will find themselves once again competing to forge interdependencies that suit their interests. This is not to say that the eventual geopolitics of hydrogen will not yield more symmetrical patterns of dependence than was the case in the old energy world. A mere shift of interdependencies to other geographies or stages of the value chain is more likely, however. Depending on which technology and market decisions manifest, current actors may find themselves in even stronger positions.

For instance, as the scenarios stress, raw material exporters will play an important role. At the same time, the scenarios highlight that new dynamics in geopolitics, energy, and climate could simply unfold without Europe in the coming years — which in turn highlights the profound importance of proactive and anticipatory action.

The policy recommendations outlined below draw from the insights gathered thus far as well as on a "windtunneling" analysis[57] (see Appendix). The latter allows for the identification of "robust" policies that are useful from today's point of view in as many of the scenarios as possible (without causing outright harm in certain scenarios). Meanwhile, and as developments unfold over time, decision-makers will need to adapt and tailor policy measures to the specific situations. The extensive set of indicators noted in Table 4 of the Appendix can help observers and decision-makers monitor the emerging hydrogen landscape, assess which future is indeed manifesting, and consider options for timely intervention.

Our recommendations for immediate action by Germany and the EU stand on four strategic pillars:

1) Acknowledge different preferences and recognise realities: A forward-looking and risk-mitigating approach to international energy relations must acknowledge the different preferences and motives of non-European actors. More than a specific measure, this recommendation demands a paradigm shift in perception and action. The prevailing Eurocentric perspective on the hydrogen sector is myopic, clouds European understanding, and limits Europe's actual ability to shape the sector.

It is unproductive to complain that potential hydrogen exporters' motives do not reflect climate ambitions. So is arguing that they should decarbonise their own power systems before joining the hydrogen economy. Outside Europe, that argument is often perceived as neo-colonial paternalism and could indeed cement unwillingness to take climate action. Moreover, such hypothetical top-down planning is irrelevant to actual climate change mitigation; even if a country ends up not exporting hydrogen, it does not imply that the country will invest in domestic decarbonisation. As far as both climate action and the successful ramp-up of a hydrogen market are concerned, Germany and the EU should take a pragmatic stance vis-à-vis the diverse preferences of potential hydrogen exporters.

57 The "windtunneling" exercise applied different possible courses of action to the different hypothetical scenarios to identify which options were most effective. See the Appendix for details.

This realism should also extend to how the EU selects its partners in the hydrogen sector. Smaller, lower-income countries may be relevant in the long run but are unlikely candidates for rapidly scaling up the hydrogen sector. They lack financing capability, experience, and infrastructure. Meanwhile, many of the more suitable prospective hydrogen exporters have other partners in mind as well — partners who are starting to look more attractive than Europe. We particularly caution against overloading hydrogen policy with unrelated agendas, as many of the goals discussed are non-trivial or even infeasible within the context of hydrogen. This applies especially to building hydrogen strategies around supposed value-based alliances or insisting they must serve global sustainable development. The latter in particular is not an automatic by-product of the hydrogen economy; instead, it requires well-coordinated planning and partnerships that promote agency and the establishment of sophisticated value chains in exporting countries. Hence, in the global competition for regulatory standards and leadership in the hydrogen market ramp-up, Europe needs to develop a more flexible and agile approach. If it does not, other actors will define market setup, technologies, and standards — and the power structures of tomorrow.

2) Promote targeted technologies and industries: In any of these scenarios, financial support to industries and technologies will be key to enabling a successful hydrogen transition and managing its risks. Hydrogen and climate goals can only be met if innovation is rapid enough, while retaining industrial capacities is also important from a geopolitical perspective. As other industrialised nations become increasing protectionist, financial support is needed to retain European leadership, also in hydrogen technology. That said, it must consider all support carefully. Depending on the scenario, indiscriminate or overly broad support (giving each industry and technology a slice of the budget) could be counterproductive.

Supporting the industry's transition to hydrogen technology — a measure that is already partly underway — is an example of a robust and necessary measure; it advances the hydrogen transition and European goals regardless of the hydrogen production technology involved, geopolitical climate, or even the success of European domestic hydrogen production. Furthermore, support for carbon capture and storage technology is generally advisable. This counterintuitive recommendation reflects that CCS leaves various technology paths open. Should the hydrogen economy develop slowly, CCS could find applications elsewhere, for example with fossil fuels. Should it develop rapidly, however, CCS would help offset the concentration of dependence along the renewable hydrogen value chain (including solar energy, electrolysis, or hydrogen imports).

We recommend that support for other technologies be contingent on how the hydrogen sector and the geopolitical environment evolve. Subsidising electricity and gas, for example (as discussed and partly implemented with the 2022 price crises), prevents deindustrialisation but creates high costs and discourages the industrial transition to new forms of energy. PEM electrolysis technology, popular in Europe, should be used primarily for globally distributed, cooperative value chains and could help Europe secure technological leadership. At the same time, the EU should support alternative, if still immature electrolysis technologies to help counteract asymmetrical relationships in the supply chain (for example in the raw materials sector) and provide a layer of protection in case Europe ends up on a solo venture in hydrogen. Keeping its hand in competing forms of technology (and therefore competing supply chains) would allow for risk diversification when diversification is not otherwise possible. (For example, if PEM electrolysers become the sole technology, as envisioned in the second scenario, raw material supply chains could become vulnerable and difficult to diversify, which could in turn limit European autonomy.)

3) Actively manage dependence: The scenarios illustrate that renewable energy and hydrogen will not necessarily reduce (or even eliminate) dependence on outside actors. Rather, they will catalyse new forms of interdependence or reinforce existing ones. Renewable hydrogen is no less prone than oil or gas to the creation of dependence relationships; it is simply different and will moreover require more intricate supply chains for raw materials and components. At the same time, it is neither feasible nor sensible to completely decouple; even a complete withdrawal from the hydrogen transition could lead to new dependencies — for example, on the import of energy-intensive goods. This would entail new risks that the EU and Germany would need to manage actively. Policymakers must take a cross-sectoral view that encompasses the entire value chain, and with both the short and long term in mind. This includes actively managing raw material supply chains, as well as prevention and refinement processes.

Dependency management must focus on physically diversifying technology, raw material, and energy imports. That means bringing a larger number of partners on board. Friendshoring is by no means a substitute for such diversification: even (seemingly) like-minded partners can radically change their positions over time; moreover, there are always (transport) risks along the supply chain. A trading partner's particular form of government, or the values that it espouses, will not necessarily determine the (in)stability or (un)reliability of trade.

However, further recommendations for managing dependency will depend on market developments. For example, hydrogen imports may promote energy resilience by reducing dependence at other levels of the value chain. In terms of transport, maritime shipping of hydrogen may not necessarily need to be complemented by pipelines, but pipelines (a more rigid form of infrastructure) should be complemented with shipping.

Policymakers should also keep in mind the importance of indirect measures to reduce risk. Though they are — certainly — not a replacement for diversification, we do recommend accompanying measures in the fields of development policy and diplomacy with (prospective) exporters of hydrogen, raw materials, and technology. Examples — depending on the choice of technology and on the partners involved — include stabilising relations with Algeria, supporting the population in South Africa, or establishing a raw material partnership with Indonesia.[58] These measures would at the very least promote sustainable development and diplomacy while at best preventing destabilisation of supply. Such measures must address locally perceived needs and happen before hydrogen endeavours, however. Paternalistic interventions could prove ineffective or even harmful, as shown in the consequences of the EU's overly ambitious criteria for sustainability in the Hydrogen (In)Dependence scenario.

4) Build global hydrogen governance: Finally, the EU and Germany should work to establish (preferably global) hydrogen governance mechanisms. This would allow for sufficient and targeted allocation of investments (contributing to rapid development of supply chains and cost degression) and mitigate the effects of a confrontational geopolitical climate. The risks — of asymmetric interdependence, of ill-fated investments, and of security incidents — will increase if the market and the hydrogen transition itself become more fragmented.

Forming a Hydrogen Alliance — a multilateral trade club of potential major importers and exporters — would be a concrete, robust governance instrument.[59] It could build on nascent institutions such as the European Hydrogen Bank, bring consistency to product and contract certification, and promote alignment in regulations and standards. A two-stage system for choosing members would be based on the varying abilities and levels of willingness of potential members to produce and trade hydrogen, identifying and including both fast adopters ("accelerators") and longer-term followers ("incubators"). The two-stage system would support both short-term and long-term goals of hydrogen transition, provide opportunities for technological exchange, and work to resolve potential goal conflicts.

Ultimately, examining the geopolitics of hydrogen and considering the hydrogen transition's many challenges raise the fundamental question of whether a hydrogen transition is necessary or should even be pursued. While in principle, it is possible to conceive a future in which other technologies (and combinations of technologies) achieve climate neutrality, hydrogen is the most mature and straightforward option for decarbonising heavy industry. Moreover, the hydrogen economy offers unique opportunities for Europe. Combining low-emissions hydrogen with renewable electricity and energy efficiency holds much promise.

Clean hydrogen can and should be a central, independent pillar of Europe's energy transformation. This is especially the case if Germany and the EU want to pursue their vision of making the continent climate-neutral while simultaneously preserving Europe's energy-intensive industries. Even apart from climate action, the desire to develop regulatory and technological leadership in a new field may incentivise Europe to enter the hydrogen arena. Taken together, these opportunities should be reason enough for taking a highly proactive stance on looming conflicts, ambivalent consequences, and other challenges associated with the emerging geopolitics of hydrogen.

58 For possible alliances of the German government in the raw materials sector, see Dawud Ansari et al., *Auf Partnersuche: neue Allianzen im Rohstoffsektor*, SWP 360 Grad (Berlin: Stiftung Wissenschaft und Politik, June 2023).

59 Ansari and Pepe, *Toward a hydrogen import strategy* (see note 7).

Appendix

Methodology and the Foresight Process

Developing scenarios is typically a multi-stage, facilitated process involving collaborative and participatory techniques to foster creativity and anticipation while reducing bias and its impact. The three scenarios presented here were developed in an eight-stage process. The facilitator outlined a series of individual stages:

- Scoping
- Environmental scanning
- Factor assessment
- Projection formation
- Scenario construction
- Scenario development
- Analysis and evaluation of scenarios
- Processing and elaboration

The process spanned approximately one year and was carried out with the assistance of a professional moderator — Foresight Intelligence — and independent participants. Adequate diversity for the group (a quality criterion for the scenario process to reduce bias) was ensured; of the 16 participants (including moderators and study authors), 32 per cent were women, and 44 per cent had a (partially) non-European background. Participants came from a range of academic disciplines, including political science, economics, finance, history, the natural sciences, and engineering; 10 participants had interdisciplinary academic backgrounds. The participants represented various sectors, including applied research, corporate consulting, policy advising, energy companies, government, development cooperation, and administration.

The process began by delineating research questions and themes; moderators and the authors implemented this with readings and policy research from June to September 2022. Our "environmental scanning" took the form of an online survey at the beginning of September 2022. Participants were asked to identify factors influencing the geoeconomics of hydrogen. Together, they mentioned more than a hundred factors, which the moderator then condensed to 42. Subsequently, we conducted the factor assessment through a virtual meeting of participants in mid-September 2022. Working in pairs, participants rated the 42 factors in terms of impact and uncertainty, thus identifying six key uncertainties as factors with the highest ratings in both categories. Over a two-day conference held at the SWP at the end of September 2022, participants formed projections, constructed scenarios, and developed these. Working pairs initially created mutually exclusive realisations of the previously identified key uncertainties (referred to as projections). Subsequently, the entire group of participants selected four scenarios as combinations of those projections based on the criteria of 1) consistency, 2) plausibility, and 3) relevance (Table 2). From these, a working group used backcasting to derive three scenarios; they then elaborated each as an initial ("raw") scenario (i.e., a rough, plausible sequence of events).

Our analysis and evaluation of the scenarios began at the September conference and continued with a second conference in November 2022. Participants began by identifying potential goals of German and European policy. Based on these, working groups then identified risks and opportunities of the individual scenarios, after which the groups proposed strategic options for managing the scenarios. A key part of this was evaluating them in the context of a "wind-tunneling" exercise (Table 3). In this exercise, participants applied the potential measures to all scenarios to identify the most effective and broadly applicable options. A measure is "robust" if it proved effective (or at least not harmful) in all three anticipated scenarios. (Conversely, any measure showing a detrimental effect in at least one scenario is "not robust" — a warning to decision-makers that they should only implement such a measure with reservations.)

Processing and elaboration took place from November 2022 to July 2023. After the facilitator's initial summary of process results (December 2022), we revised and refined the scenarios (January—June 2023). That process involved closing (plausibility) gaps; introducing new actors; deepening event chains; and conducting a new strategic analysis with the consent and feedback of the participants. We extended the time horizon from 2035 to 2040 in order to account for new policy developments; more significantly, we widened the focus from geoeconomics to geopolitics. Finally, we updated and expanded the windtunneling analysis (Table 3) and created a set of indicators (Table 4) to help observers and decision-makers track elements of the scenarios (or which combination of them) as they materialise.

To maintain the participatory nature of the scenarios, in July 2023, additional regional experts from the SWP and participants in the original foresight process were invited to review the draft.

Participants in the Foresight Process and Acknowledgments

The strategic foresight process implemented for this study relied on the valuable contributions of all participants. The expertise and in-depth insights they contributed significantly enhanced the quality and depth of this study. The authors and the SWP express their heartfelt thanks to the participants for their thorough preparation, dedicated participation, and valuable input. This input provided an important basis for the scenarios and was treated with the utmost care — with the consent and feedback of the participants — as the scenarios were being elaborated. The participants agreed to the publication of their names:

- **Jochen Bard**, participant in the scenario process, “Hydrogen (In)Dependence” raw scenario
- **Anne-Sophie Corbeau**, participant in the scenario process, “Hydrogen Imperialism” scenario
- **Gniewomir Flis**, participant in the scenario process, “Hydrogen Realignment” raw scenario
- **Johannes Gabriel**, moderation, preparation, and processing/elaboration
- **Julian Grinschgl**, participant in the scenario process, “Hydrogen Realignment” raw scenario
- **Marcel Hadeed**, moderation and processing/elaboration
- **Rainer Quitzow**, participant in the scenario process, “Hydrogen Realignment” raw scenario
- **Laurent Ruseckas**, participant in the scenario process, “Hydrogen Realignment” raw scenario
- **Manal Shehabi**, participant in the scenario process, “Hydrogen Imperialism” scenario
- **Manuel Villavicencio**, participant in the scenario process, “Hydrogen (In)Dependence” raw scenario
- **Kirsten Westphal**, participant in the scenario process, “Hydrogen (In)Dependence” raw scenario
- **Yana Zabanova**, participant in the scenario process, “Hydrogen (In)Dependence” raw scenario

Table 2: Projections and assumptions in the scenarios

Projections	Reference	Scenario: H_2 Realignment	H_2 (In)Dependence	H_2 Imperialism
Global demand for clean hydrogen	EU and major economies push hydrogen	Major and developing economies outside the EU	EU (virtually) alone	EU and other major economies
Geopolitical powers and international relations	New powers and conflicts	New powers and conflicts	Current global powers but new conflicts	Current global powers and cooperation
Focus and concentration of low-carbon technology innovation (chains)	Focus on diverse technologies and global supply chain	Focus on diverse technologies and concentrated supply chain	Focus on diverse low-carbon hydrogen technologies and concentrated supply chain	Focus on hydrogen and global supply chain
Extent and nature of international trade in clean hydrogen and necessary infrastructure	Some international transport of hydrogen and derivatives, dominated by shipping	Some international transport of hydrogen and derivatives, dominated by shipping	Few to almost no trade in hydrogen and derivatives and no infrastructure developed for cross-border trade	Excessive global trade in hydrogen through a network of pipeline connections and shipping routes
Scarcity and concentration of mining and refining capacity for renewables and green hydrogen	Not enough and concentrated capacity	Enough but concentrated capacity	Not enough and concentrated capacity	Enough capacity, sufficiently diversified
Global scope of hydrogen exports	Few exporters (e.g., US, Canada, Australia, Gulf States) and bilateral trade	Relatively many exporters (e.g., US, Canada, Australia, Gulf States and some developing countries)	Hardly any exporters	Many exporters (e.g., US, Canada, Australia, Gulf States, many developing countries)
Assumptions				
Access to capital	Given			
Role of the state in emergence of the hydrogen economy	Important			

Table 3: Results of the windtunneling analysis

Policy measure ...

↑ is very helpful ↗ is somewhat helpful → has balanced or no effect ↘ is somewhat harmful ↓ is very harmful

✓ could be robust ⊗ would not be robust

Policy field	Policy measure	Scenario: H_2 Realignment	H_2 (In)Dependence	H_2 Imperialism	Rating
Industrial and innovation policy	Subsidies for electricity or gas	↑	→	↓	⊗
	Funding for conversion to hydrogen	↗	→	↗	✓
	Funding of PEM electrolyser industry	↘	→	↑	⊗
	Funding (e.g., re-search) for electro-lyser technologies which are not yet ready for the market	→	↑	↘	⊗
	Onshoring / building alkaline electrolyser value chains	↘	↗	↓	⊗
	CCS promotion in EU	↑	↑	→	✓
Infrastructure policy	Parallel expansion of all import infrastructures	↘	→	↑	⊗
Diplomacy and development policy	Stabilisation measures for raw materials and hydrogen exporters	→	↗	↗	✓
Sectoral governance	Establishment of a “Hydrogen Alliance”	↗	↗	↑	✓

Table 4a: Indicators

	Scenario		
	H_2 Realignment	H_2 (In)Dependence	H_2 Imperialism
Economic and industrial dimension	High gas and electricity prices harm Europe's economy	High costs of hydrogen revolution burden Europe's finances	
	Severe job decline in Europe; extensive job creation in Afro-Eurasia	New jobs in Europe's hydrogen sector	New jobs in the hydrogen sector worldwide
	Profound sectoral change and economic development in several developing and emerging economies		Only superficial economic development of hydrogen exporters
	Closure of chemical/steel plants in Europe and their reopening in other parts of the world	Preservation of heavy industry and Europe as an industrial location	Flourishing heavy industry in Europe
	Globally confrontational behaviour in the hydrogen economy	No global dimension to the hydrogen economy	Global cooperative behaviour in the hydrogen economy
	Balanced procurement costs for hydrogen	High procurement costs for hydrogen	Low purchase costs for hydrogen, but high public cost for security
	Gulf States emerge as central economic powers and integrate into new intra-Asian energy, financial, and goods trade patterns		Gulf States increasingly marginalised in industry and energy
Energy trade dimension	European imports focused on energy-intensive products	European imports focused on raw materials	European imports focused on hydrogen and its derivatives
	Hydrogen trade by freighter and occasionally also pipeline	Almost no hydrogen trade	Hydrogen trade, depending on geography, equally through pipelines or shipping
	Formation of trade corridors for raw materials, electrolysers, and hydrogen away from the West	No global trade in hydrogen, but an EU trade corridor for raw materials	Hydrogen, derivatives, and commodities trade along several North-South axes
	Moderate trade in fossil fuels	High trade in fossil fuels (outside Europe)	Low trade in fossil fuels
	Hardly any trade policy autonomy for Europe	(Limited) trade policy autonomy for Europe and high value orientation of (energy) trade	Tendency of high trade policy autonomy for Europe with low value orientation of (energy) trade
Legal and institutional dimension	Limited regulation of a global hydrogen market (e.g., CBAMs and standards)	Strong regulation of a European hydrogen market (e.g., CBAM and quotas for the use of renewable hydrogen)	Strong regulation of a global hydrogen market (e.g., agree-ments on critical raw materials, technology sharing, and import prices)

Table 4b: Indicators

Scenario	H_2 Realignment	H_2 (In)Dependence	H_2 Imperialism
Legal and institutional dimension (continued)	Regulatory leadership through China	Regulatory leadership through Europe	Regulatory leadership through all major hydrogen importers
	Creation of numerous institutions, alliances, and standards away from the West	Creation of purely European or European-led institutions	Creation of a global hydrogen oligopsony
Technological and innovation dimension	Accelerated progress in hydrogen technologies	Slow progress in hydrogen technologies	Rapid progress in hydrogen technologies
	Focus on hydrogen innovation in the US and China; comprehensive technology leadership	Only in Europe is there a focus on hydrogen innovation	Innovation focus in hydrogen divided globally; technology leadership only in specific technologies
	Moderate focus on hydrogen innovation	Parallel global progress in a wide range of climate protection technologies, especially CCS	Clear focus on hydrogen innovation
	Alkaline electrolysers dominate the global market	PEM electrolysers dominate the global market	Different, complementary electrolyser technologies coexist
Social and domestic policy dimension	Polarisation of Europe's political landscape paralyses the policy process	Polarisation of Europe's political landscape leads to new alliances (especially between green and right-wing actors)	
	Political deadlock in EU stymies far-reaching reforms and investment	Despite differing viewpoints, parties forge policies and support broad hydrogen subsidies	
	Growing social inequality within Europe	Growing inequality between regions	Growing inequality between North and South
Security and geopolitical dimension	Regional cooperation and hegemonic relations gain importance	Transregional value- and interest-based cooperation (e. g., BRICS, value-based partnerships) gain importance	Transregional sectoral cooperation (e. g., energy governance) gain importance and partially replace other formats of the global order
	Geopolitical tensions remain largely constant	Geopolitical tensions escalate more frequently	Geopolitical tensions resolve in an increasingly cooperative manner
	High import dependency of the EU on energy-intensive goods	High import dependency of the EU on raw materials	High dependence of the EU on hydrogen and its transport routes
		Hydrogen-related dependencies impact EU security policy and value-based action (Taiwan)	Hydrogen-related dependencies impact EU value targets

Table 4c: Indicators

	Scenario		
	H_2 Realignment	H_2 (In)Dependence	H_2 Imperialism
Security and geopolitical dimension (continued)			Increasing willingness to embed energy and commodity issues in security policy; militarisation of energy
		Supply chain incidents threaten strategic autonomy	Supply chain incidents threaten hydrogen energy security
	EU's strategic autonomy decreases comprehensively	EU's strategic autonomy increases, but is not crisis-resistant	EU demonstrates strategic autonomy even in crises
	Influence of many developing and emerging countries increases; new hegemons gain agency		Many developing countries lose influence and agency; relations between exporters and importers become hegemonic
	Developing countries are increasingly taking their cue from China, Gulf States, or the US		Hydrogen exporting countries are primarily oriented towards their major power trading partners
	Shift of geopolitical power towards Asia	Increasing decoupling and decentralisation of geopolitical power centers	Emergence of a polycentric world order
	Africa and Eurasia intertwine	Hydrogen is highly regionalised (Europe only)	Silos form along North-South axis, while global energy becomes unbundled
		Accusations of European neo-colonialism	Intensification of eco-colonialism
Cultural and other dimensions	Europe's citizens associate hydrogen with climate crisis and techno-dystopia	Europe's citizens associate hydrogen with independence, home, and strength	Europe's citizens associate hydrogen with climate protection and international development, but also with militarisation and autocracy
	"Degrowth" becomes a central narrative of European climate action	"Independence" becomes the central narrative of European climate protection	"Technology" becomes the central narrative of European climate protection
	Greenwashing of poverty spreads, helped by esoteric and semi-religious narratives	Greenwashing of nationalism increases (e. g., solar panels on border walls)	Green paternalism in development policy spreads

Abbreviations

ANC	African National Congress (South Africa)
BRICS	Brazil, Russia, India, China, and South Africa
CBAM	Carbon Border Adjustment Mechanism
CCS	Carbon Capture and Storage
CCUS	Carbon Capture, Utilisation and Storage
COP27	27th Conference of the Parties
GCC	Gulf Cooperation Council
CSU	Customs and Security Union — *see Hydrogen (In)Dependence scenario*
GW	Gigawatt
IAEA	International Atomic Energy Agency
IEA	International Energy Agency
IRA	Inflation Reduction Act (US law passed in 2022)
IRENA	International Renewable Energy Agency
kW	Kilowatt
OHIC	Organisation of Hydrogen Importing Countries — *see Hydrogen Imperialism scenario*
PEM	Polymer-Electrolyte-Membrane
SMR	Steam Methane Reforming
SWIFT	Society for Worldwide Interbank Financial Telecommunications
UAE	United Arab Emirates
WTO	World Trade Organisation

Sources for map (p. 9) "The new hydrogen world: Raw materials, infrastructure, resources"

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Wind Energy Potential

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(average wind power density at 100-meter height above the ground, status as of 2019).