

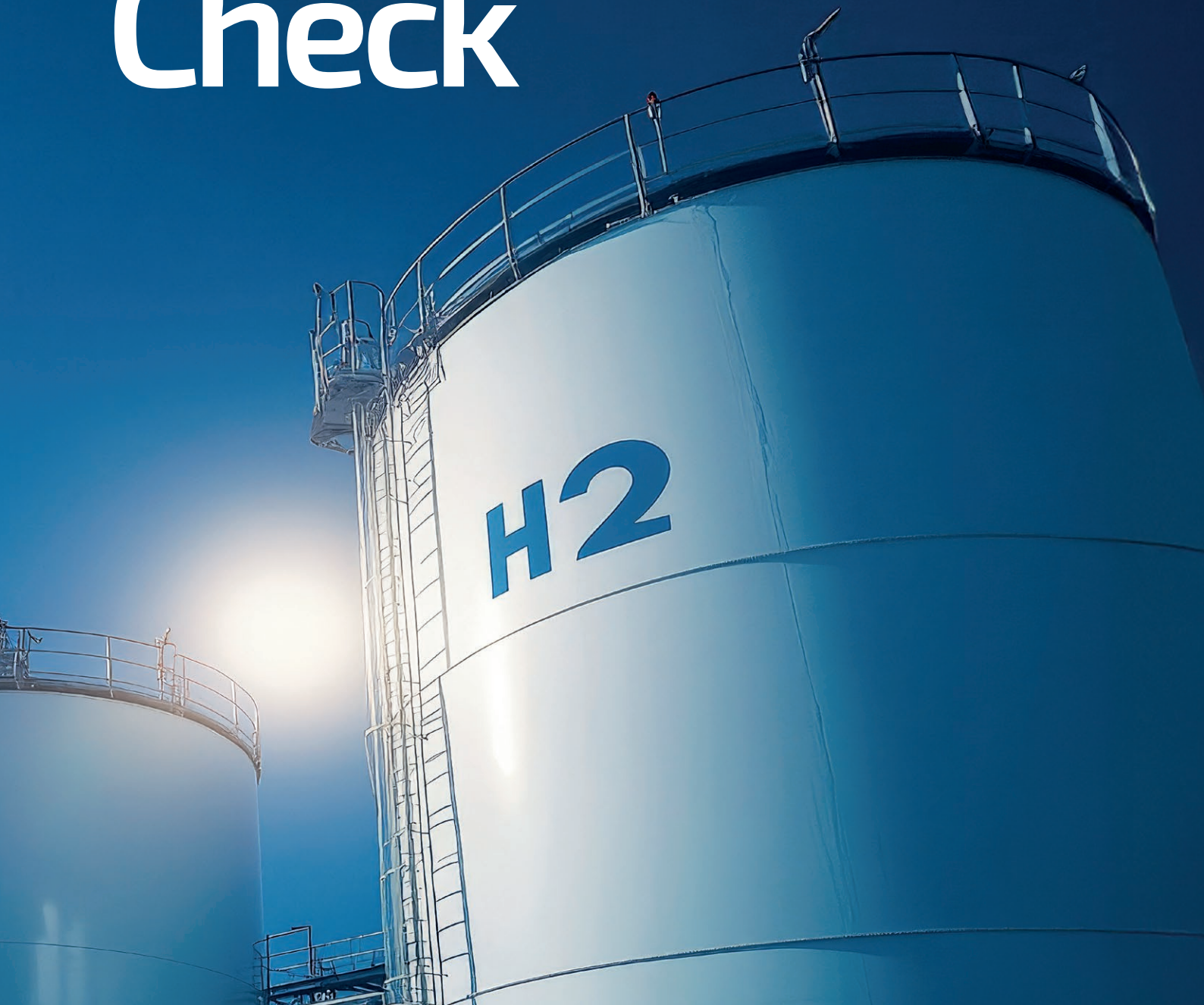


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Institute of Energy Economics
at the University of Cologne
Exploring energy markets –
enhancing decisions.

Reappraising the EU's H₂ Strategy in a New Era of Geopolitical Disruptions

H₂ Reality Check







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**European
Climate
Foundation**

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Forword

Written by Dr. Enrico Fels (CASSIS)

Dear reader,

In our 2023 report on [Global Energy Transitions](#) of the annual Bonn Future Lab on Strategic Foresight, I suggested that although hydrogen has a promising potential as a preferred energy carrier, European leaders urgently need to recognize today's more hazardous geopolitical environment while transforming significant portions of their industrial and energy sectors into more hydrogen-based economies. In my take on the matter, I outlined the necessity for an "evidence-driven ,H₂ Reality Check' to strategically assess the long-term geopolitical and geoeconomic sustainability of European hydrogen plans".

Given this backstory, it is now a great privilege and personal pleasure to provide a forword to this extensive study that does indeed provide such a dearly needed reality check of the European Union's hydrogen strategy. Kindly funded by the European Climate Foundation and conducted by multiple experts from the Center for Advanced Security, Strategic and Integration Studies (CASSIS) at the University of Bonn and the Institute of Energy Economics (EWI) at the University of Cologne, this report offers a rather sobering, yet very detailed reassessment of the EU's strategic stance on hydrogen.

Today's world is marked by a profound *Zeitenwende* – a strategic turning point in the global order – characterized by increasingly fragmented and deglobalized markets, reviving and flourishing nationalism, and a further escalating geopolitical competition. The robust changes in the trajectory of current world politics are undeniably fundamental. Combined with recent developments – like the reelection of Donald J. Trump as the President of the United States – these and other global megatrends force EU institutions and European leaders to truly recognize the central shifts that are currently taking place – and acknowledge the need to revise both strategies established only a few years ago as well as to reconsider long-held political priorities. For better or worse, the disruptive policies of the second Trump administration can perhaps "help" Europe to adopt an ontological shift towards more political realism and less moralistic complacency. In light of this, the EU's commendable ambitions for hydrogen as a cornerstone of the bloc's climate-neutrality strategy demand rigorous scrutiny that blends geopolitical insights with geoeconomic pragmatism. In my opinion, the study at hand rises to that challenge excellently.

As mentioned, hydrogen has long been declared to be a transformative energy carrier, poised to bridge the gap between renewable electricity surpluses and the decarbonization needs of hard-to-electrify sectors such as heavy industry and trans-



Dr. Enrico Fels (CASSIS)

portation. The EU's targets from 2020 reflect an optimistic vision of a green hydrogen economy as a driver of both environmental sustainability and economic competitiveness. Alas, as this report meticulously outlines, the fundamental developments of the last years have exposed the strategic brittleness of that grand hydrogen vision. Rising production costs, persevering technological immaturities, and – perhaps most importantly – shifting global energy dynamics have cast serious doubts on the feasibility of the bloc's strategic objectives. Moreover, the geopolitical upheavals following Russia's 2022 invasion of Ukraine have shed ample light on the huge risks associated with great import dependencies in an increasingly unstable world. Of course, there are lessons to be learned from past mistakes in order to strengthen one's future position.

Considering this, the authors of *H₂ Reality Check* are to be commended for adopting a comprehensive, transdisciplinary approach. They dissect the EU's hydrogen strategy across four critical axes: the current policy landscape within the bloc and its member states; the cost and technological readiness of hydrogen production and application; the geopolitical risks tied to import (over)reliance; and, finally, the role of hydrogen in industrial decarbonization efforts amidst competing pathways such as electrification. Their findings are both sobering and urgent. Green hydrogen, once projected to

achieve cost parity with blue hydrogen by around 2030, remains persistently more costly than its fossil-based equivalent. Meanwhile, revised global demand forecasts do suggest a far smaller role for hydrogen as an energy carrier than previously anticipated. These grim economic and technological headwinds are further intensified by a geopolitical environment marked by de-globalization. Supply chain disruptions, protectionist policies (with former free trade champions like the U.S. even taking a global lead under President Trump in this regard), and heightened strategic rivalries with proxy wars threaten not only the stability of energy imports, but also many other segments of world affairs.

What sets this joint study apart from other reports is its focus on the strategic interplay between geoeconomics and geopolitics – a nexus surprisingly and quite too often dismissed in the often technical discussions of energy transitions. However, both dimensions are of crucial importance for ensuring not only energy security itself but also the necessary transitions towards a more greener energy usage to safeguard global sustainability efforts. The EU's historical vulnerability to energy dependencies is perhaps best exemplified by Germany's overreliance on Russian gas until 2022. This persisting geoeconomic dependency has clear geostrategic repercussions to this day.

Again, important lessons are to be learnt: In a world of increasingly challenged sea lines of communication, unstable maritime choke points, and rising great power competitions – most notably between the United States and China, with the latter continuing to dominate the critical raw material sector as well as electrolyzer manufacturing – the EU and its member states have to seriously rethink their earlier hydrogen strategies. Hydrogen security cannot be divorced from the broader questions of resilience towards geoeconomic and geopolitical shocks – and the fundamental necessity to regain greater strategic autonomy in an unfortunate world drifting towards a Second Cold War (a very worrying development indeed!). The report recommends to prioritize hydrogen usage in sectors where at least for now no viable alternatives exist, while at the same time strengthening attempts to diversifying import sources and reducing overall dependency. All in all, the authors try to strike a pragmatic, evidence-based balance between laudable green ambitions and the harsh geoeconomic and geopolitical realities of the turbulent times ahead.

I believe that this *H₂ Reality Check* arrives at a critical moment for policymakers within the EU and its member states. The new European Commission and Parliament, facing the triple imperatives of the energy triangle (cost competitiveness, supply security, and climate action), certainly need to tackle very challenging trade-offs. The projected oversupply of LNG and the tenacious cost disadvantage of green hydrogen further underline the strategic necessity for a recalibrated EU hydrogen strategy. Moreover, the bloc and its member states need to rethink the strategically perilous overreliance on innovative and cost-efficient Chinese technologies for pursuing their important green transition – that is at least, if the Europeans do not want to become even more dependent on external

actors in geopolitical affairs in the future. As the authors argue, this recalibration must have a true strategic character and needs to go beyond mere technical fixes in order to truly address the seismic shifts of the *Zeitenwende*. The rise of concepts like 'friend-shoring' and 're-shoring' as reactions to the heightening geopolitical fragmentation of our times certainly offers new opportunities. However, they also involve the risk of turning Europe merely inward at a time when international partnerships – with Norway, Africa, Latin America, and beyond – remain essential. Moreover, continuing engagement and exchange even with rivaling international powers will remain important not only for the EU's prosperity (and security) in the future, but also for successfully tackling humanity's common global challenges: The necessity to adapt to climate change, using globalization's economic and cultural benefits for lifting people out of poverty as well as fighting bad governance and extremism in its various forms in order to improve the livelihoods of humans all over the world.

While reading the different segments of this study, I was struck by its scientific rigor and its academic audacity in challenging current orthodoxies. The authors do not shy away from addressing uncomfortable truths: that the EU's hydrogen targets may very well be unachievable given current geopolitical and geoeconomic conditions; that blue hydrogen's resurgence could undermine the bloc's ambitious climate goals; and that hastening the green transition, for all its economic promise and ecological necessity, actually risks establishing new, often overlooked strategic dependencies on other important international actors. Without a doubt, a holistic risk assessment of old and new dependencies is needed in order to successfully steer the EU and its member states through the troubled times ahead.

In my judgment, this report provides not only a diagnostic tool, but also a roadmap for navigating the turbulent years of the *Zeitenwende* for scholars, practitioners, and policymakers alike. The EU's hydrogen strategy, once a symbol of visionary optimism, must now evolve further into a strategic framework grounded in greater risk awareness and the courage for deliberate strategic resilience. The citizens of the continent deserve a European approach that recognizes strategic limits in an era of geopolitical and geoeconomic disruption, while steadfastly seizing the considerable opportunities that remain and wait to be exploited.

Clearly, sustainable energy security and ambitious climate imperatives cannot and should not be separated from the overall geopolitical and geoeconomic realities of national security. This makes the study at hand so crucial. The authors remind us that the path to a sustainable, prosperous and secure future is neither linear nor assured, but rather a complex, reiterating negotiation between technological innovation, ever-shifting power distributions, and – perhaps most importantly – cunning political pragmatism that balances visionary leadership with the fundamentals of Realpolitik. I sincerely hope that the *H₂ Reality Check* by CASSIS and EWI will further stimulate evidence-based academic debates and informed political actions that this critical issue demands. To conclude, I wish to convey my greatest gratitude to the authors involved from CASSIS and EWI, the project team, and, most importantly, the European Climate Foundation for its generous funding that made this research endeavor possible. As this study greatly benefitted from the in-depth discussions of its three expert workshops in Bonn, Berlin and Brussels, I would, last but not least, also like to thank the Konrad Adenauer Foundation for helping to organise them in the German and Belgian capital.

Forword

Written by Marcus Lippold
(European Commission)



Marcus Lippold
(European Commission)

This study represents a very valuable contribution to the wider debate and taking-stock of how successful the EU's energy transition has thus far been, what still needs to be done and what could or should be done differently, especially as the EU now re-focuses on its global industrial competitiveness. By taking a detailed look at the EU's production, usage, import, technical readiness and relevant cost factors towards realizing sufficient Green Hydrogen availability for the EU, this analysis holistically zooms in on all the relevant determinants of one of the EU's most ambitious elements of its energy transition towards its net zero aims. The EU Green Hydrogen targets and strategy, future and new import-dependencies, updated cost analysis, changing global logistics chains and their reliability as well as current technical readiness levels in the EU are all getting critically discussed. This analysis invites the reader to critically re-assess our current speed and path of travel regarding the EU's green hydrogen aims, whether these are still deemed realistic and which adjustments might need to be made in order to benefit the wider energy transition aims.

I congratulate the authors for the very timely chosen topic and hope that this study will be widely read and discussed, thus giving a significant impulse to a necessary debate.



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Executive Summary

Hydrogen is considered a vital energy carrier in the EU's climate-neutrality strategy, anticipated to store excess renewable electricity and deliver high-density energy for challenging-to-electrify sectors such as industry and transportation. The future geopolitical risks of a supposedly high-import dependence on hydrogen and its derivatives depend on Europe's future hydrogen demand and related import demand. The objective of this study is to analyze the changing geoeconomic and geopolitical conditions for the EU's future hydrogen supply security. This present study focuses on (i) assessing the present status quo of the hydrogen policies of the EU and its member states, (ii) analyzing cost and maturity of hydrogen provision and application in the industry, (iii) examining the EU's future geopolitical import risks and challenges as well as new hydrogen partnerships with non-European countries, and (iv) reviewing the role of hydrogen for the industry in the decarbonization pathways and highlighting the different geopolitical risks of hydrogen imports during the green energy transition in the next years.

The EU has a target of installing 40 GW electrolyser capacity in the EU and producing 10 Mt and importing an additional 10 Mt of hydrogen in 2030. A hydrogen demand ramp-up is targeted in various sectors especially the industry, electricity, and transport sector. The member states of the EU have published strategies, roadmaps and national energy and climate plans stating measures designed to reach this EU target, but they are heterogeneous in ambition and level of detail. Observed investment lags behind ambitious targets for green hydrogen which creates uncertainty regarding the extent to which the targets are achievable. The EU's hydrogen targets for 2030, defined in 2020, are unlikely to be reached under current circumstances.

New global analyses and forecasts on hydrogen have decreased the future global and European hydrogen demand due to new and more cost-efficient electricity technologies in the transport and buildings sectors, higher projected costs (materials, labor, inflation, etc.), decarbonization needs of potential H₂ exporting countries, insufficient subsidies and funding and commerciality, and profitability of H₂ projects for the industry. Even in the energy-intensive industries, electrification may expand with new technologies. It could further decrease the future EU and global hydrogen demand.

Technology & Economy

During the last years, green hydrogen production costs have increased instead of decreased as previously forecasted. The original estimate that green hydrogen will become cost-competitive with potential blue hydrogen around 2030 is now considered unrealistic. Green hydrogen production in Europe is presently about two times more expensive than potential blue hydrogen (including costs for CCS/CCUS). Costs do not reflect prices; those might potentially be higher especially in countries that are dependent on hydrogen imports. Further, as natural gas prices might decline in the short to medium term due to a possible LNG oversupply, the price gap between blue and green hydrogen as well as natural gas could even further increase in the forthcoming years. It might slow down the expansion of green hydrogen as the willingness to pay of almost all industrial sectors is expected to be below the production costs of green hydrogen within the EU and the supply costs from outside the EU in 2030.

Green hydrogen production technologies show a Technology Readiness Level (TRL) in the Demonstration or Early Adoption phase. Blue hydrogen production with a high carbon capture rate is only at the Prototype level. Hydrogen transportation via Ammonia or Liquid Organic Hydrogen Carrier is at a mature stage whereas liquid hydrogen trans-

portation is less developed. Technologies at low TRLs are not yet viable for large-scale deployment, which is essential to meeting ambitious hydrogen production and consumption targets. Investment is still needed into research and development of these technologies but might be held back due to numerous uncertainties.

Infrastructure development within the EU takes up slowly, but a hydrogen grid – connecting major import, production, and demand hubs – is planned within the European Hydrogen Framework. The future hydrogen transportation via pipeline as well as storage allocation will need major coordination between the member states of the EU and stakeholders such as natural gas and hydrogen network operators.

Electrification might serve as a cost-competitive alternative to decarbonize some of the processes in the industrial sector. The TRL of electrification is significantly higher than for hydrogen-based applications for some industrial sectors such as aluminium and glass but is lower in other sectors. Electrification and hydrogen use in the energy-intensive industries can be seen as complimentary pathways rather than one excluding the other, but the optimal technology mix requires extensive system analyses.



Geopolitical dependencies

The EU's import and external (over)dependencies have left Europe vulnerable to market instabilities and geopolitical risks and blackmail as Germany's excessive gas pipeline dependence until 2022 has been highlighted as a historical lesson. In the new world of a geopolitical 'Zeitenwende' (change of an era) and fragmented global markets with increasing worldwide supply chain disruptions, resilience of supply security and stable imports will play a much more important role in the future.

Numerous new studies and articles on the EU's hydrogen import policies have focused on hydrogen production and export prices, the export capacities as well as the geopolitical risks of potential hydrogen export countries of the MENA-region, Africa, and Latin America. But the worldwide systemic geoeconomic and geopolitical changes of nationalistic as well as protectionist policies of the major powers (China, Russia, India, the U.S., etc.) - leading to fragmented global markets, trade conflicts, and geopolitical priorities and trump multilateral policies and organizations - have hardly been addressed or even integrated as systemic factors in the analysis of the EU's potential rising hydrogen import dependency.

These geoeconomic and geopolitical changes since 2020 have wide-ranging impacts on balancing the three objectives of the 'energy triangle': cost- and industrial competitiveness, as well as resilience of energy (supply) security (including 're-shoring' and 'friend-shoring' of the EU's critical supply chains), will play a much more prominent role in the political discussions in the forthcoming years as the new European Commission and member states, as well as political fractions in the new European Parliament, have already announced. Hence, to reduce the geopolitical risks, the potential import depend-

ency from outside Europe needs to be reduced alongside prioritizing the use of hydrogen in the hard-to-abate energy-intensive industries where no cost-efficient technological alternatives are available.

The forthcoming oversupply of LNG could not only slow down the expansion of green hydrogen for at least some years. If an even less-costly blue hydrogen production would expand faster globally than previously anticipated, it will be detrimental to the worldwide climate change even by using CCS or CCUS as methane gas may increase along its entire supply chain. For geopolitics, it has the additional impact that Europe would remain largely dependent on the same exporters as for its LNG imports and increase its dependency on those exporting countries in the mid-term transition period. In comparison, green hydrogen imports can be much more diversified for the EU member states in the mid- and longer period. But in the short- and medium-term, they remain the most expensive import option, contradicting the EU's new focus on its future industrial competitiveness.

Globally, the future shipping of hydrogen and its derivatives will further increase the international shipping and expansion of maritime transports via unstable SLOCs and Choke Points. Hydrogen partnerships and long-term contracts with African and Latin-American countries are an important and useful instrument of political support and necessary to diversify the EU's future import dependencies. However, neither of these instruments provides any real guarantee, especially in times of crisis and rapidly changing framework conditions. Negotiated and agreed bilateral hydrogen partnerships for joint (production) H₂ projects should not be equalized automatically with H₂ imports to

Europe. Most of these proclaimed and negotiated hydrogen partnerships cannot be translated directly into stable hydrogen exports from non-European partner countries as, ultimately, the private energy industry must sign commercial H₂ contracts based on commerciality and profitability.

The EU's future green hydrogen import demand and supply security depend not just on its own production and electrolyser capacities, but also on whether sufficient hydrogen volumes will be available in the exporting countries – and therefore on the worldwide global balance between supply and demand. The newly forecasted decreased global and EU hydrogen demand also offers a perspective of a reduced hydrogen import demand from outside Europe (even down to just 10-15 % of its overall demand in a best-case scenario according to new studies) – primarily from Norway as the EU's main gas supplier today and its closest energy partner (as a stable democracy and market economy) in addition to the European supplies of the EU-Scandinavian countries Denmark, Sweden, and Finland. A lower hydrogen import demand from abroad will also reduce potential geopolitical risks from unstable non-European countries.

However, the creation of a hydrogen economy and huge electrolysis capacities demands a further increase in the mining, refining, and processing of critical raw materials (CRMs). In addition, the EU may become ever more dependent on Chinese electrolysis technologies (controlling 40% of the global market) and manufacturing capacities (controlling even 60% of the global market). Hence, the EU needs to rebalance its future imports of Chinese extracted and refined CRMs as well as cheaper green technologies for faster decarboni-

zation and green energy transition with the need for an enhanced resilience of a stable supply of hydrogen and electrolysis technologies as well as a domestic production capacity.

Thereby, the newly emerging geopolitical risks, resulting from its hydrogen import dependency, must also be integrated in a new holistic risk analysis of the EU's overall rising geopolitical dependencies: development of green technologies and industries are inevitably linked with CRMs and global green technology supply chains – often dominated and controlled by China. Despite the introduction of the EU's 'Critical Raw Materials Act' in 2024, its targets for 2030 (such as the production of CRMs in Europe like rare earths) appear equally unrealistic to achieve by 2030. Alongside of the geopolitical risks due to rising unstable hydrogen imports, the global dependence on China's market dominance in the worldwide electrolysis capacities and technologies could further increase the EU's geoeconomic and geopolitical dependencies on China. The EU also needs to consider the combined geopolitical risks of import dependencies on China as the result of the electrification, digitalization, and the expansion of green hydrogen and electrolysis technologies.

Up to now, the worldwide systemic geoeconomic and geopolitical changes of nationalistic as well as protectionist policies of the major powers (China, Russia, India, the U.S., etc.), leading to fragmented global markets, trade conflicts, and geopolitical priorities and trump multilateral policies and organizations, have been hardly addressed or even integrated as systemic factors up to now in academic studies on the EU's future hydrogen import policies.

Political Recommendations

Written by Dr. Frank Umbach (CASSIS)

In the light of the analysis and the summary of the results of our study, the following political recommendations are made:



Dr. Frank Umbach (CASSIS)

- Redefining the 'energy triangle': The EU needs to rebalance and redefine its ambitious energy and climate agenda with industrial competitiveness, cost efficiency, and resilience of supply chains in an era of new financial constraints and geo-economic and geopolitical changes – including for its future hydrogen import strategy.
- Coping with increasing financial constraints: Giving the mounting financial constraints on the EU side and its member states (incl. Germany as the largest financial contributor to the EU budget) and the need for redirecting funds to security and defence sectors, the 'European Green Deal' and other energy programmes will face increasing difficulties to subsidize the EU's ambitious energy and climate policies as in the past. Therefore, the EU needs to define clear priorities for its funding policies in its ambitious energy and climate policies. For its hydrogen development, it means to focus more than ever on the hard-to-abate sectors such as the energy-intensive industry (steel, chemical, refineries, etc.) and long- distance aviation, where no alternative cost-efficient technological options are available.

- Consequence of new European and global geoeconomic changes in fragmented global markets with rising geopolitical rivalries: The EU needs to build up more European green hydrogen production and electrolysis capacity and decrease its import demand as part of a resilient energy security in contrast to the old world of liberalised global markets, when the old assumption of "it's the economy, stupid" was still prevailing in Western democracies, governments, and industries.
- EU hydrogen import route diversification: Regarding the potential hydrogen import routes, the EU needs to focus on the northern import routes from the Scandinavian countries (incl. Norway as the EU's traditional main energy partner as a stable democracy and a proven market economy). The remaining imports via unstable Sea Lanes of Communications (SLOCs) and Choke Points need to be diversified as much as possible between exporting regions and countries. Ukraine can also become an important hydrogen supplier for Europe as indicated in the EU's and Germany's hydrogen strategies of 2020. But the pre-condition is that the Ukraine war will end soon with a sustainable peaceful solution accepted by all sides.
- Potential US-Hydrogen Imports: As the U.S. is already the largest LNG supplier for Europe, it could also become an important exporter of hydrogen for Europe as the U.S. was projected to become the world's largest hydrogen producer and supplier by 2030. But as a trade conflict between the U.S. and the EU cannot be excluded in the forthcoming years, the new U.S. Trump government could even be tempted to use its potential hydrogen exports (and Europe's LNG import dependency) from the U.S. as a geoeconomic weapon in a trade conflict with the EU (albeit a weaponization of US energy exports by private companies cannot be equalized with Russia's and its state-owned companies). As part of its energy security strategy, the EU therefore needs to ensure that it does not become too dependent on its potential future hydrogen imports (as well as its present LNG imports) from the U.S. or any other potential exporter (who could weaponize its exports) and rather diversify both imports.
- Import Diversification as an Overall Guiding Principle: Diversification of the EU's imports needs to be the overall guiding principle, regardless of who is the hydrogen supplier. Even the present high gas import dependence from and a potential future hydrogen import dependence on Norway can be shortsighted and counterproductive, if Russia, for instance, would sabotage the critical Norwegian offshore and onshore energy infrastructures as well as subsea electricity and internet cables as NATO, EU, and independent security experts have warned.

1. Introduction

Written by Dr. Frank Umbach (CASSIS)

Hydrogen is viewed as an indispensable energy carrier in climate-neutrality pathways for the EU, expected to provide storage for surplus renewable electricity and high-density energy for hard-to-electrify applications in sectors like industry and mobility. Because of such projections, the EU and many member states have developed hydrogen strategies to foster the adoption of hydrogen as a fuel since 2020.

At the same time, the geopolitical situation for the EU has dramatically changed over the past years, leading to a significant reappraisal of policy priorities in many fields, especially with respect to protecting and building a globally competitive industrial base in Europe and growing European military capabilities in the short- and medium-term. Russia's invasion of Ukraine in February 2022 has highlighted the EU's and Germany's overdependence on Russian gas pipeline imports and their collective strategic miscalculations in its supposedly bilateral 'energy partnership' with Russia. The Kremlin's invasion has shattered long-standing myths and narratives in Germany and Europe that 'change through trade' and mutual (symmetric) interdependence will lead to a civil society and a democratic Russia as well as that foreign, energy, and trade policies can be separated from the nature of the (autocratic-dictatorial) regime.

Moreover, critical supply chains (as highlighted by the global pandemic since 2020) have become fragmented due to an increasing geoeconomic and geopolitical competition and conflict between Western democracies and autocratic-dictatorial regimes. The Western-defined 'rule-based world order' and international law is increasingly challenged by Russia, China, and their "axis of evil" (Iran, North Korea, Yemen, etc.) as well as some countries of the Global South with an opposing geoeconomic and geopolitical agenda for international relations. The EU's overdependence on CRMs and green technology imports from China has led to new EU-policies of 'de-risking-' and 're-shoring' of industrial capacities back to Europe to enhance its resilience of critical supply chains in the light of a deteriorating bilateral relationship with China.

Russia's military invasion of Ukraine has also been used by the EU to fasten its ambitious decarbonization for a green energy transition in the mid-term perspective by 2030/35 and net-zero carbon emissions by 2050 at the latest. The European Commission had already published in July 2020 its EU hydrogen strategy (European Commission 2020) after the EU agreed on its newly codified target of reducing the EU-27 CO₂ emissions by 50-55% by 2030. As 75% of the EU's greenhouse emissions result from the energy system, the European Commission has considered hydrogen as a central element of its newly released 'Energy System



Integration Strategy' and the 'European Green Energy Deal' (EGD) of December 2019 (Umbach 2020a and b).

Its hydrogen strategy has been designed using a phased approach to increase the hydrogen share by 2050. Already in 2020, the European Commission (and Germany with its most ambitious hydrogen strategy within the EU) realized that they would become heavily import-dependent for their future hydrogen demand and supply.

As part of its 'REPowerEU-Plan' for reducing the EU's dependence on Russian fossil fuels and accelerating its green energy transition the EU has increased its green hydrogen import and production goal to accelerate its green energy transition (European Commission 2020b). In 2023, the European Commission proposed a 'Net-Zero Industry Act' to scale up the manufacturing of green technologies in the EU. It included electrolysers needed for producing green hydrogen based on renewable energy sources (RES) (European Commission 2023a).

As the EU's largest economy and by declaring becoming the world's leading supplier of state-of-the-art hydrogen technology, Germany's national hydrogen strategy of June 2020 (Federal Government 2020) and the implementation of its targets which includes investment in the national market and hydrogen projects outside the EU is a pre-condition for implementing the EU's hydrogen strategy and its targets. Germany's Federal Government presented an update of its hydrogen strategy of 2020 in 2023 (NHS 2023; BMW Government 2023). The Update of the National Hydrogen Strategy (NHS 2023) has doubled the national target for the expansion of electrolyser capacity from 5 to 10 GW by 2030. It has emphasized a focus on imports from Denmark and Norway, while also securing imports of 'blue hydrogen' from natural gas using Carbon,

Capture and Storage (CCS) technology to mitigate related emissions. Furthermore, the NHS 2023 has paid attention to its development of hydrogen storage which will integrate the conversion of existing gas storage facilities and the construction of new storage capacity for the future power system that is based on volatile renewable energy sources.

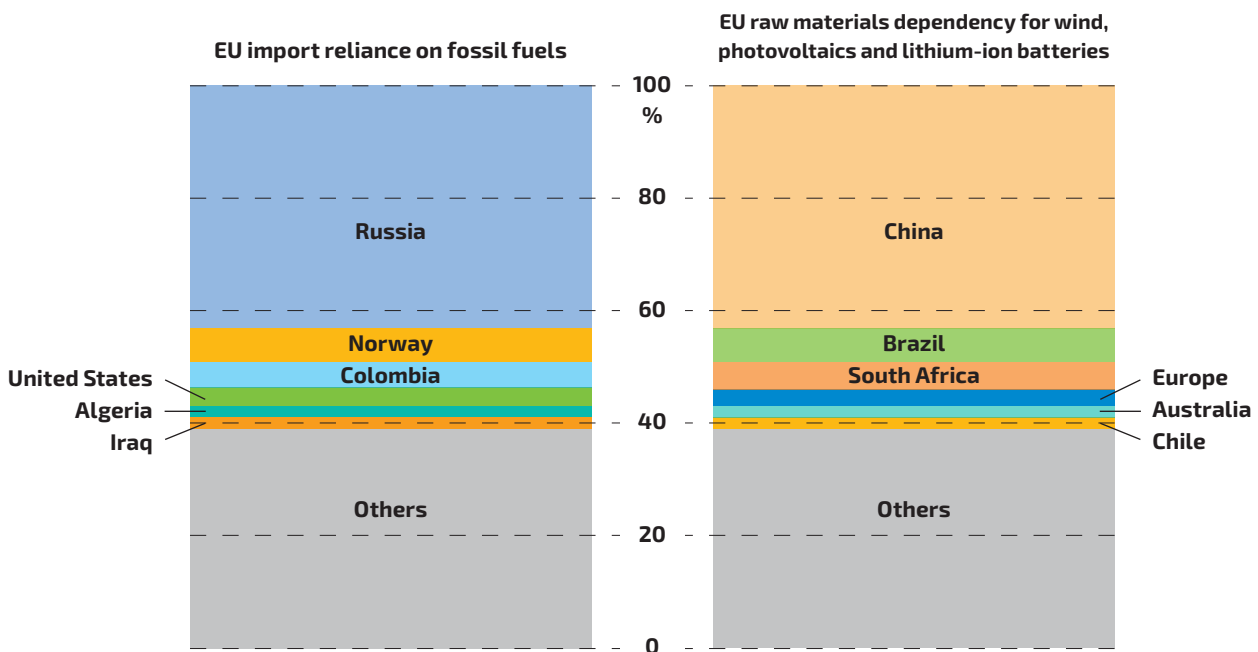
The government seeks to overcome Germany's "excessive dependence" on energy imports from individual countries (particularly Russia), to ensure sufficient availability of hydrogen and its derivatives as well as to fasten the national decarbonization. In this context, the Federal Government has also published a 'Hydrogen Import Strategy' in 2023 as it expects that Germany's future hydrogen demand might only be covered by 30-50% of domestic production, but 50-70% of the updated total demand of 95-130 TWh by 2030 need to be imported primarily from outside Europe (BMW 2024a). At a time of fragmented global markets, disrupted supply chains and a growing geopolitical rivalry with autocratic-dictatorial regimes, Europe may just replace its previous and present fossil fuel import dependence with growing imports of renewable energy resources, critical raw materials, green energy technologies (all mostly from China), and hydrogen primarily from more unstable countries outside Europe (see [Figure 1](#)).

Geopolitics does not end with the end of fossil fuels. Thus, a high hydrogen import dependence on potentially more unstable and unreliable non-European countries might significantly increase the geopolitical risks of disruption of Europe's future import supply chains of energy as well as technologies and threaten its future energy security. The new U.S. Trump presidency has also raised new geoeconomic and geopolitical concerns about the future world order, global stability and transatlantic economic as well as security relations.

Furthermore, since the beginning of 2024, representatives of the industry, independent experts, and organizations have warned that the EU's and Germany's hydrogen strategies and their targets by 2030 are no longer realistic and sustainable (European Court of Auditors 2024; Hancock 2024b) if the EU and the member states governments are not

willing to support and subsidize much more light-house projects and create adequate regulatory conditions for a faster buildup of hydrogen projects and closing the gap between the agreed targets by 2030 and the real progress on this way (see also [Chapter 2.2](#) in more detail).

Figure 1: Replacing fossil fuel with raw material import dependencies



Source: GIS/Financial Times (2021)

Against this background, the study will analyze the changing geoeconomic and geopolitical conditions for the EU's future hydrogen supply security. The future geopolitical risks of a supposedly high-import dependence on hydrogen depend on Europe's future hydrogen demand and related import demand. Therefore, the study will first ([Chapter 2](#)) critically assess the present status quo of the hydrogen policies of the EU and its member states and address the gap between the agreed targets by 2030 and the progress that has been made up to now. The [third chapter](#) on technology and economy will assess in more detail hydrogen provision and application in the (energy-intensive and



hard-to-abate) industry, any reconsiderations of the hydrogen application range due to new conditions, the supply-demand balance, the costs of hydrogen imports, and the implications on hydrogen supply for the industry and resulting infrastructure needs (incl. by considering also other cost-efficient technological options such as electrification). The [fourth chapter](#) on dependency will analyze the EU's future geopolitical import risks and challenges as well as new hydrogen partnerships with non-European countries, the new geopolitical landscape and fragmented global markets. Thereby, it will give an overview of the global hydrogen developments with a focus on green hydrogen versus blue hydrogen (the colors of hydrogen are explained in detail in Table 1), critically review the EU hydrogen import demand, the potential non-European suppliers, the perspectives of cost-competitiveness of maritime transport and concrete geopolitical risks of specific

import routes. [Chapter 5](#) on the European energy transition will review the role of hydrogen for the industry in the decarbonization pathways and highlight the different geopolitical risks of hydrogen imports during the green energy transition in the next years and decades.

The study has greatly benefitted from the three organized expert workshops in Bonn, Berlin, and Brussels in November 2024 and the expertise as well as insights from around 90 experts from think tanks, international organizations, industries, ministries, the European Commission, and other stakeholders as well as members of the German and European parliaments. The workshops were conducted under Chatham House rules. The experts' contributions and responses to our presented preliminary results of the study have enriched our discussions and are included in this report.

Table 1: Colored hydrogen options based on different energy resources

Green Hydrogen:	Produced with electrolysis and renewable electricity usually based on solar and wind.
Blue Hydrogen:	Produced from fossil fuels (mostly from natural gas) in combination with Carbon Capture, Use and Storage (CCUS).
Grey (or Brown) Hydrogen:	Produced from fossil fuels (hard coal, lignite or natural gas).
Turquoise Hydrogen:	Produced by methane pyrolysis with carbon black as a by-product.
Pink Hydrogen:	Produced with electrolysis and electricity from nuclear power plants.
White (or natural) Hydrogen:	Naturally occurring hydrogen in underground deposits.

Source: Dr. Frank Umbach

2. Status quo

Written by Michaele Diehl,
Nada Fadl, and
Dr. Philip Schnaars (EWI)

2.1 Hydrogen Strategies of the EU and its Member States

Developments in targets and key regulations

Hydrogen has various applications across economic sectors, either as a feedstock or as an energy carrier. Its most significant advantage is that it does not emit CO₂ if produced using renewable energy sources, making it a viable option for decarbonizing consumption and power sectors. This makes green hydrogen vital for the EU's goal of achieving carbon neutrality by 2050. However, currently, hydrogen constitutes only a small part of the global and EU's energy mix, with most production still relying on fossil fuels, leading to significant CO₂ emissions. Currently, global CO₂ emissions from producing grey hydrogen are estimated to range between 70 Mt to 100 Mt, about 0.3% of all global CO₂ emissions (European Commission 2020).

The EU's hydrogen strategy was introduced in 2020 with the aim of supporting a ramp-up of the hydrogen economy. It integrates and advances various pre-existing policy actions, addressing the entire value chain and aims for investments into the hydrogen ramp-up of EUR 180-470 bn by 2050. The strategy outlines policy measures in five key areas with the aim of promoting private investment in supply and demand as well as infrastructure for

hydrogen. A goal of 40 GW installed electrolyser capacity in the EU and 40 GW in potential exporting countries is stated (European Commission 2020). Various documents¹ contribute to shaping many of the actions outlined in the EU hydrogen strategy's policy areas, particularly investment and promoting demand and production.

In 2022, the European Hydrogen Bank was launched with the objective to secure investments for renewable hydrogen production. Acting as a financing instrument, the European Hydrogen Bank aims at creating an initial market for renewable hydrogen. Based on a fixed premium in EUR/kg of verified and certified renewable fuel of non-biological origin (RFNBO) hydrogen produced, the funding is provided by the bank. In 2023, the first hydrogen bank auction took place, where EUR 720 m was awarded to seven renewable hydrogen projects with a total capacity of only 1.5 GW (European Commission 2023b). It highlights the gap to meet the EU's target of 40 GW by 2030 (Walstad 2024; Moore 2024). Six out of the seven projects have signed the grant agreement (European Commission 2024d). These projects must produce renewable hydrogen within 5 years otherwise a penalty must be paid. The second auction opened in December 2024 (European Commission 2023b).

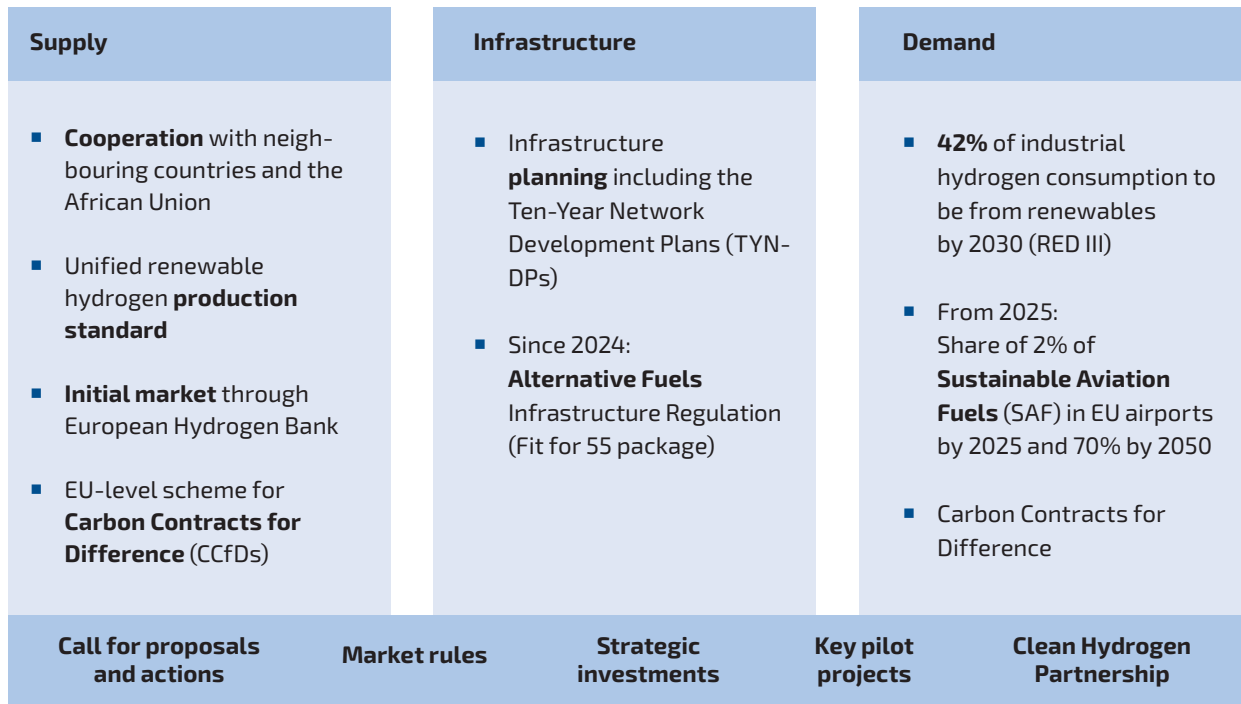
¹ EU Hydrogen Roadmap (Fuel Cells and Hydrogen 2 Joint Undertaking 2019); Renewable Energy Directive (European Commission 2018c); COM (2018) 773 final (European Commission 2018a), COM (2018) 773 (European Commission 2018a), Directive (EU) 2018/410 (European Commission 2018b), Directive (EU) 2019/944 (European Commission 2019), RED III (European Commission 2023c)



On the demand side, the Renewable Energy Directive III (RED III) was adopted as part of the Fit for 55 packages in 2023. Among other aspects, a binding target quota is stated for the use of RFNBOs in the industrial sector by 2030. By 2030, 42% of the hydrogen used in the industry must meet the requirements of the RFNBO and 60% by 2035. RFNBOs are targeted to make up 5.5% of the total energy consumed in transport, with a minimum of 1% specifically from

RFNBOs. Additionally, by 2030, at least 1.2% of the energy used in maritime transport is expected to come from RFNBOs as an indicative goal (European Commission 2023c). The EU has not set targets for the production or usage of blue hydrogen. Furthermore, specific goals regarding the infrastructure such as pipelines and hydrogen storage are not yet set. Figure 2 gives a brief overview of the EU's hydrogen targets and strategies.

Figure 2: EU Hydrogen targets and strategic development



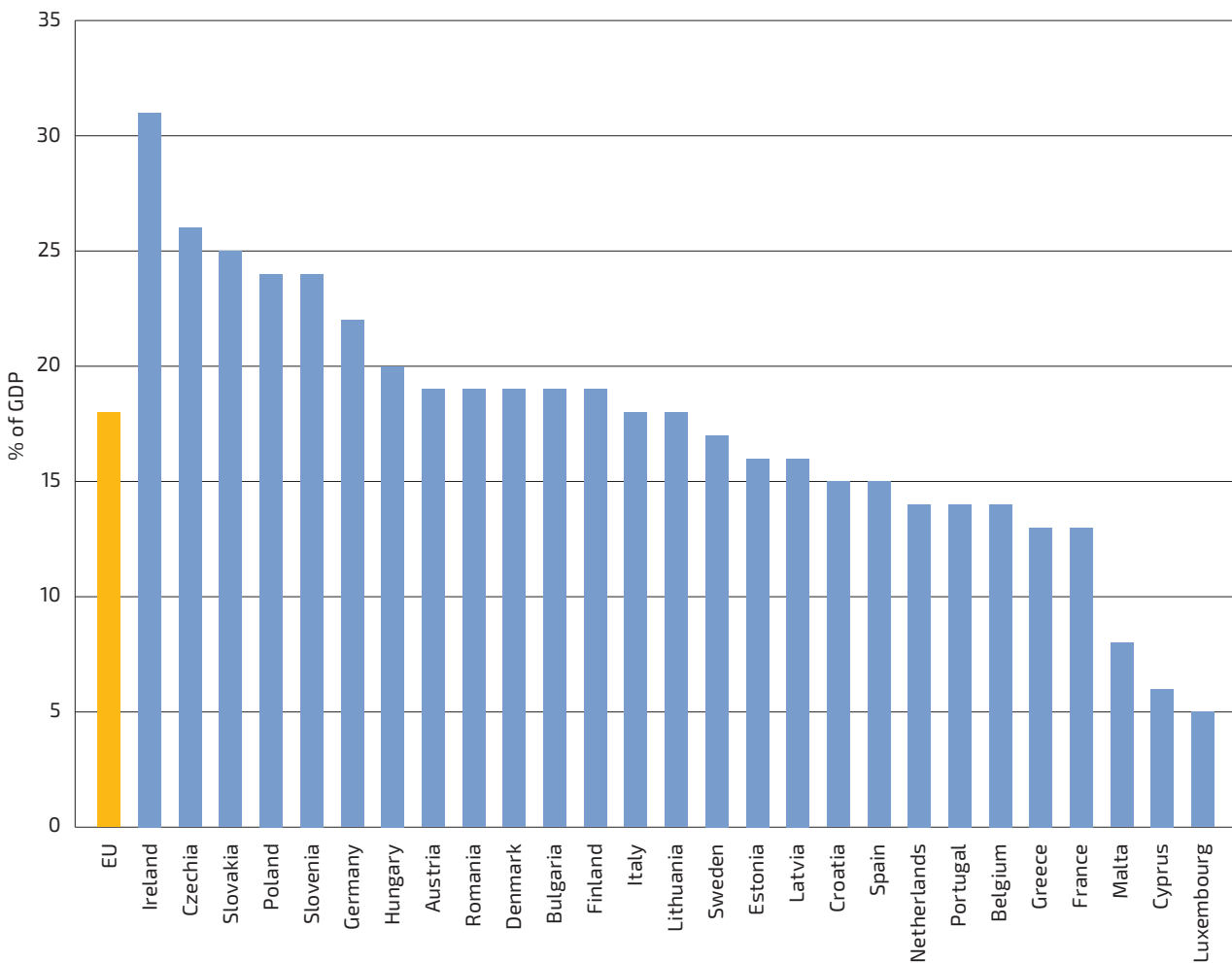
Source: EWI illustration based on European Commission (2020); European Commission (2024b); IEA (2021); European Parliament (2023a)



The industry sector has a significant role in decarbonizing the economy due to high shares in both the gross domestic product (GDP) and the greenhouse gas emissions in the EU. Figure 3 illustrates the gross value added by the industrial sector (excluding construction) as a percentage of GDP for 2023. On average 18% of GDP belongs to the industry sector. Countries such as Germany, Ireland, and Slovenia show a higher share of industrial gross value added compared to the total of the EU, while France

and Spain, among others, demonstrate significantly lower shares. Notably, industrial gross value added accounts for more than 10% of GDP in nearly all EU member states. In 2023, the industry sector (mainly manufacturing) in the EU contributed 21% of the total greenhouse gas emissions (Eurostat 2023). Due to the significant contributions to the national economies and the emissions, the industry sector will be a focus of this report.

Figure 3: Gross value added of the industry sector (except construction) in 2023



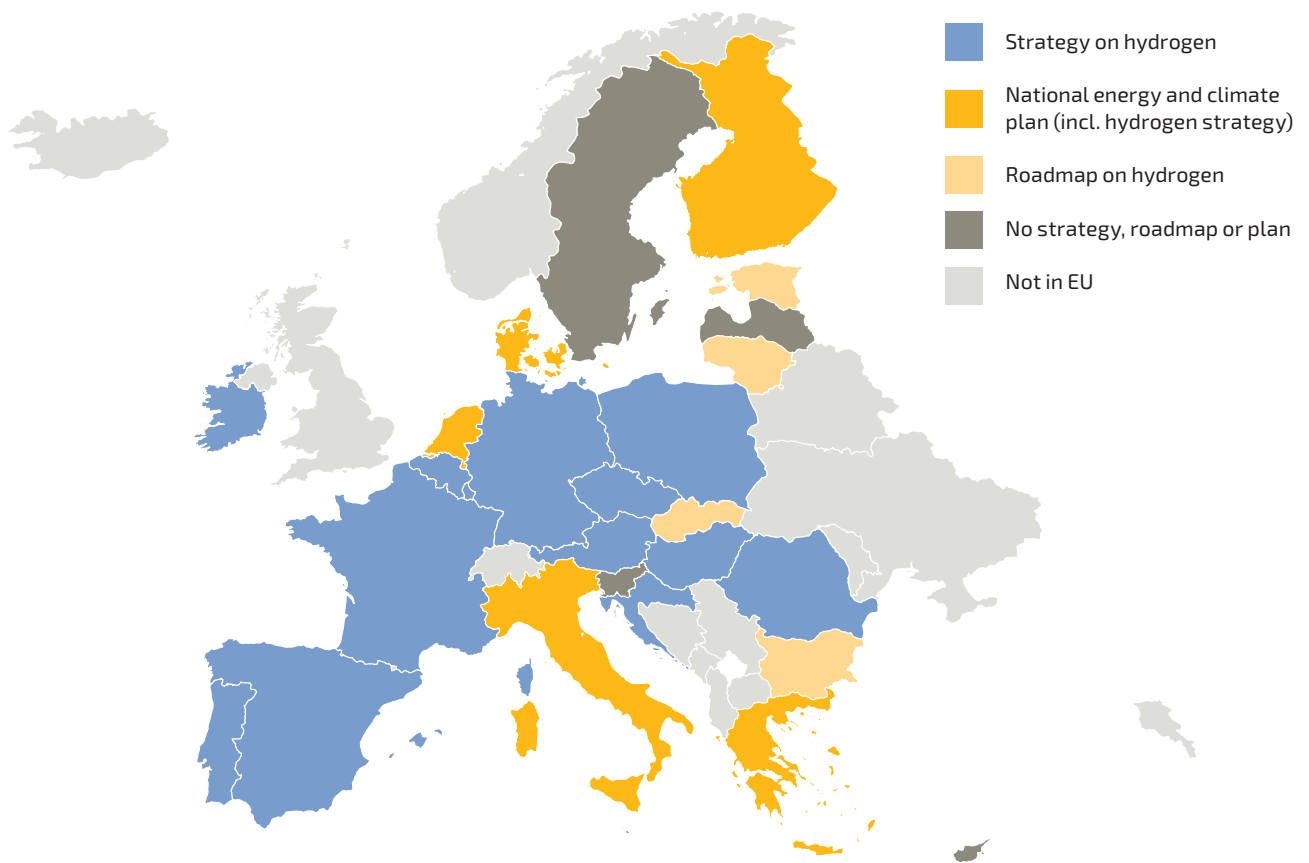
Source: EWI illustration based on Eurostat (2024)

National Hydrogen Strategies and Plans

Achievement of hydrogen targets relies on the realization by the individual member states (European Council 2023; Lambert, Schulte 2021). Therefore, they may develop a strategy on how to reach these targets on their road to climate neutrality. Most of the member states already published hydrogen strategies/roadmaps as a separate document or as part of their National Energy and Climate Plan (NECP) as depicted in Figure 4. The national hydrogen strategies designed by the member states agree on a few common goals. Importantly, these

common goals include (i) reaching climate neutrality between 2040 to 2050, (ii) decarbonizing the industrial sector using renewable hydrogen, (iii) development of necessary hydrogen infrastructure, as well as (iv) efficient and focused use of hydrogen to ensure supply security. Targets and plans are more clearly defined for the production and supply of hydrogen. Policies to support its adoption in end-use sectors, such as industry, appear to be less developed and imprecise. Further information on the hydrogen plans and strategies of the member states can be found in the Appendix.

Figure 4: Hydrogen strategies progress of EU member states as of October 2024



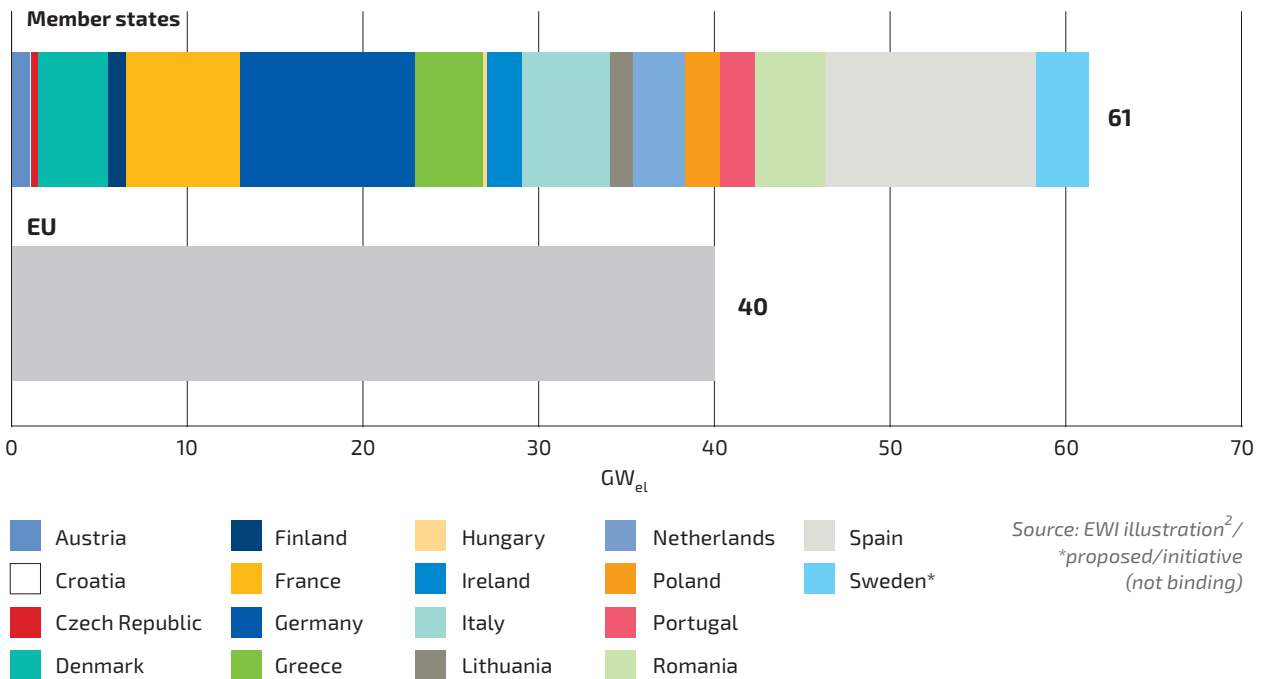
Source: EWI illustration² /*proposed/initiative (not binding)
 © GeoNames, Microsoft, Open Places, OpenStreetMap, TomTom

Figure 5 shows a comparison of the planned electrolyser capacity of the EU member states and the overall planned capacity by the EU². The EU member states targets aim to reach a total of 61 GW by 2030, compared to 40 GW as an EU target. The target supply goal is defined by most countries in terms of GW electrolysis. The highest goals can be observed in Spain (12 GW), Germany (10 GW), and France (6.5 GW). Some EU member states do not have a capacity goal included in their hydrogen development plan while Belgium, for example, states a goal of being an import and transit hub of hydrogen. In principle, the amount of planned electrolyser capacity shows a positive indication for achieving the EU hydrogen supply target. Although these individual goals exceed the common goal by far, current development shows a slow uprise in electrolysers and needs a fast uptake to potentially reach the goal

otherwise they might prove to be unattainable. Additionally, the EU aims at producing 10 Mt of hydrogen by 2030 within the EU, though none of the 24 member states have set specific targets for hydrogen production in their national strategies (Hancock 2024a). Depending on the utilization, the EU target may indicate a higher capacity than 40 GW and might therefore be a more ambitious goal to be achieved.

However, comparing current installed electrolysis capacity to targets indicates a slow uptake in electrolyser capacity. For instance, in 2024 0.2 GW electrolyser capacity are installed in the EU and an additional 2 GW have reached FID status (IEA 2024a; European Union Agency for the Cooperation of Energy Regulators 2024). This is far from the targeted goal of an installed capacity of 6 GW for 2024 by the EU (European Commission 2020).

Figure 5: Targets for installed electrolysis capacity by 2030



2 Belgian Federal Public Service Economy (2022); Federal Ministry for Climate Action, Environment, Energy, Mobility, Innovation and Technology (2022); BMWK (2023a); Ministry of Innovation and Growth (2023); Danish Energy Agency (2023); Department of the Environment, Climate and Communication (2023); DGEG (2020); European Commission (2022a); Fossil Free Sweden (2021); Gandiglio & Marocco (2024); Government of Hungary (2021); IEA (2021); IEA (2022a); Organisation for Economic Co-operation and Development (2023); IEA (2023a); Ministry of Climate and Energy (2024); Ministry of Climate and Environment (2020); Ministry of Climate and the Ministry of Economic Affairs and Communications of the Republic of Estonia (2023); Ministry for Ecological Transition and Demographic Challenge. (2020b); Ministry of Economic Affairs and Employment (2024); Ministry of Economic Affairs (2019); Ministry of Economic Development (2020); Ministry of Economy and Sustainable Development (2022); Ministry of Economy (2023); Ministry of Energy (2020); Ministry of Energy and Spatial Planning (2021); Ministry of Energy (2023); Minister of Energy of the Republic of Lithuania (2024); Ministry of Environment and Energy (2023); Ministry of Industry and Trade (2024); Ministry for the Environment, Energy, and Regeneration of the Grand Harbour (2023)

Another key indicator of how committed member states are to achieving their targets is the level of their announced planned investments. Almost half of the member states have planned and allocated public funds to accelerate the hydrogen ramp-up. Portugal, France, and Germany planned the highest investments in relative terms as percentage of their GDP, while Germany, France, and Italy planned the highest investments in absolute terms³. The realization of investments is, however, not ensured. Nevertheless, the amount of planned investment points in the right direction and might support a hydrogen market ramp-up in some of the EU-countries, while it is not yet clear how countries with no or low targets will evolve.

Hydrogen Infrastructure Development

Developing a hydrogen infrastructure is critical for linking production hubs with demand regions.

Additionally, storage facilities are necessary to efficiently manage supply fluctuations and disruptions. The official European hydrogen strategy does not mention specific infrastructure goals. To establish Pan-European hydrogen infrastructure projects, a group of TSOs cooperate to form the European Hydrogen Backbone (EHB) initiative, which currently consists of 33 network operators in Europe (European Hydrogen Backbone 2023). Additionally, member states have begun appointing hydrogen network operators to join the European Network of Network Operators for Hydrogen (ENNOH) and take part in the planning and development of the European hydrogen network from 2025 onwards (IEA 2024a). Table 2 depicts current important developments in European hydrogen infrastructure. While EU-wide plans exist based on the private initiative of the EHB, only three member states show key developments initiated by the governments. As a private initiative the EHB is not binding and therefore does not legally ensure the hydrogen infrastructure expansion.

Table 2: Key developments in hydrogen infrastructure

Country	Key developments
EU	<ul style="list-style-type: none"> Private initiative for a Pan-European hydrogen pipeline network to be accomplished by 2030 covering 31,000 km Development of 31 projects on onshore and offshore hydrogen pipelines, consisting of repurposed and new hydrogen pipelines By 2027-2029, begin of operation of 2,700 km of new and repurposed hydrogen transmission and distribution pipelines
Denmark	<ul style="list-style-type: none"> Project of Common Interest (PCI): Danish Backbone West The interconnector between Germany and Denmark got postponed by three years (2028 to 2031)
Germany	<ul style="list-style-type: none"> Hydrogen core network in Germany is estimated to be accomplished by 2032, extensions are possible until 2037. The network covers 9,040 km PCI: Aquaductus, H₂ercules, HyPipeBavaria Hyperlink 3, Flow – making hydrogen happen
Netherlands	<ul style="list-style-type: none"> Initiated construction of 1,200 km of the hydrogen backbone to be partially operational by 2025

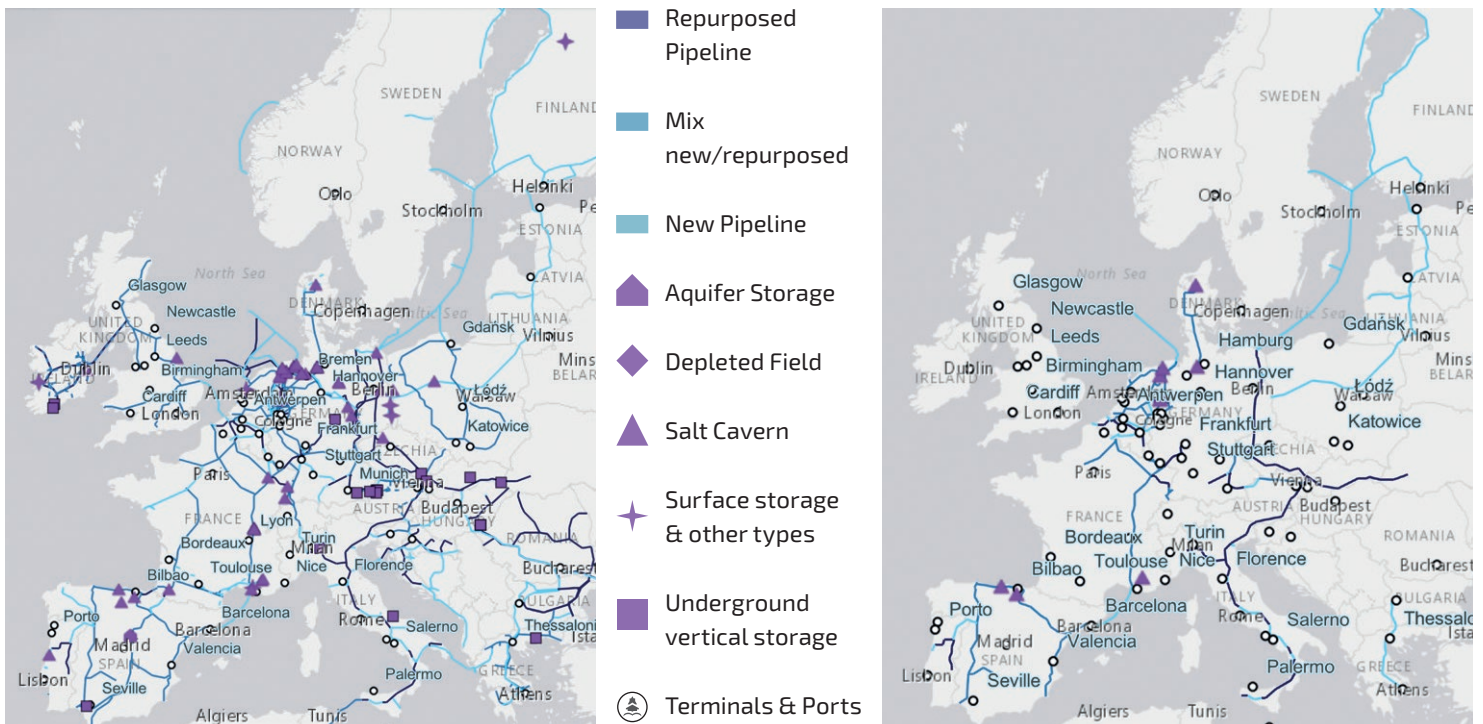
Source: European Commission (2024a); IEA (2024a); European Hydrogen Backbone (2024)

3 Based on IEA (2021); IEA (2022a); IEA (2023a); Federal Ministry for Climate Action, Environment, Energy, Mobility, Innovation and Technology (2022); European Commission (2022a); Belgian Federal Public Service Economy (2022); Ministry of Economy and Sustainable Development (2022); Danish Energy Agency (2023); Organisation for Economic Co-operation and Development (2023); Ministry of Economic Affairs and Employment (2024); Gandiglio & Marocco (2024); Baringa (2022); Ministry of Economy (2023); Minister of Energy of the Republic of Lithuania (2024); Ministry for Ecological Transition and the Demographic Challenge (2024)

A share of the projects mentioned in [Table 2](#) have PCI status (European Hydrogen Backbone 2024). Projects of Common Interest (PCIs) are key cross-border infrastructure projects that link the energy systems of EU countries. They are considered essential for completing the European internal energy market and for achieving the EU's energy policy objectives, including affordable, secure, and sustainable energy. PCIs can receive funding from the Connecting Europe Facility (CEF), a centralized EU funding instrument aimed at promoting growth, jobs, and competitiveness through targeted infrastructure investment at the European level. This might help to commission projects faster (European Commission 2023d).

Furthermore, Important Projects of Common European Interest (IPCEI) influence the infrastructure development in the EU. IPCEIs are large-scale, cross-border projects that address significant market or systemic failures, contributing substantially to the EU's strategic objectives, such as sustainable growth, competitiveness, and resilience. They are primarily funded by the member states which allows for significant public investment (European Commission 2024a). The IPCEI Hy2Infra includes pipelines, electrolyser and storage projects in seven member states (European Commission 2024e).

Figure 6: The European hydrogen backbone (left) including only PCI projects (right)



Source: ENTSOG (2024)

[Figure 6](#) shows an overview of the EHB plan and progress which shows a widespread hydrogen grid that connects wide parts of Europe. Currently and until 2025, the EHB is in the development phase, which is prior to a Final Investment Decision (pre-FID). This phase is concerned with conducting feasibility and technical studies, approving regulatory framework, and securing demand. The construction and operations phase (post-FID) of the hydrogen network and infrastructure is planned to take place from 2025 to 2030. Only a few projects with Projects of common Interest (PCI) status can currently be observed. However, some member states provide other options in financing a hydrogen grid. One example is the amortization account that is implemented to finance the German core network based on grid fees (BMWK 2023b).

Summary of the EU's hydrogen strategies

Overall efforts to support a hydrogen ramp-up within the EU can be seen not only on EU level but also in the member states themselves. The hydrogen strategies of the EU member states are heterogeneous in ambition and level of detail but mostly include specific targets for the supply side as shown above, while being less precise on desired developments on the demand side. There is also a noticeable lack of detailed planning regarding the infrastructure necessary to support the desired ramp-up on the supply side, which creates

uncertainty about how these targets can be realized in practice. This conclusion is also in line with the European Union Agency for the Cooperation of Energy Regulators (ACER 2024) on their assessment of EU member states targets in terms of varying ambition levels. In addition, the EHB is still prior to Final Investment Decisions (pre-FID), which raises concerns about the (timely) implementation. Furthermore, the EU has not yet conducted a formal review of the progress made by either itself or its member states towards implementing the established hydrogen strategies beyond its current report on the State of Energy Union (European Commission 2024c).

Not only targets and investments play a huge role in the hydrogen ramp-up, but also technological, economic aspects and (geo)political risks are important aspects that should be considered when looking at the realization of the increase in hydrogen supply and demand as well as the achievement of EU goals in this area. As rising demand of hydrogen within the EU will not be fulfilled purely by production within the EU, imports will play a major role to satisfy demand in a carbon-neutral industry. But the future EU hydrogen import demand depends on the overall hydrogen demand and supply and this question depends on whether the agreed targets and strategies for 2030/35 are still realistic or have already become as too ambitious due to worldwide rapidly changing (geo)political, financial and technological factors.

2.2 New Uncertainties and Challenges for the EU's Green Hydrogen Ambitions

Written by Dr. Frank Umbach (CASSIS)

Since the end of 2023, an increasing number of independent experts and international organisations as well as other research institutions have begun to address the increasing gap between the EU's and Germany's declared and agreed hydrogen target and the real progress that has been made up to now in Europe as the following examples highlight:

- The IEA already warned in 2023 that “lagging policy support and rising cost pressures” have put investment for low emissions hydrogen at risk (IEA 2023a; Elissaiou, Simon, Tylor 2023).
- The European Court of Auditors (ECA) criticized in 2024 the lack of “robust analyses” for defining production and import targets totaling 10 Mt of renewable hydrogen by 2030 (and another 10 Mt of imports) in its counterstrategy of blocking off Russian fossil fuels after Moscow's invasion of Ukraine in 2022. That has resulted in overly ambitious targets not founded on existing capacities and a realistic pathway. The ECA report also recognises that the legal framework for the EU's climate policies was adopted too quickly and is far too bureaucratically complex and lengthy for the implementation of European hydrogen legislation. The EU's funding of EUR 20 bn for hydrogen projects through 2027 is scattered among various programmes and too complex and difficult for companies to access those funds. The ECA has called on the Commission to review the overall hydrogen strategy, detailing the role of hydrogen imports and what role it can play in cross-sectoral renewable legislation and the overall decarbonization and European energy transition (European Court of Auditors 2024).
- Former ECB-President Mario Draghi called in his report on “The Future of European Competitiveness” last September 2024 for a new EU industrial strategy to restore price competitiveness and strategic orientation in the short-term future. He has warned of “existential threats and challenges” for the European industries losing their global competitiveness. The strategic report has offered concrete recommendations to overcome the obstacles and problems to innovation, high energy prices, funding needs, regulatory simplification, and the urgent need for digitalisation and defence capacities. The report also recognizes the pivotal role of hydrogen in defining Europe's future competitiveness but has criticized the effectiveness and rationalization of the EU's hydrogen strategy and its legislation, regulation, governance and financial funding to achieve its agreed targets by 2030, lack of sufficient public subsidies and rising costs. But at the same time, the report has also favored electrification and electromobility as a more cost-efficient technological option in other sectors (such as transport and buildings) (Draghi 2024).
- Germany's National Hydrogen Council (NWR), advising the government on its hydrogen policies, warned last June that immediate measures are urgently needed. Otherwise, the national hydrogen targets by 2030 cannot be realized and Germany can lose its international leadership role in hydrogen policies and attractiveness for foreign investments. It could also have impacts for the EU's hydrogen ambitions and targets by 2030 (NWR 2024a). In contrast to the official target of 10 GW hydrogen production capacity by 2030, a total of FIDs can presently only guarantee 1 GW in Germany (EWI 2024a). The German industry still lacks a clear business case for higher private investments to realize both the hydrogen

targets as well as the emission reduction plans by 2030 (NWR 2024a). Therefore, the Council recommends much more public investments and the completion of adequate regulation at a time when the government is facing increasing financial constraints and the need for huge short-term investments for modernizing, digitalizing, and expanding its electricity grid network with EUR 100-300 bn and more than EUR 584 bn within the entire EU by 2030 (Umbach 2023a).

- Furthermore, many EU and German hydrogen projects have been delayed and costs are rising due to regulatory uncertainties, lack of sufficient public subsidies and other rising costs. Our expert workshops have confirmed an alarming gap between the Commission's and the German government's self-perceptions of its defined regulations and the views as well as interpretations of the industry, financing banks, and international investors. The recent postponement of the key Dutch hydrogen pipeline for four years, for instance, has wider implications also for the EU hydrogen policies and targets, including to meet its 2030 climate targets (Martin 2024). Denmark has also delayed its planned cross-border hydrogen pipeline to Germany from the beginning to operate in 2028 to the end of 2031 at the earliest (Paraskova 2024).
- Other new studies have recently concluded that the actual costs of using green hydrogen are projected higher than previously estimated (IEA 2024a). Moreover, production costs are just one factor. Storage and distribution costs make up one-third to half of the total delivered price. They could make hydrogen a "prohibitively expensive abatement strategy across many major sectors," according to a new Harvard study. Hence, future production cost reductions could have only a marginal impact on the overall costs and ultimate market prices (Yee Ong 2024).

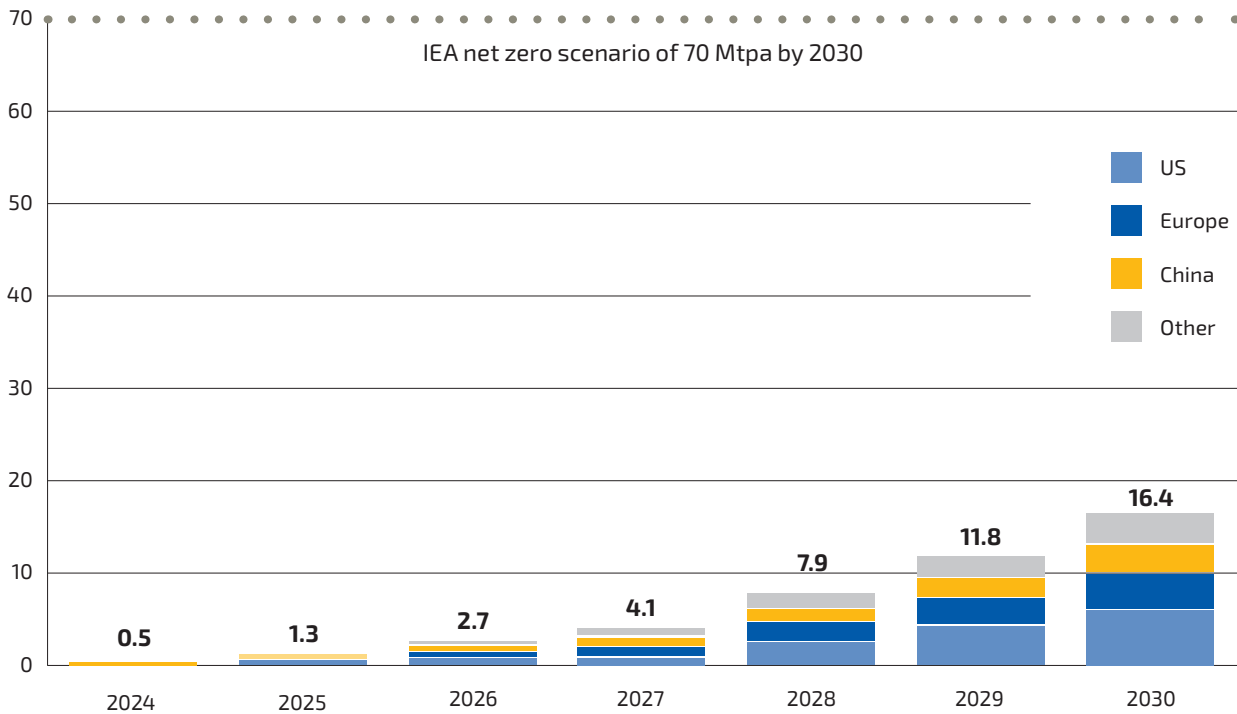
In addition, Bloomberg New Energy Finance (BNEF) and the think tank Energy Transition Commission (ETC) have recently admitted that their previous analyses on the global hydrogen demand have been overestimated. Instead of previously forecasted 500-800 Mt per year by 2050 to reach net-zero, their new analyses have decreased it to just around 390-450 Mt per annum. The consultancy BNEF has recently estimated that the achievable figure for global hydrogen production capacity in 2030 would be around 16 Mt per annum (Mtpa) rather than the previously estimated 70 Mtpa (BNEF 2024a und b; Palladino 2024) (see [Figure 7](#)). According to the IEA in its latest global hydrogen review 2024, government policies and targets for demand will grow just to 11 Mt by 2030 (3 Mt lower than projected in 2023) due to downward revisions for hydrogen use in industry, transport, and power generation (IEA 2024a).

In its newest cost forecast, BNEF has more than tripled its original production cost estimate by 2050 due to higher costs of the electrolyser themselves as well as other cost factors (BNEF 2024b and 2024c). Its forecasted higher costs – falling less than previously estimated – for producing green hydrogen without larger subsidies or incentives will continue to be challenging to decarbonize hard-to-abate sectors. Only green hydrogen in China and India has been considered for becoming cost-competitive.⁴

4 Its newest forecast for green hydrogen falls from the current range of US\$ 3.74 to US\$ 11.70 per kilogram to US\$ 1.60 to US\$ 5.09 per kilogram in 2050 – but it is three times high as the previous one. For comparison: 'grey hydrogen' costs will remain in the range of US\$ 1.11 to US\$ 2.35 per kilogram by 2050.

Figure 7: Hydrogen volumes by 2023 likely to fall well short of target

Forecast low-carbon hydrogen supply (by market and commissioning year, Mtpa)



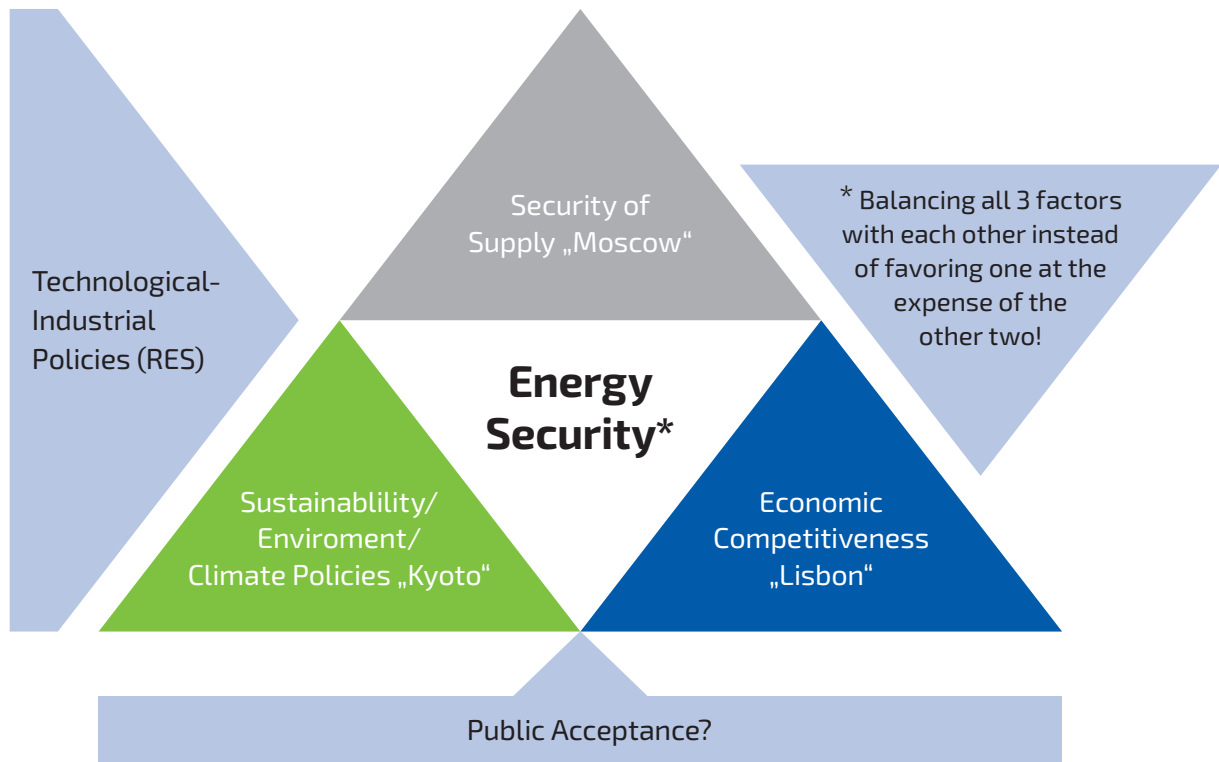
Source: Financial Times/BNEF (2024)

The European Commission and the governments of the EU member states have already redirected funds from its cohesion fund (aimed at reducing economic inequality between EU countries) to security and defence due to Russia's invasion of Ukraine, Russian (nuclear) threats against European NATO countries and the limited military capabilities of the European armed forces. It could shift about a third of the EU's common budget (some EUR 392 bn from 2021-2027) to security and defence (Tamma 2024). As a result, it might also leave much less funds available for the future energy and climate protection policies – including subsidizing its ambitious and costly green hydrogen policies.

Both the new European Commission and European Parliament have also announced that in the forthcoming years cost efficiency and industrial competitiveness will play an ever more important role. Accordingly, the balance of the three major strategic objectives of the 'energy triangle' (or 'energy

trilemma') will also change (see Figure 8). The conflict of the three strategic objectives might also increase such as between industrial competitiveness and cost efficiency and the targets of climate change and the reduction of emissions or between climate protection and energy supply security. But the success of the green energy transition requires finding a balance between the three strategic objectives. In the view of many international energy security experts, the biggest challenge has been seen in maintaining the balance between the three strategic objectives of the 'energy triangle' instead of favoring one at the expense of the other two. Otherwise, neither national nor regional or global energy security can be guaranteed (Umbach 2018; Umbach 2021). The neglect or marginalization of energy supply security requirements and overlooking of the EU's and in particular Germany's gas pipeline dependency on Russia and its potential for 'weaponization' by the Kremlin has confirmed many previous warnings and studies.

Figure 8: The energy triangle



Source: Dr. Frank Umbach

The most important strategies for enhancing energy supply security and its resilience are the diversification of the energy mix, diversification of imports and import routes or import dependencies, but also energy efficiency and other dimensions of energy policies. Renewables can further diversify the energy mix and are often seen as a domestic energy resource, which would reduce the import dependencies of fossil fuels (especially oil and gas). But producers of renewables are also becoming dependent on new import dependencies, notably CRMs (CRMs such as rare earths, lithium, cobalt, and other) and the most important green technologies (incl. electrolyser technologies and capacities). Those strategies for enhancing energy supply security must cope with a supposedly high hydrogen import dependency on unstable exporting countries (such as in the Greater Middle East, Africa, and Latin America). The specific geopolitical risks related to the main EU's import routes will be evaluated in [Chapter 4.4](#).

This section has already provided some important insights into the demand development of the years since the hydrogen strategy of the EU was published and gives some perspectives into the development of the upcoming years. An increase in costs and a decrease in demand could lead to increasing uncertainties about the hydrogen market ramp-up and how EU targets might be reached. Although the war in Ukraine has led to more ambitious targets, on the other side, these uncertainties are one factor that also determines low investments in building up a hydrogen market. Demand-side incentives, technological development and the market penetration with blue hydrogen might be options and are being discussed to increase investment into a hydrogen ramp-up. A closer geoeconomic in-depth look will be necessary to understand the underlying current and future aspects of these factors before analysing the rapidly changing geopolitical landscape both globally as well as in Europe and its impacts on the future EU hydrogen policies.

Take aways from the expert workshops:

Status quo of hydrogen strategies of the EU and its member states

Industry

- Hydrogen targets are set at a challenging level to achieve by 2030
- Instruments or subsidies are needed for a hydrogen market ramp-up
- Insecurities about regulation in the future hold back investment

Academia & Think tanks

- Financing cannot be done completely through tax spending
- Policymakers must have a plan for a demand-driven approach
- Quotas in certain sectors might be a solution
- Although regulation is needed in the future, current regulation is observed as too strict

Politics

- Although the need for realistic hydrogen targets was recognized earlier, the European Commission pushed for overly ambitious goals, leading to potential misalignment with market realities.
- Unrealistic targets, driven by external pressures, undermine the credibility and effectiveness of hydrogen strategies, requiring a pragmatic approach to goal setting.
- This reflects the need for reassessment of feasibility and resource allocation.

New uncertainties and challenges for the EU's green hydrogen ambitions

Industry

- Given the recent cost rise of green hydrogen and electrolyser projects, the future cost competitiveness of green hydrogen (not before 2035 as presently indicated) with blue hydrogen by around 2030 has become unrealistic and may take longer.

Academia & Think tanks

- They have recognized the various challenges of the overambitious (green) hydrogen targets and the need for subsidies. But to which extent the hydrogen projects can be funded in the forthcoming years due to the EU's and Germany's financial constraints, remains an open question.

Politics

- The urgency of hydrogen adoption has been amplified by geopolitical developments, such as the invasion of Ukraine and the geoeconomic conflicts between China and the U.S. as well as the EU, highlighting its necessity despite challenges.

Take aways from the study:

Common goals of member states

- Reach climate neutrality between 2040 and 2050
- Decarbonize industry and transport by using renewable hydrogen
- Develop necessary hydrogen infrastructure
- Strengthen resilience of security of energy supply

Status quo

- Most of the member states of the EU have a hydrogen strategy/ plan including clearly defined targets and plans for the production and supply of hydrogen.
- The observed investment lags behind ambitious targets for green hydrogen which creates uncertainty regarding the extent to which the targets are achievable.

Infrastructure

- Only a few countries (Germany, Netherlands, Denmark) have detailed, federal planning on a domestic hydrogen grid.
- The European Hydrogen Backbone envisions a pan-European hydrogen network by 2030. As a private initiative, the EHB is not binding and therefore does not secure the hydrogen infrastructure expansion.
- The PCI and IPCEI status of projects might have a significant influence on the development of the hydrogen system. The status helps to faster commission projects.

New uncertainties and challenges

- The EU's agreed hydrogen targets for 2030 have become increasingly unrealistic.
- New studies have concluded (1) a lower global and European hydrogen demand than previously projected; (2) rising electrolysis, storage, and distribution costs in the short-term rather than decreasing ones which will decline later and more slowly if no new technological innovation takes place.
- The global market share of European electrolysis capacity is declining. Hence Europe could also become increasingly import dependent on China's cheaper electrolyser capacities. Beijing already controls more than 40% of the global electrolyser markets.

Expert workshops

- Different expert groups during the workshop agreed that hydrogen targets are challenging and might not be reached. A misalignment between ambitious targets and market realities can be seen.
- Uncertainties about future regulations might hinder investment. Whereas current regulations might be too strict and need adjustment.

3. Technology & Economy

Written by Michaele Diehl,
Nada Fadl, and
Dr.-Ing. Ann-Kathrin Klaas (EWI)

Hydrogen plays an important role in the future global energy system, especially in the so-called hard-to-abate applications, where reaching carbon neutrality is difficult. For a shift towards hydrogen applications in these sectors, it is relevant to analyze current progress and future development of the costs of hydrogen and the technological maturity.

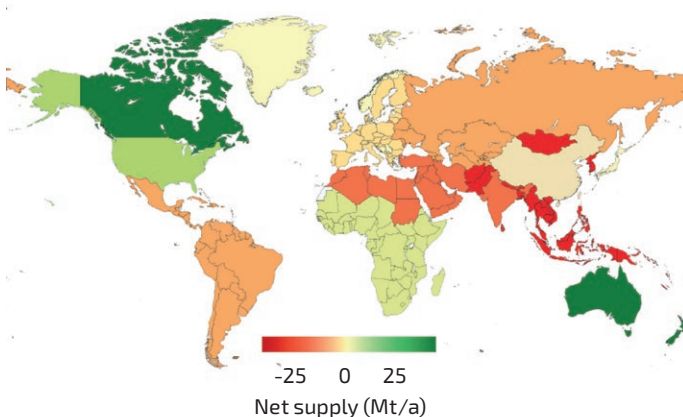
European hydrogen demand may not be fully covered by production within the EU, as it is presented in a recent global analysis by Terlouw et al. (2024). Instead, countries of the EU may rely on the import of hydrogen from destinations that are able to export hydrogen due to their high renewable energy potential. Especially Germany, the Netherlands, Belgium, and Italy might be dependent on cost-competitive green hydrogen imports, other countries within the EU might be able to self-supply their hydrogen demand (Wietschel et al. 2024). The EU

hydrogen strategy has stated to develop an import capacity of 40 GW in countries outside of the EU by 2030 (European Commission 2020).

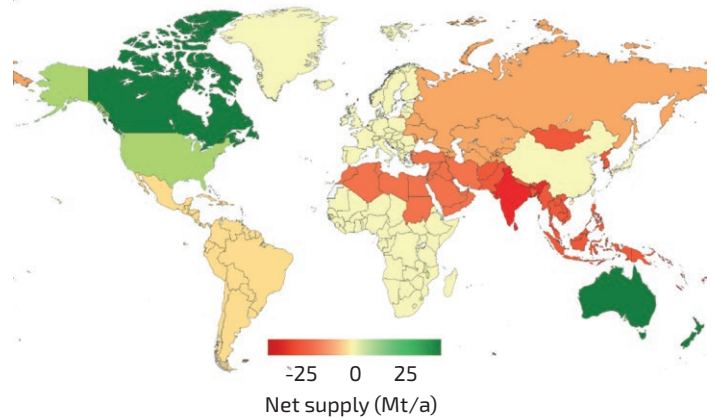
According to Terlouw et al. (2024), a mismatch is likely to emerge between regions that can produce hydrogen cost-effectively and those where demand for hydrogen is concentrated. Under the scenario of large-scale hydrogen deployment across the world, Figure 9 depicts the mismatch between hydrogen demand and supply based on a 2°C and 1.5°C climate scenario. Regions like North America, Australia, and Africa demonstrate an oversupply of hydrogen. By contrast, Europe and the Middle East may experience an undersupply of hydrogen. These results may pose a challenge, as EU policymakers are planning to expand trade with countries like Algeria, Morocco, Egypt, and Tunisia. However, these countries may struggle to produce enough hydrogen to decarbonize their own industries while also exporting surplus volumes to Europe. It is therefore necessary to observe how supply costs and potential from a variety of import countries might develop and what causes a rise in demand.

Figure 9: Global hydrogen net supply

H₂ under- and oversupply in 2°C (REMIND)



H₂ under- and oversupply in 1.5°C (REMIND)



Source: EWI illustration based on Terlouw et al. (2024) in line with the CC BY 4.0 License



Michaele Diehl (EWI)



Nada Fadl (EWI)



Dr. Ann-Kathrin Klaas (EWI)

3.1 Technology readiness level of hydrogen supply

Hydrogen may see an uprise in demand and supply in all parts of the world – but rather in the mid- and long-term future. The technological readiness of the different technologies serves as an indicator for the maturity of the technology, and therefore also for future development, investment, and deployment. Technology readiness levels are defined and applied by various institutions. The IEA defines eleven levels, starting from an initial idea to a mature technology (Figure 10). A commercial operation of applications starts at TRL 9, while before that, applications are still in the prototype and demonstration phase.

Green hydrogen may be produced via a Polymer electrolyte membrane electrolyser (PEM), Solid oxide electrolyser cell (SOEC) or an Alkaline electrolyser. The production of green hydrogen is assigned a TRL of 8–9 and is therefore considered to be in the demonstration to early adoption phase, as seen in Figure 10. Blue hydrogen is considered an option to facilitate the implementation of a hydrogen economy regarding infrastructure and demand by various stakeholders. Blue hydrogen, also known as low-carbon hydrogen, is produced with a steam methane reforming process using carbon capture to reduce or eliminate greenhouse gas emissions (refer to Table 1). However, blue hydrogen production also still faces technological risks. According to the IEA, production via steam methane reforming (SMR) with a CO₂ capture rate of 90% is still at a TRL of 5–6 and therefore not available on a large scale. CO₂

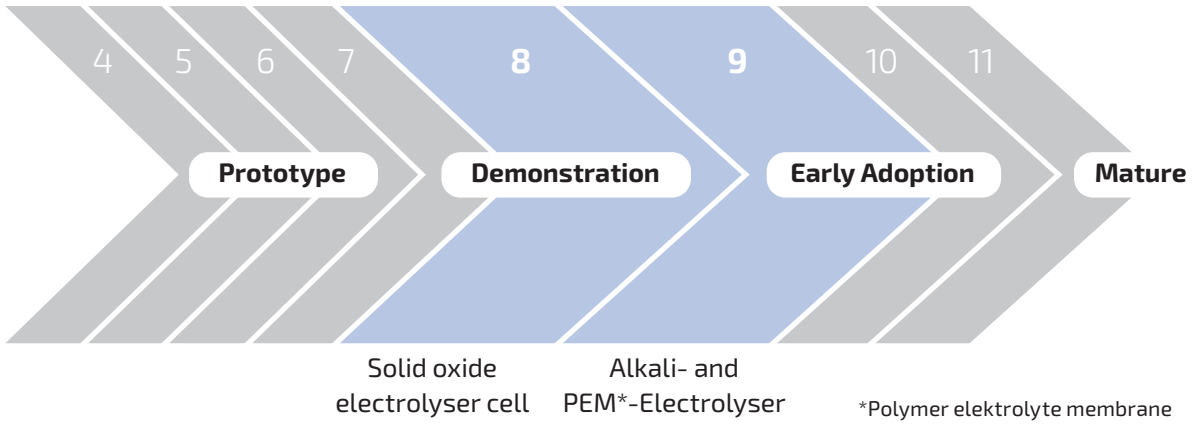
storage shows a TRL of 7–9, CO₂ transport via pipeline of 10 and via ship of 6–7 (IEA 2024b).

Hydrogen can be transported via pipeline or via ship. Via ship it can either be transported as liquid hydrogen (LH₂), liquid organic hydrogen carrier (LOHC) or ammonia. The technology readiness level (TRL) of the transport methods for liquid hydrogen is still relatively low at 7, while it has reached a mature status of 10 to 11 for ammonia and LOHC. Pipeline transportation shows levels of 8 (repurposed) and 9 (new) (IEA 2024b).

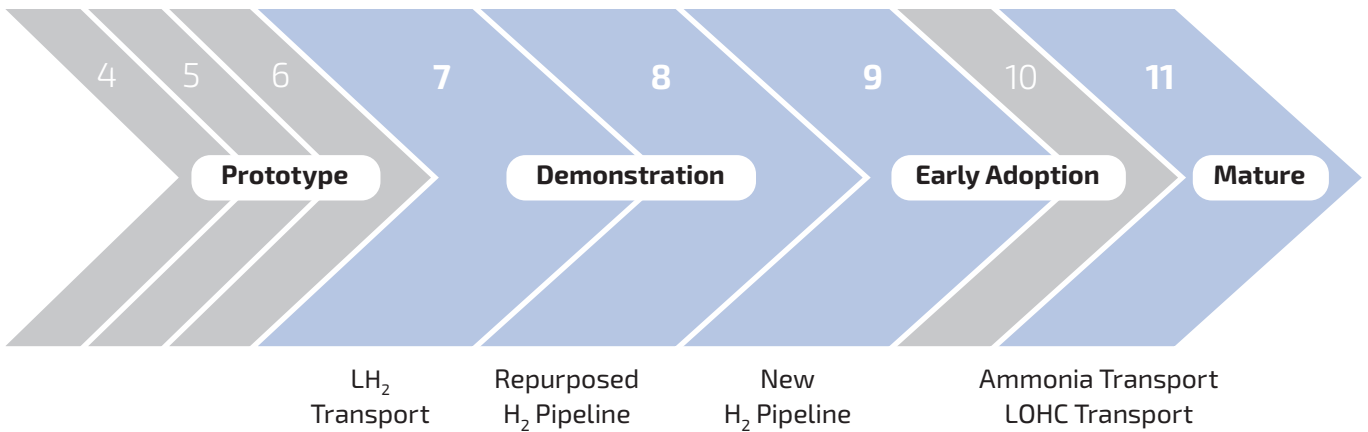
A high share of green or blue hydrogen production technologies and hydrogen transportation shows a TRL in the Demonstration or Early Adoption phase. This means a proven prototype or commercial demonstration, but the processes need evolutionary improvement and further integration efforts to become or stay competitive. This affects their readiness for market introduction and might also lead to lower investments as low TRL technologies are perceived as risky due to the uncertainty. Technologies at low TRLs are not yet viable for large-scale deployment, which is essential to meeting ambitious hydrogen production and consumption targets. Furthermore, government support such as subsidies or regulatory frameworks might be necessary to advance towards commercialization. Therefore, the observed technology readiness level might potentially withhold the overall hydrogen market ramp-up in the short and medium term.

Figure 10: Technology readiness level of hydrogen production and transport according to the IEA

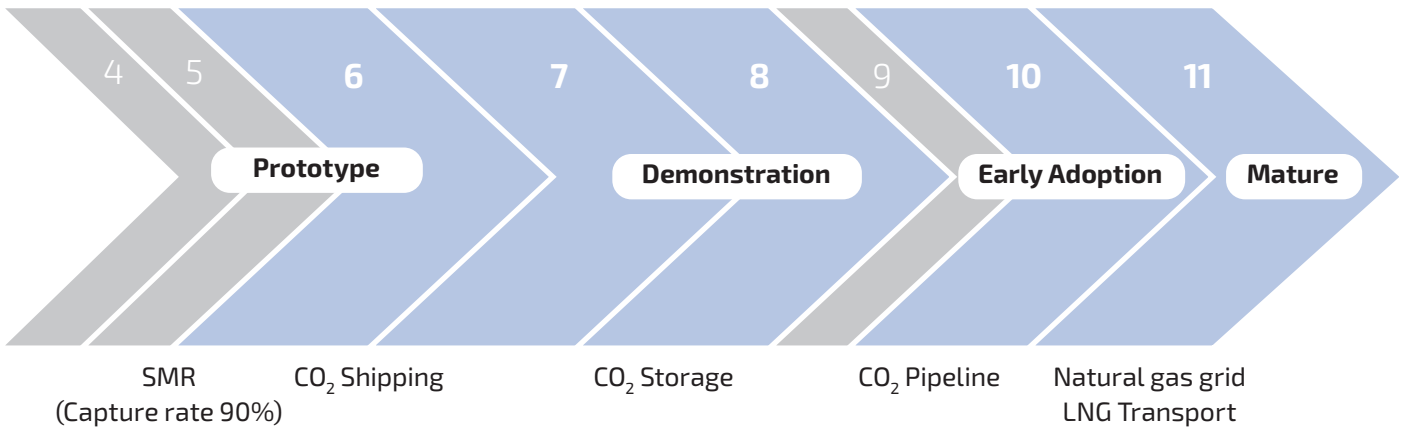
Green hydrogen production



Hydrogen transport



Blue hydrogen production



Source: EWI illustration based on IEA (2024b)

3.2 Levelized costs of hydrogen supply

Current cost estimates show that electrolyser costs are rising due to higher CAPEX, increasing labor costs, an increase in the risk-free rate, costs for critical raw materials, and costs of materials which lead to an increase in costs of hydrogen production (IEA 2024a; Dodd 2024; Palladino 2024; McKinsey & Company 2024a). Production costs therefore might be twice as high as previously expected (Roth et al. 2024). The cost of hydrogen production is determined foremost by the regional potential of renewable energy sources and the investment conditions (EWI 2024c). Countries with a high renewable energy source (RES) potential are well suited to exporting large quantities of hydrogen. Therefore, the geopolitical and geoeconomic conditions might change and exports might be realized from other countries than current natural gas exporters. Another important factor that determines the costs of hydrogen supply from export countries is the weighted average cost of capital (WACC) that serves as an indicator of the economic risk of a country and needs to be considered for investments in the hydrogen projects in this country. Furthermore, a risk premium may be included in the WACC due to the technology risk of insufficiently mature hydrogen technologies. A ramp-up of hydrogen technologies could potentially decrease technology risks and manufacturing costs and therefore supply costs.

The EU might depend on imports from outside the EU to a certain extent to meet uprising hydrogen demand. Currently, the EU hydrogen strategy states to import 10 Mt of hydrogen by 2030 (European Commission 2020). The following analysis focuses on the non-EU hydrogen partnerships of Germany as an example of the underlying cost structure of potential future hydrogen imports. A closer look at the partnerships of other European countries has shown similar countries to be of interest. In addition to the imports, the EU will likely cover a part of the hydrogen demand itself. Therefore, import costs from outside the EU are also compared to the

production costs within the EU and Europe. The following analysis is based on the EWI Global PtX Cost Tool⁵ (EWI 2024b).

[Figure 11](#) shows the supply costs for potential import countries as well as production costs within the EU. Import costs include the costs for transport via pipeline or ship. Pipeline transport is less expensive for smaller distances while transport via ship is beneficial for longer distances. The costs of pipeline transport depend highly on the availability of former natural gas pipelines and the cost structure of newly built pipelines. Of the chosen importing countries, Turkey is the only one where import via pipeline to Germany is feasible. For the other countries, transportation via ship is evaluated. Of the eight partnership countries, Saudi-Arabia might deliver the cheapest hydrogen at 202 EUR/MWh and Namibia is showing the highest supply costs of 280 EUR/MWh in the evaluated baseline scenario. The investment costs into local green hydrogen production sites are driven by the domestic weighted average cost of capital (WACC). The WACC might be significantly higher in developing countries compared to EU countries. For example, in this analysis, the WACC of Germany is 10%, and 16% of Namibia, both including a technology risk premium of 4% (EWI 2024b). With an international interest in the ramp-up of hydrogen production in developing countries, the investment conditions in these countries might improve and the import costs might decrease.

Supply costs within the EU range from 111 EUR/MWh to 223 EUR/MWh and are on average slightly cheaper than imports from outside of the EU. For all export countries that might transport hydrogen to Europe by ship, the production cost advantage due to high RES potential might be compensated by high transport costs due to long distances. While domestic production of green hydrogen might be cheaper than imports under these assumptions, due to limited electrolyser capacity, renewable energy

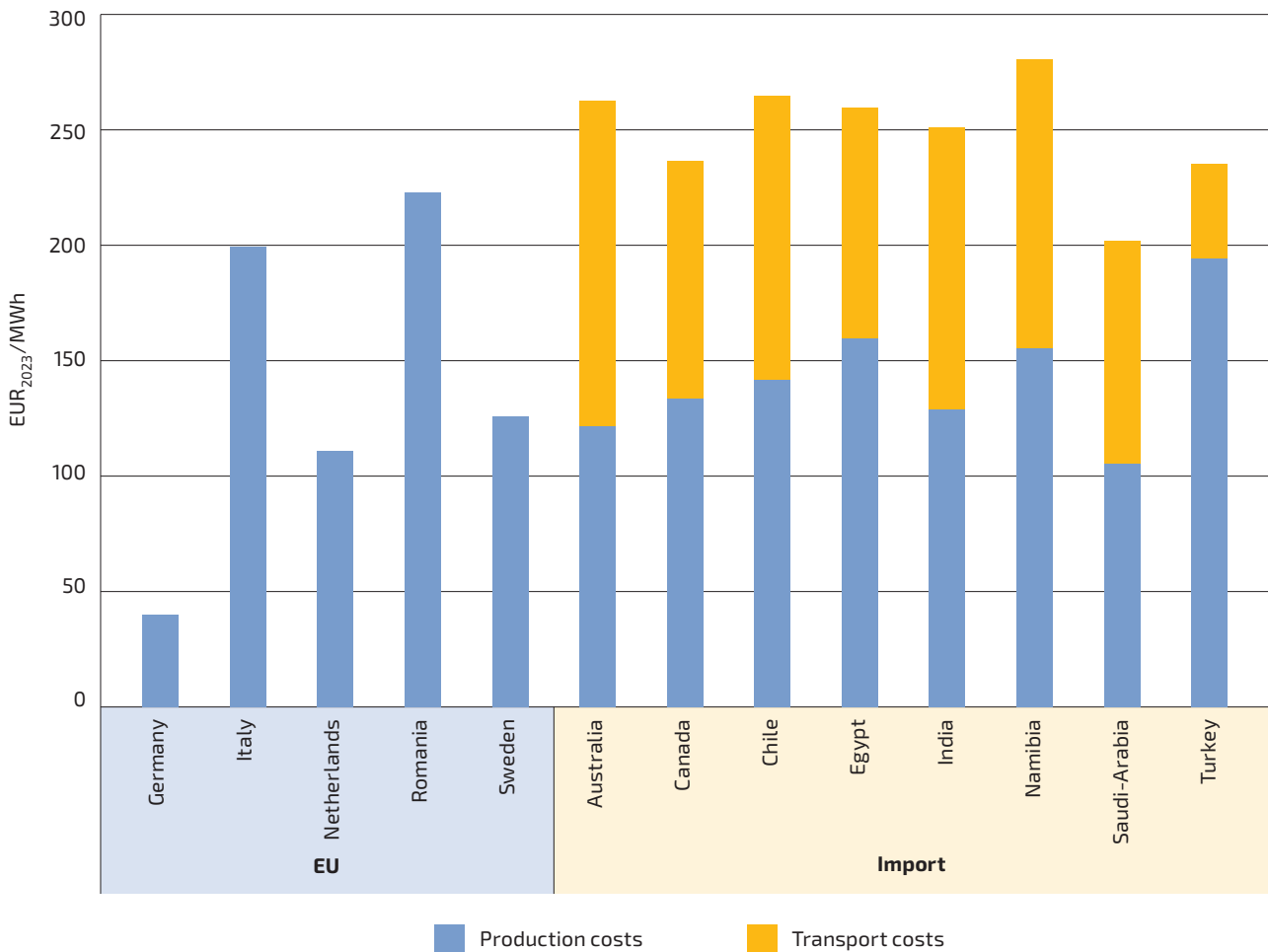
⁵ Underlying assumptions: baseline scenario, volatile delivery profile, low costs to build new pipeline, greenfield investments, hydrogen supply of 100 TWh

capacities and land availability, the EU might still depend on imports.

It is important to consider that supply costs do not equal end-user prices. While supply costs consist of the costs of production and transport, they do not include factors such as grid charges or profit margins. Future import prices therefore might be higher than analyzed costs. This might especially hold true for countries such as Germany that might not be able to fulfill future demand with domestic production and thus depend on hydrogen imports. Here, prices might be much higher than other EU countries as those importing countries might not profit from the cheapest hydrogen supply (Wietschel et al. 2024).

High supply costs and uncertainties of future prices are factors that might have a significant impact on the amount of hydrogen imported and the competitiveness of the industry. As costs are reflected in the prices that will be faced by the hydrogen consumers, to keep the competitiveness of the European industry on a high level internationally, subsidies might be needed to ensure a hydrogen market ramp-up. Those might enable the industry to shift technologies and pay higher fuel costs without reflecting this directly in the end-consumer prices. Furthermore, infrastructure ramp-up needs to take place first to transport hydrogen within the EU or import hydrogen from outside the EU.

Figure 11: Hydrogen supply costs, equal to production costs for selected EU countries and the sum of production and transport costs for selected non-EU countries in 2030



Source: EWI illustration based on EWI (2024b)

Although in this analysis, the transport of liquid hydrogen or LOHC is the cheapest transport option for green hydrogen, ammonia shipping might be a viable alternative, as it is an already advanced transportation method and therefore a short-term option. However, ammonia cracking, the process of turning ammonia into hydrogen, takes up a significant amount of total supply costs. Therefore, supply costs may decrease when the end-product needed is not hydrogen but ammonia. Hydrogen derivatives such as green ammonia, which might play a significant role in addition to hydrogen (Fleiter et al. 2024; Transport & Environment 2024) also depend on a cost-competitive supply of green hydrogen.

In 2030, blue hydrogen production is estimated to account for up to 26% of global hydrogen production according to the IEA (IEA 2023e). Nevertheless, the rise in production projects for blue hydrogen also develops slowly. The costs of producing hydrogen in Europe range between EUR 86/MWh and EUR 98/

MWh, under an assumed natural gas price of EUR 45/MWh in 2030, depending on future CO₂ transport and storage costs (EWI 2025). In any case, blue hydrogen production costs, including CCS, are expected to be lower than any cost estimations of green hydrogen production in or supply to the EU in the medium term. The highest uncertainty in the costs of blue hydrogen are the costs for the CO₂ transport and storage, varying also for each country of the EU (Agora Energiewende; Agora Industry 2024).

Green and blue hydrogen supply costs significantly exceed the current natural gas price, which amounted on average to EUR 32/MWh in Q1-Q3 2024 (EEX 2024). Therefore, looking only at fuel costs a switch to hydrogen-based processes is not cost-competitive for the industry. As the costs of blue hydrogen show to be lower than for green hydrogen, this might serve as a transitional solution although market uptake is still uncertain.

3.3 Technology readiness level of hydrogen demand applications

Hydrogen will likely play a large role in the decarbonization of the industry, as it may be the only viable option to eliminate greenhouse gas emissions in certain applications. A short-term increase in the use of hydrogen in industrial applications to reach the hydrogen targets will be highly influenced by the maturity of the climate-neutral applications. However, in most scenarios and in the EU strategy, the technology readiness of the different hydrogen applications might be overestimated. Therefore, this section gives an overview on the TRL of some potential hydrogen applications in the industry.

To convert processes currently powered by fossil fuels to hydrogen, extensive research and development efforts are still required. This includes advancing burner technology as well as, more importantly, testing the overall system to ensure

suitability for industrial production. Switching from natural gas to hydrogen as a heat source significantly alters critical process parameters. An additional challenge arises for facilities that use solid fuels as part of their process; in these cases, entirely new plant concepts must be developed and tested to accommodate hydrogen use (Fleiter et al. 2023).

As seen in [Figure 12](#), most hydrogen applications in the industry are still in the phase of prototyping or in the demonstration phase. Differences in the TRL can be observed between the industrial sectors. While in the Cross-cutting industry and Chemicals and Plastics some applications already show a higher TRL of 8 to 9, in the other sectors a share of applications is less developed with TRLs below 5. According to the IEA, no hydrogen application in the industry sector reaches TRL 10 or above so far (IEA

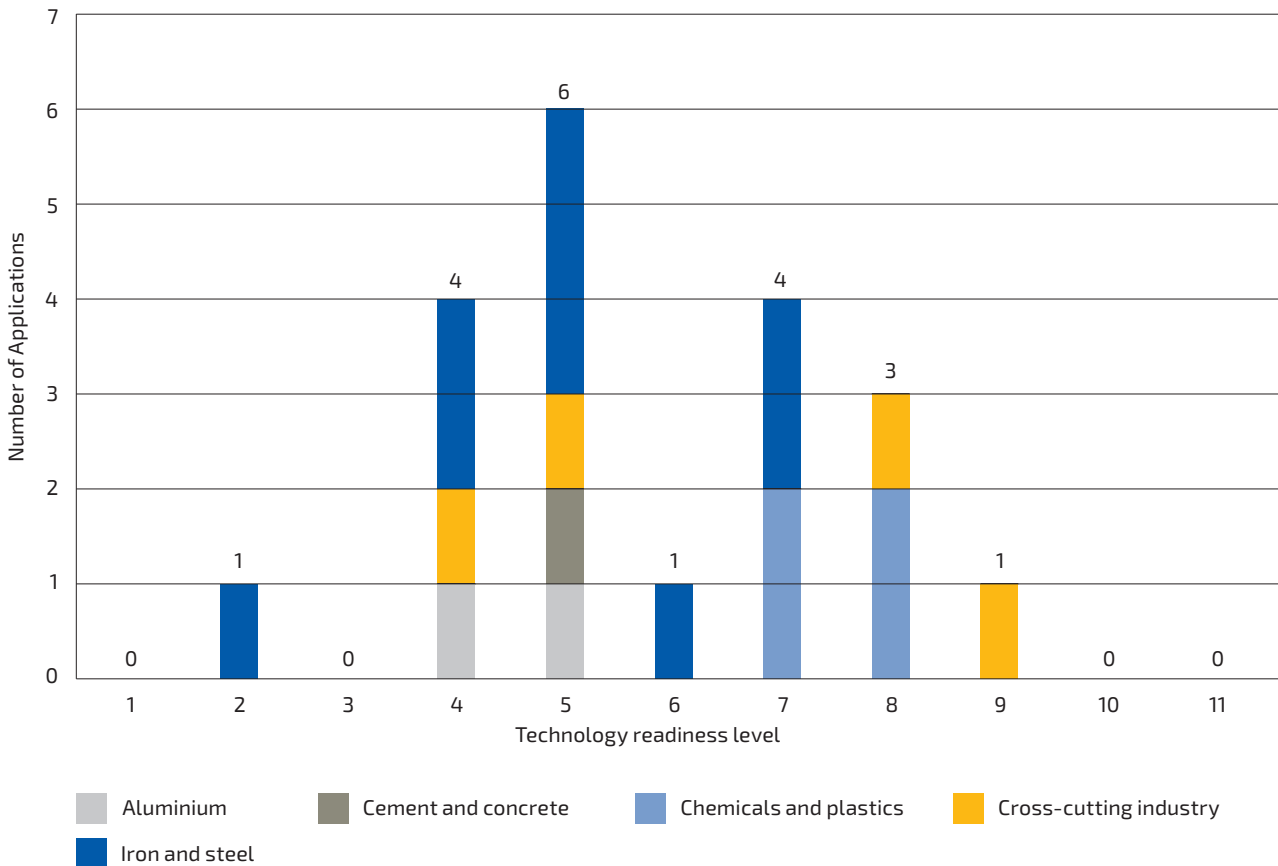
2024b). Investments in the improvement of the technology and further R&D are necessary to ensure the establishment of these technologies as a subsidiary to a conventional technology.

Regarding R&D, the question arises until which extent public financing can reduce the risks of investment by improving the TRL of specific applications. A higher TRL may also lead to lower investment costs as automation of production and expertise in construction increases between 2020 and 2024 government spending on R&D of hydrogen technologies in Europe has increased by five-fold (IEA 2024b). Further improvement of TRL might depend on continuous federal funding.

Using direct electrification to decarbonize industrial processes instead of hydrogen might be a complementary way to achieve climate goals (Fraunhofer ISI 2024; Schreyer et al. 2024). Current studies show that electrification can be a viable option for many

industrial processes which might reduce industrial energy demand, some of them showing a significantly higher technology readiness level than hydrogen deployment, although the adoption rate of electrification technologies is still uncertain (Energy Independence Council 2024; Hasanbeigi et al. 2024; Springer et al. 2024). Process heat may be provided with heat sources such as heat pumps, induction and turbo heaters as well as electrical boilers and mechanical vapor recompression. These differ in temperature ranges and maturity (McKinsey & Company 2024). According to the German Environmental Agency, the maturity of process heat provision via direct electrification is mostly independent of the process temperature but depends on process specifics and the desired end-product (Fleiter et al. 2023). For example, in the aluminum, foundry, and copper industry, applications with temperatures of up to 1500°C show a mature TRL of 9 out of 9 for electrification, which is significantly higher than for hydrogen applications (TRL of 4 to 5).

Figure 12: Technology readiness level of hydrogen applications in the industry



Source: EWI illustration based on IEA (2024b)

In other industries such as the lime, steel, and cement industries, hydrogen applications show to have a slightly higher TRL of 4 to 5 out of 9 than direct electrification (TRL of 2 to 3) and might thus be more likely to decarbonize the processes in these

industrial sectors. For providing low-temperature process heat in the form of steam, both electrification and hydrogen have a high TRL of 9 out of 9 (Fleiter et al. 2023).

3.4 Willingness to pay of hydrogen demand applications

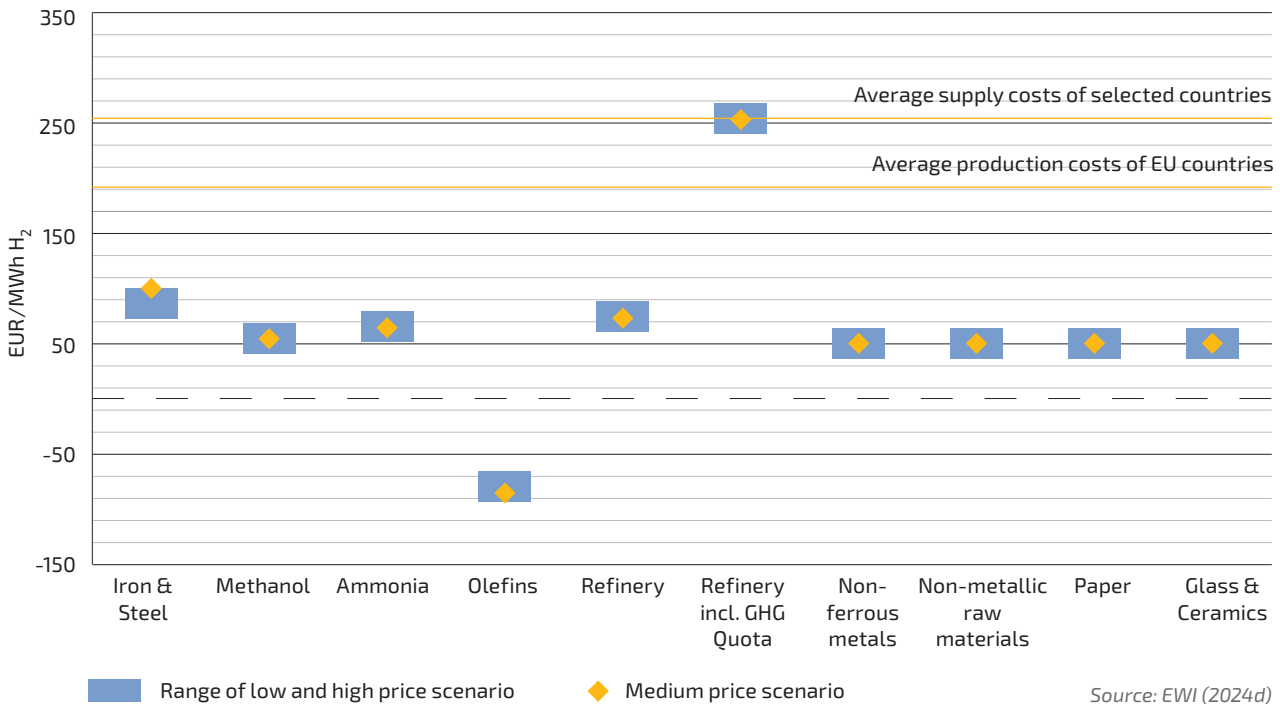
Not only uprising supply and technological readiness of the demand-side determine the hydrogen market ramp-up, but also the industry's willingness to pay will have major influence on the increasing hydrogen demand. The hydrogen ramp-up is expected to be driven by increasing hydrogen demand, especially in the industrial sector. The sector might face a combination of EU production prices and import prices from outside the EU. Supply costs do not directly reflect prices. Nevertheless, they serve as an important indicator for future prices. Current analyses suggest that supply costs of green hydrogen might exceed the industry's willingness to pay and make subsidies a necessary tool to keep the industry competitive and to accelerate the hydrogen ramp-up.

In a former analysis by EWI, supply costs and the willingness to pay of the industry sector in Germany were compared (EWI 2024d). The analysis quantifies the application-specific break-even price for hydrogen as the difference in the Total Cost of Ownership (TCO) between the conventional and the alternative, hydrogen-based application. The TCO refers to the total cost of an application over its lifetime, including capital expenditures (CAPEX), operational expenditures (OPEX), tolls, and taxes. Within this analysis, only greenfield investments into both processes are compared. Other modes of decarbonization, such as direct electrification, are not analyzed.

The results of the analysis demonstrate the break-even prices in 2030 as in [Figure 13](#). The price range illustrates different fossil fuel, electricity, and carbon emission price scenarios (low, medium, high). The highest break-even price for hydrogen in the industry sector is shown by the refinery industry (incl. GHG quota), where it ranges around EUR 250/MWh. The GHG-quota obliges emission reduction to a certain extent to produce petrol and diesel fuel (Federal Emission Control, § 37a Abs. 4 BImSchG). The penalty payment for missing this reduction goal amounts to EUR 600/t CO₂ equivalent emitted (§ 37c Abs. 2 BImSchG). The quota increases the willingness to pay for this application significantly.

Additionally, the break-even price for hydrogen use in the iron and steel industry is comparatively high, where it is between EUR 80/MWh and EUR 100/MWh. A deep dive into the iron and steel sector can be found in Infobox. Nevertheless, in all of the industrial sectors besides Refinery (incl. GHG quota) the willingness to pay lies below the estimated import costs from all analyzed countries and production costs within the EU. Additionally, future prices will most likely range above estimated costs as e.g. grid charges or profit margins will increase prices. If the hydrogen demand in these industrial applications is to be incentivized nevertheless, subsidies may be needed to cover the difference between the break-even price and the market price of hydrogen.

Figure 13: Greenfield break-even prices for hydrogen in the industrial sector in 2030



Production costs of green hydrogen within the EU lie on average above the willingness to pay of the industry under the analyzed circumstances. Therefore, subsidies might be necessary to ensure the establishment of hydrogen applications in the industry in the short and medium term. One possibility to incentivize the shift towards hydrogen applications in the industry could be Carbon Contracts for Difference (CCfDs). Those contracts offer companies planning security as the government pays for additional costs that arise due to the substitution of technologies. At the same time the companies need to refund the state when additional profits are made due to the shift in technology. Therefore, climate-friendly technologies might see a ramp-up, and know-how about the technology itself, the infrastructure and hydrogen supply might increase (Federal Ministry for Economic Affairs and Climate Action 2024). Those subsidies could boost the hydrogen market ramp-up and thereby enhance a transition towards a carbon-neutral industrial sector.

Electrification has already decreased the hydrogen demand in other sectors, such as the transport and building sector with fast development of new cost-efficient battery technologies and heat pumps. According to the German Environmental Agency, some industrial processes show lower levelized cost of heat with electrification compared to shifting to hydrogen as a heat supply source. Also, hybrid heat supply using electrification and hydrogen might be a cost-competitive option. This includes processes in the aluminium and paper industry (Fleiter et al. 2023). Additionally, electricity-based technologies such as electrothermal batteries may offer a cost-competitive solution to decarbonize some of the processes in the hard-to-abate industry (Palladino 2024). New industrial heat electrification options, particularly in the low- to medium temperature range, also offer new perspectives for reducing the hydrogen demand in the energy-intensive industries (McKinsey & Company 2024b). Nevertheless, industrial process heat from both electricity and hydrogen is not expected cost-competitive to the use of natural gas now and in the future (Fleiter et al. 2023).

Infobox: The iron and steel industry

The iron and steel industry is one example of an industry that has great potential of using hydrogen to decarbonize its production processes. Direct reduction plants (DRI) might use a share of natural gas and hydrogen where the share of hydrogen could increase over time (BCG et al. 2024). In 2030, the steel sector could demand up to 1/3 of total German hydrogen demand. However, the TRL of CO₂ neutral (hydrogen and electricity) applications are still much lower than natural gas-based applications. The IEA ranks the DRI based on 100% hydrogen at a TRL of 6 (IEA 2024b). Furthermore, the German Environment Agency has ranked electricity and hydrogen-based processes at a TRL below 4 out of 9, whereas natural gas-based processes have a TRL of 9 (Fleiter et al. 2023). Due to the high hydrogen costs the production costs in the iron and steel sector are estimated to increase by 5 to 25% depending on the share of hydrogen used.

According to EUROFER, there are currently 60 projects for low-carbon steel production announced in the EU. Three examples:

STEGRA drives sustainable energy transformations with a focus on decarbonizing the steel sector in Sweden. It promotes green technologies, including hydrogen-based methods and renewable energy integration, to achieve significant CO₂ reductions and support global climate goals (Stegra 2024).

SALCOS is a German pioneering initiative by Salzgitter AG to produce green steel using hydrogen-based direct reduction and renewable energy-powered electric arc furnaces. The project aims to reduce CO₂ emissions by up to 95%, setting a benchmark for sustainable steel production (Salzgitter AG 2024).

The Hydra project in Italy is led by RINA and supported by the European Commission. Backed by EUR 88 m under the NextGenerationEU program, it includes a hydrogen-powered pilot plant in Italy to demonstrate sustainable steelmaking by 2025 (RINA 2023).

The steel sector makes a significant contribution to the EU's greenhouse gas emissions and is therefore the most affected by climate policy among the energy-intensive industries. While the iron and steel sector show a relatively high willingness to pay, the TRL of the specific applications is relatively low compared to other industrial sectors. Both financial willingness and technological readiness are necessary to introduce hydrogen as an energy carrier in this industry. It is particularly important to ensure a level playing field with competitors from third countries for the transition to climate neutrality in this sector. The success of these low-carbon steel projects requires a supportive regulatory framework that effectively addresses carbon emissions both during and after the transition (European Steel Association AISBL 2024).

3.5 Implications on the hydrogen transition from a techno-economic perspective

In the future, hydrogen may be essential for specific industry applications where direct electrification is not possible. However, the optimal integration of hydrogen varies depending on infrastructure, production methods, and policy frameworks. Investment in green hydrogen on both the supply and the demand side is currently falling short of declared targets, even when considering subsidy schemes. One reason may be that supply cost estimates for green hydrogen exceed the willingness to pay of the industry. Furthermore, security of supply for the industry may be threatened due to a lack of coordination in the hydrogen infrastructure development. A more prominent role of blue hydrogen and electrifying more industrial processes instead of using hydrogen are discussed as alternative or complementary options with potentially lower costs and a diversified supply risk.

EU-Coordination of Hydrogen Infrastructure?

The planning and construction of infrastructure for a new energy commodity exhibits various challenges. The European hydrogen grid is planned to transport hydrogen to rising hydrogen demand centers. As uprising demand may develop slower than expected and might not reach foreseen values, the capacity of the grid might be overly extended in the short to mid-term but potentially also in the long term. In Germany, the core grid might transport nearly three times of current estimated demand in 2030. Overestimation of transport capacity might lead to high grid fees for future customers, who might have to cover a higher share of the initial investment costs. This leads to high uncertainties regarding uprising grid fees faced by the customers. In Germany, an amortization account is supposed to bridge the gap between grid fees paid by the customers and those that would be necessary to cover investment costs. No other country in the European Union has developed such a system until now.

The EHB consists to a large extent of repurposed natural gas pipelines. Repurposing natural gas pipelines offers opportunities to lower costs and expedite project timelines by leveraging existing infrastructure (IEA 2024a). It also involves challenges, such as the lower volumetric energy density of hydrogen compared to natural gas (Telesy et al. 2024). Furthermore, those pipelines are not available anymore to transport natural gas, which may affect the supply security of natural gas during the transition period from natural gas to hydrogen. Therefore, it is important to consider natural gas supply when evaluating the transition of repurposing the network (Schlund 2023). In addition, coordination challenges may occur between stakeholders of hydrogen, methane, and electricity systems, as well as stakeholders in different countries (Frontier Economics 2023). Here, it is necessary to consider all stakeholders' interests and needs in the further planning of a hydrogen grid, which may be included in the coordination of stakeholders of the ENNOH to establish a hydrogen infrastructure (IEA 2024a). The PCI is another example of European coordination of infrastructure projects that are elected as a project that has a positive effect on a variety of European member states.

Hydrogen storage plays an important role in the future security of supply in times of varying hydrogen imports or high demand. The future required hydrogen storage capacity and its regional distribution are uncertain. Total hydrogen storage requirements in Europe are estimated to be between 145 TWh and 247 by 2050 depending on the scenario (EWI 2024e), where salt caverns take on the largest role in future hydrogen storage. The storage potential is subject to geological preconditions. Hydrogen may be stored in underground salt caverns, or to some extent in pore storage facilities. As salt caverns are centralized at specific areas in Europe (e.g. Germany) (Caglayan et al. 2020), hydrogen storages may be more centralized than current natural gas storages and therefore lead to a higher coordination effort between the member states of the EU.

The disparity in infrastructure development in the EU member states can create challenges, as for cross-border trading, where the more advanced country may be ready to supply hydrogen, but the neighboring country might not have the necessary infrastructure in place to import, transport, or utilize it efficiently. This imbalance could lead to delays, inefficiencies, or even missed opportunities in cross-border hydrogen trade, as each country faces a higher investment risk and might decrease investment in the development of building up a hydrogen infrastructure. This emphasizes the need for coordinated infrastructure development between neighboring countries to ensure a smooth integration of hydrogen markets. Subsidies might be needed to overcome the investment retention of private companies. A key issue is the lack of comprehensive strategies across all EU countries to manage the systems of natural gas and hydrogen, especially when coordination is required across different stakeholders, sectors, and borders during the transition period.

Contribution of Blue Hydrogen?

The costs of blue hydrogen production including CO₂ transport and storage could be significantly lower than the costs of green hydrogen. Therefore, blue hydrogen might be an option to decrease hydrogen supply costs for the industry and increase investment in hydrogen-based applications. But the extent of the cost-advantage of blue hydrogen is uncertain and varies with the natural gas and CO₂ price. In addition, the cost scaling of capturing and storing the emitted CO₂ is also uncertain and will only dissolve with an increasing technology readiness level. Current estimates for the technology readiness level of Carbon-Capture and Storage (CCS) range between 5 and 9 depending on the CO₂ capture rate (90% or 60%) of the production process (IEA 2024b). For a widespread production of blue hydrogen, an extensive CO₂ infrastructure would be needed. Other risks that currently hinder investment activity such as counterparty risk in

bilateral trade or uncertainty about infrastructure development and associated grid fees remain with the use of blue hydrogen. Additionally, blue hydrogen is not climate-neutral and can therefore only be considered as a bridging technology for the hydrogen ramp-up, but it is not a permanent option in a climate-neutral energy system.

Alternative of Direct Electrification?

A hydrogen market to the extent identified in common energy system transformation studies might be hard to achieve, as costs for green hydrogen and associated risks appear to be higher than previously anticipated. Electrification might serve as an alternative to decarbonize the industry. The technical efficiency of electrified processes is consistently higher than in hydrogen-based processes, opening a potential for cost savings. The full extent of this potential is not analysed in this study but is also dependent on further technology innovation as the new studies have highlighted. Further techno-economic and geopolitical aspects of electrification must also include an in-depth analysis on the feasibility of electrification of the specific industrial processes, potential grid extensions and resulting grid fees, supply security issues within the EU as well as resulting import dependencies from outside the EU. In a highly electrified energy system, hydrogen will play a critical role for energy storage, to balance supply and demand by storing surplus renewable electricity for use during periods of low generation.

Industrial demand flexibility might be another option to significantly increase the share of electrification in energy systems. By adopting flexible production schedules and processes, industries can adjust their energy consumption to align with periods of high renewable energy availability, thereby reducing reliance on storable energy carriers like hydrogen. This approach helps to maximize the utilization of renewable electricity in the energy system while mitigating the challenges posed by supply-demand imbalances.

Assessment of Total System Costs?

A discussion of technology options allowing decarbonization of the industrial sector should consider full system costs, consisting of investment and operating costs along the value chain supply, storage, and transport as well as demand. For example, the technical efficiency of electric processes is generally higher than those based on hydrogen, potentially allowing for a reduction of system costs in this aspect. However, choosing electrification instead of hydrogen might require additional investments in electricity grids which is generally more expensive than a hydrogen grid. The net-effect is not assessed in this study. Most energy transition studies (EWI 2021; Prognos, Ökoinstitut, Wuppertal-Institut 2021) such as assume fundamental price-building based on production factors and a willingness to pay based on a predefined and enforced carbon emission cap to reach climate neutrality. Additionally, these studies often neglect or underestimate certain aspects of the energy system costs, such as infrastructure needs on the distribution level.

Take aways from the expert workshops:

Industry

- The global hydrogen economy is rapidly evolving, with significant activity concentrated in the U.S. and China.
- Supporting existing hydrogen projects and ensuring their continuity is critical to maintaining momentum.
- Sector-specific solutions are essential to drive adoption and scaling.
- Early scaling, e. g. in refineries, is limited, as the targets for other sectors fail to generate sufficient downstream demand.
- Flexibility in the hydrogen ramp-up is crucial, including utilizing diverse hydrogen sources (e.g. blue, grey) rather than exclusively focusing on green hydrogen. The source of hydrogen is initially irrelevant to building the necessary infrastructure.
- Current top-down regulatory approaches might artificially inflate costs.
- Limiting criteria within the Delegated Acts hinder market growth. The regulatory framework for interim solutions stifles entrepreneurial practices. The future regulatory landscape for hydrogen remains uncertain, adding to investor hesitation.
- The first percentage points of hydrogen adoption require targeted promotional measures. Blending options, particularly for electrolyzers connected to the natural gas grid, provide operational flexibility.

- A European hydrogen amortization account could be essential for the establishment of a pan-European hydrogen network.
- Relying solely on electrification is not a viable path for the energy transition. Hydrogen can ensure stable energy supplies for industries, albeit at a high cost.
- The gap between the hydrogen market price and the willingness to pay can be narrowed through subsidies and reduced risk premia in capital costs. A small share of public funding contribution can attract a great share of private investment.
- The environmental impact and ethical considerations of poorly regulated blue hydrogen flooding the market must be addressed to ensure sustainable practices.
- Strategic industries within the EU might shift geographically as the economic landscape adapts to hydrogen and related infrastructure needs.

Academia & Think Tanks

- Investments outside of Europe remain limited, with significant challenges arising from water scarcity and the need for desalination plants in potential production regions.
- Achieving economies of scale is essential for cost reduction, but the feasibility of creating these economies within the EU requires further exploration.
- Blue hydrogen emerges as a strong cost competitor to green hydrogen, creating challenges for prioritizing low-carbon solutions.
- The lack of infrastructure for Carbon Capture and Storage (CCS) delays the deployment of blue hydrogen, raising questions about its role as a necessary interim solution and its ability to coexist with the green hydrogen ramp-up.

Politics

- While realism is essential in setting hydrogen targets and expectations, there is no viable alternative to pursuing hydrogen as a cornerstone of the energy transition. A clever combination of subsidies and industrial offtake targets is required to drive market growth while ensuring economic sustainability.
- Transmission System Operators (TSOs) and consumers are heavily reliant on hydrogen imports, necessitating the development of targeted financing mechanisms to support infrastructure and supply chain stability.
- A relatively small proportion of announced hydrogen projects have been cancelled, indicating strong overall commitment and resilience in the sector despite challenges.
- The safeguarding of critical hydrogen infrastructure, particularly in cases where pipelines or facilities traverse geopolitically sensitive regions, remains an unaddressed issue. A lack of clear responsibility for ensuring infrastructure security exacerbates the vulnerability of these supply chains.

Take aways from the study:

Technology Readiness

- The TRL on the supply side of green and blue hydrogen and for hydrogen transportation varies highly.
- The transition of many industrial applications relies on applications with a TRL in the prototype or demonstration phase. Some industrial applications show higher TRL with direct electrification.
- Investment into R&D might be needed to make a process shift feasible.

Supply costs

- For the ramp-up of hydrogen-based applications, a secure supply and cost-competitiveness is needed. High costs and a lower willingness to pay for hydrogen might prohibit the wide-spread integration of hydrogen applications in the industry sector.
- Supply costs are driven by potentials of renewable energy sources, transport distances and methods as well as investment circumstances and risks associated with the technological maturity.
- Green hydrogen might be significantly more expensive than natural gas. Blue hydrogen might be less expensive than green hydrogen, but still show higher costs than fossil fuels.

Implications for the transition period

- EU-wide infrastructure development is dependent on coordination between the member states. Hydrogen storage is centralized in certain areas within the EU and increases the need for coordination and an EU-wide hydrogen grid.
- Blue hydrogen is a cost-competitive alternative to green hydrogen that might increase investment into hydrogen infrastructure and demand. It is, however, not climate-neutral and can thus only be considered a bridging technology.
- Electrification might serve as a complementary solution that decreases demand for and dependencies on hydrogen. The share of these complementary solutions is subject to a complex system of interdependencies regarding energy sources, different infrastructures and feasibility and costs on the demand side.

Expert workshops

- Industry stakeholders agree that a hydrogen ramp-up is crucial, but the current regulatory framework is too narrow, inflexible, and the existing subsidies are insufficient and intransparent in the application process, although the scaling of technologies is still a necessity for the market uptake.
- Industry and Academia agree that blue hydrogen can be a solution to increase the supply of hydrogen in the short-term. Although the costs are much lower for blue hydrogen than for green hydrogen, Academia still sees various challenges regarding a short-term uptake and the role of blue hydrogen as a bridging technology. A low-carbon Delegated Act is seen as essential for the future development.
- Political experts recognize a necessity of a hydrogen market ramp-up and its economic and geopolitical challenges.
- Although industrial stakeholders were questioning the near-term ramp-up of a green hydrogen, Academia emphasized the comparably small number of cancelled projects.
- Coordination of the member states for a hydrogen infrastructure is crucial.
- A huge gap between the supply costs of green hydrogen and the willingness to pay of the industry is observed in practice.
- Hydrogen is seen as a complementary solution to the electrification of the industry and other parts of the economy.

4. Dependency, Geopolitical Risks and Hydrogen Supply Chain Risks

Written by Dr. Frank Umbach (CASSIS)

The future hydrogen economy will result in completely new industrial value, supply, and logistics chains – and alongside new import dependencies and geopolitical risks (IRENA 2022; Umbach 2021b). As hydrogen is only an energy carrier and not an energy resource itself, the expansion of 'green hydrogen' production requires a huge increase in additional solar and wind energy capacities. But in densely populated countries (like Germany) and regions in Europe, such an additional huge expansion of renewable energy capacities – in addition to those which are needed to replace Europe's fossil fuel consumption – appears unrealistic. As a result, the EU and Germany will become heavily import dependent in hydrogen – officially as in the case of Germany up to 50-70% (European Commission 2020a; BMWK 2020; Quitzow, Zabanova 2024). But the EU's future hydrogen imports ultimately depend on (1) the EU's overall hydrogen demand, (2) its future own domestic production of green hydrogen and European electrolysis capacity, and (3) whether sufficient as well as affordable hydrogen supply becomes available on the global market.

[Chapters 2.2](#) and [3](#) have already highlighted the future EU overall hydrogen demand as well as its H₂ import demand might be significantly lower than previously estimated due to alternative cost-efficient electrification technologies in the transport, building, and potentially also parts of the industrial sectors. This forms the basis for the following analysis of the geopolitical risks of Europe's remaining

hydrogen import risks, vulnerabilities, and supply disruptions.

Many geopolitical risks resulting from a growing hydrogen import dependence are not very different to those of the previous and current fossil fuel import dependencies (Umbach 2003, Umbach 2018 and Umbach 2021). Various political, economic, social, and climate change factors (see [Figure 14](#)) as well as bilateral relations and regional stability need to be considered and included in comprehensive, holistic geopolitical risk analyses (EWI 2023a), which can also be quantified in different risk indexes (EWI 2023b).

But as large investments in new production and transport infrastructures need to consider time horizons of at least 30-40 years for commercialization and profitability, dynamics of those various factors particularly in developing countries (like e.g. government changes and political upheavals) can rapidly change previous geopolitical risk analyses (see also [Chapter 4.4](#)). Following a wave of resource nationalism (McCormick, Hodgson 2024), new governments may also no longer respect previous commercial contracts with foreign partner countries and companies. Thus, qualitative analyses must also define strategic priorities for investments as well as energy and hydrogen partnerships. They also need to consider import diversification requirements as those short-term dynamics of geopolitical changes both regionally and globally cannot be excluded.

Figure 14: Geopolitical risks



*Hydrogen derivatives are e.g. ammonia, methanol, and synthetic fuels ("e-fuels").

Source: EWI (2023a)

In addition to those geopolitical risks, the present and future green energy transition and decarbonization – and particularly the electrification and digitalization of the transport, industry as well as other sectors – multiply the risks of cyberattacks and their cascading impacts on critical (energy and maritime) infrastructures alongside of the rise of the physical sabotage of those critical infrastructures (Umbach 2018a and Umbach 2021b; Piebalgs, Schmitt, Umbach 2024). It will also include those of the future hydrogen infrastructures.

Furthermore, in contrast to the years and decades prior to 2022, the new geopolitical era with fragmented global markets and geoeconomic rivalries and potential trade conflicts needs to be considered much more structurally in any economic-technological analyses – including for the future global and regional hydrogen markets. The times of believing in liberalized global markets, a continuing expansion of cross-border trade and a naive reliance on (volatile) global markets and their self-balancing of supply and demand as during the last 30 years have already ended. They have resulted in problematic long-term dependencies on unreliable exporting countries and unstable supply chains. Energy

security and resilience of supply chains have now been prioritized over affordability and sustainability in the U.S., the EU, and other countries. 'Re-shoring' and 'friend-shoring' of key industrial manufacturing of critical goods and domestic or European supply chains now play a much more important role in the EU's future energy and industrial policies. But those new policy instruments will also raise supply chain costs (at a time when less public funds will be available for energy and climate policies), hinder global collaboration, and might slow the European decarbonization efforts and green energy transition. Enhancing the resilience of energy and CRM supply security and critical technology supply chains has a cost side.

Another point for the consideration and discussion of geopolitical risks of the EU's future hydrogen import dependency are already existing threats and import vulnerabilities in the other EU's energy policies during its energy transition and decarbonization process. The following geopolitical risks of its green energy transition also need to be considered and not separated from the EU's overall energy security and combined, holistic risk analyses:

- The EU's traditional import dependence on fossil fuels from politically unstable and unreliable countries – such as the countries in North Africa or the Gulf region or Russia – is already problematic for energy supply security and potential supply disruptions. This fossil fuel dependence is partially already replaced by numerous new geopolitical risks and import dependencies on other or the same states (see again [Figure 1](#) p. 18 on newly identified import dependencies – and particularly on China – already prior to Russia's invasion into Ukraine in February 2022).

Given the EU's rapidly growing import dependence on CRMs (such as rare earths, lithium, cobalt, etc.) for its green energy (renewables, electromobility, and battery production, digitalization, and artificial intelligence, etc.) and defence industry sectors, this dependence will further increase with their technology expansion (EWI 2024f; Umbach 2024a; Umbach 2024c). Also, the creation of a hydrogen economy and huge electrolysis capacities demands a further increase in mining, refining, and processing of CRMs. Thereby, Europe is already heavily dependent on China though it seeks – together with the U.S. and other Western G7 countries – to de-risk its CRM import dependency in collaboration with these countries (Umbach 2024a and Umbach 2024c; IEA 2024c). China had already weaponised its production and export monopoly of Rare Earth Elements (REEs) as early as 2010 and later as a weaponized threat towards the U.S. since 2019 (Fels 2022). The first weaponization was the result of an escalating maritime territorial and resource conflict with Japan, which led to the imposition of an export ban on REEs to Japan without any prior notice. At that time China controlled some 97% of the global production of REEs, despite having less than 40% of the world's reserves and only 57% of global resources. At the end of the 38-day diplomatic conflict between China and Japan in the autumn of 2010, the US and the EU were also drawn into the conflict when Japan began

importing Chinese REEs from them, thus circumventing the direct export ban (Umbach 2020d; Umbach 2019; Umbach 2018). Despite the introduction of the EU's 'Critical Raw Materials Act' in 2024, its targets for 2030 (such as the production of CRMs – such as rare earths – in Europe) are considered equally unrealistic to achieve by 2030 (Umbach 2024a; Umbach 2024c).

- Furthermore, Europe is not only heavily dependent on Chinese solar cells and wind power technology components (e.g. magnets) and is presently facing a massive import of Chinese electro vehicles. Also, China is already controlling some 40% of the global electrolysis capacities. The aimed scaling of the EU's electrolyser capacities up to 120 GW, which would be needed to produce the target of 10 Mt by 2030 might result in even more CRM imports and technology components from China – and thus further increase the EU's import dependence on Chinese CRMs and green technologies (Ansari, Grinschgl, Pepe 2022). Hence, the EU needs to re-balance its future imports of Chinese extracted and refined CRMs as well as cheaper green technologies for a faster decarbonization and green energy transition with the need for an enhanced resilience of a stable supply of hydrogen and electrolysis technologies as well as domestic production capacity for both its energy security as well as industrial competitiveness.

Therefore, the foreign, security, and geopolitical impacts of an increasing import dependence on both hydrogen volumes and hydrogen technologies should be strategically analyzed at an early stage. The results of this analysis must be considered in adequate strategies for future hydrogen supply security. However, this will require a major rethink of European and, in particular, German energy policy, which has traditionally separated economics, trade, and energy resources from geopolitical and security dimensions. Even purely commercial energy and other economic projects can have geopolitical implications. They must be considered in

advance and not just post-facto as had often been the case in the past (i.e. Nord Stream 1 and 2 gas pipeline import dependence on Russia). It demands more than ever public-private partnership (PPP)-collaboration between political and industry stakeholders.

The following sub-chapter will review the present development, based on the newest global analyses, of the worldwide hydrogen supply-demand balance as it will have significant impacts on the EU's own hydrogen policies and its imports from non-European countries.

4.1 Global Hydrogen Development and Green Hydrogen Perspectives

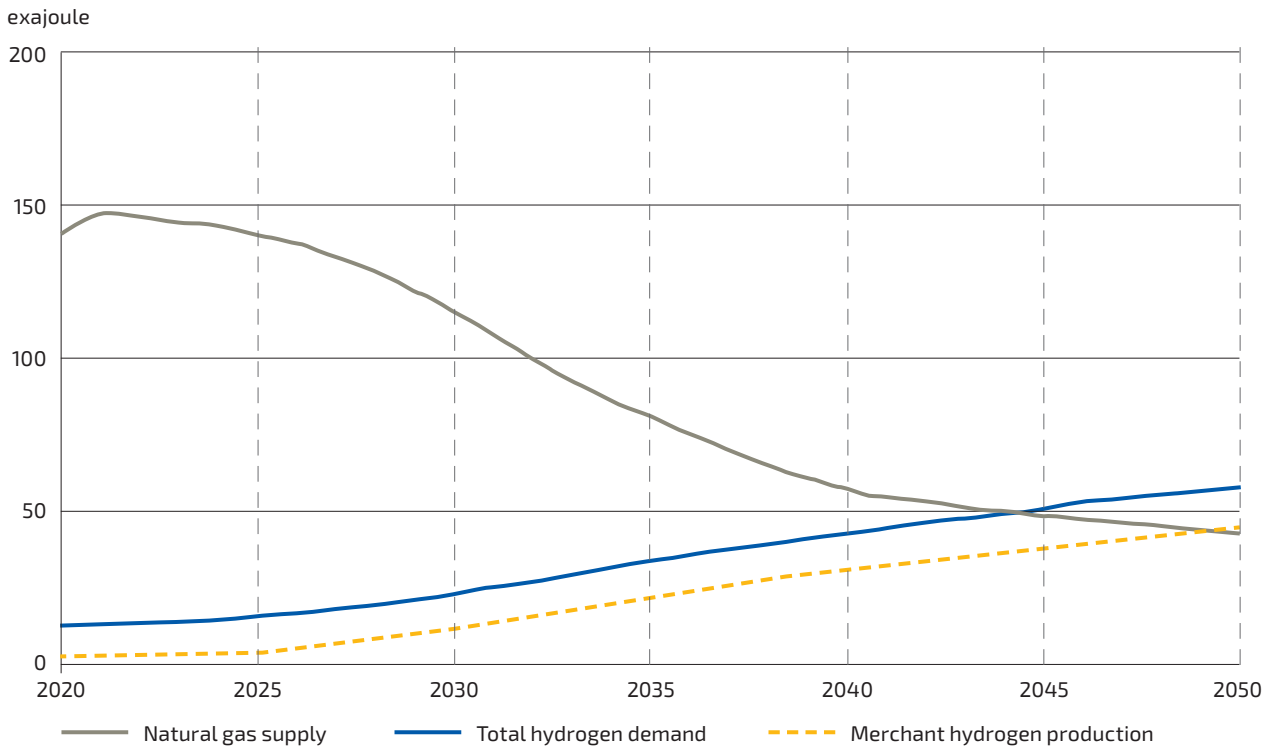
The EU's future green hydrogen import demand and supply security depends not just on its own production and electrolyser capacities, but also on whether sufficient hydrogen volumes will be available in the exporting countries – and, therewith, on the worldwide global demand-supply balance.

In 2023, the global hydrogen demand accounted for 97 Mt – only a modest increase of 2.5% towards 2022. Low-emission hydrogen production was just 1.4 GW. China was responsible for four-fifths of that capacity (with 95 Mt) (IEA 2024a; IEA 2024c; IEA 2023b; IEA 2023c). The containing energy equalizes to about 2.5% of global final energy consumption. The IEA has estimated that by 2050 the worldwide green hydrogen production could reach 3,000–5,000 GW, depending on the different scenarios (IEA 2024d). It could abate more than 20% of the global energy demand. But like the forecasts and scenarios of BNEF and others, it has also decreased at least its mid-term perspectives (see also again [Chapters 2.2](#) and [3](#)). Even if clean hydrogen supply can skyrocket 30-fold to 16.4 Mt per year by 2030 (which appears rather unrealistic and has been downsized to around 11 Mt), it will be insufficient to meet most governmental targets – including in Europe. Only 30% of all currently announced H₂ projects will be commissioned by the end of this decade – therewith two-thirds of the global supply will be missed due

to longer project completion timelines, insufficient policy support, and rising costs (BNEF 2024b). Thereby, China, Europe, and the U.S. could account for over 80% of clean hydrogen supply worldwide – with the U.S. expected to become the world's largest producer by 2030 (BNEF 2024b).⁶

Hence, by 2030, the global H₂ demand and production are expected to grow only modestly (see also [Figure 15](#)): it could avoid 14 bcm/y of natural gas use, 20 Mt of coal and 360,000 bd/y of oil use. An estimated 12 Mt of H₂ could be exported annually. But a projected production of 30–40 Mt by 2040 from less than 1 Mt today of blue H₂ demands a cumulative investment of US\$ 170 bn in electrolyser capacity and carbon, capture, utilization, and storage (CCUS) projects. At present, hydrogen is responsible for about 830 Mt of CO₂ per year. Grey and brown hydrogen contribute to higher global CO₂ emissions rather than abate them (with 6% based on global natural gas and 2% global coal demand). Producing hydrogen is currently still relatively cheap in natural gas producing countries such as North America, Russia, and the Middle East. It is more expensive in natural gas importing countries and regions like Europe and North-East Asia (Japan, South Korea, and China) (RANE 2024a).

6 The IEA has developed an interactive tool for the global progress of the worldwide 2,000 hydrogen projects – see IEA (2023c).

Figure 15: Global natural gas and hydrogen supplies' projection

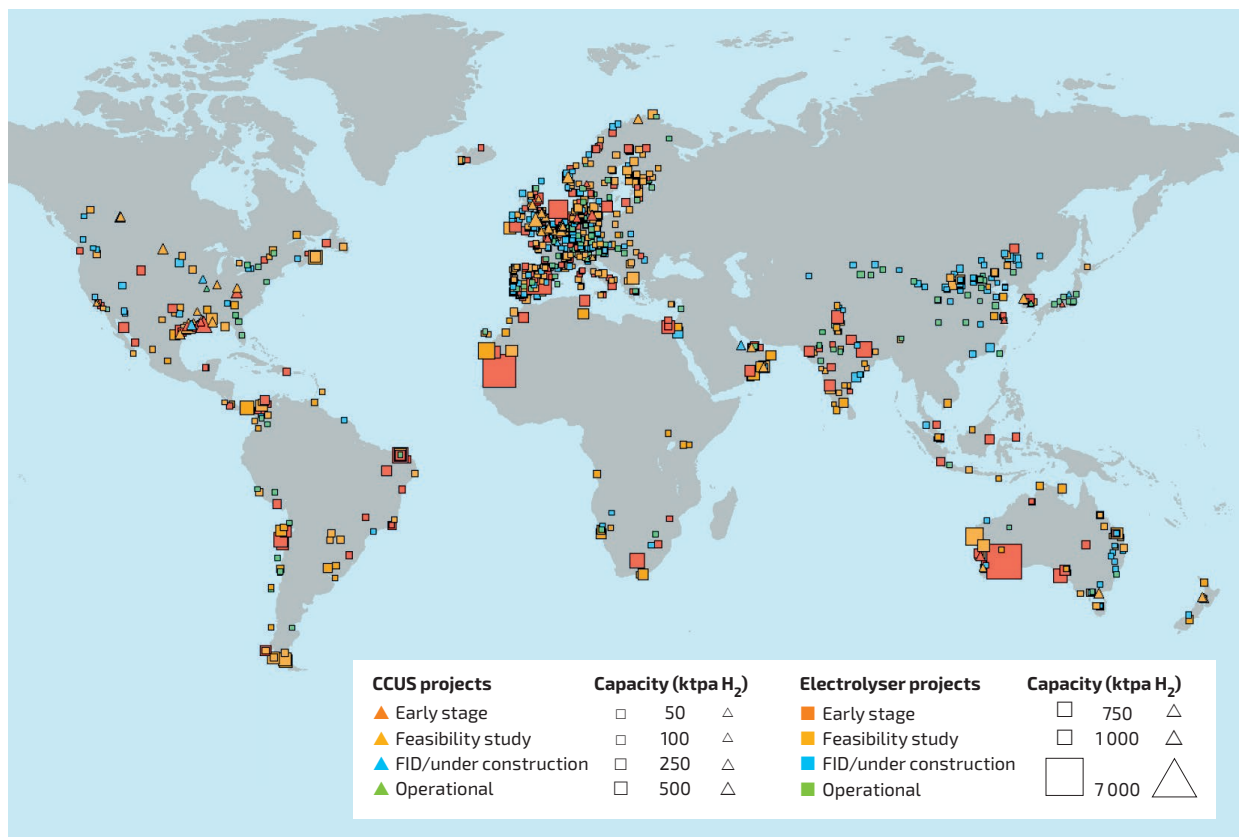
In its net-zero emission by 2050 scenario, the International Energy Agency sees hydrogen supply surpass natural gas in 2045.

Source: GIS/IEA (2023)

The realisation of the EU and German hydrogen strategies, and their hope to become leading hydrogen technology suppliers are largely dependent on technology innovation and technology-neutral pathways which should not exclude any technology option. A “technology-neutral” position is not just contested in Germany and the EU, but also in other Western democracies such as in the US, Australia, New Zealand, and other countries, due to arguments of “underwriting fossil-fuel-projects with public funds”, creating long-term path dependencies and subsidising old “dying” oil and gas industries. ‘Turquoise Hydrogen’ with gas pyrolysis, for instance, is a dry process without any water requirement and produces carbon black as a by-product. It may be transported by rail or truck, promises comparable advantages as it does not require CCUS (as does ‘Blue Hydrogen’) and might prove to be cost-competitive. But the technology – like many others – is still in the early stages (Umbach 2023b).

Outside of Europe, many other countries (see also [Figure 16](#); such as Japan and Australia in their Hydrogen Energy Supply Chain/HESC project) still favor not just green hydrogen, based on renewables and electrolysis, but also blue hydrogen, which includes the CCUS process. But whether those projects will meet the requirements defined by the buyers and offer commercial viability (due to even a higher energy demand and lower energy efficiency by including CCUS and the shipping costs), is equally uncertain at the present stage of development (IEA 2024a). Despite some progress with CCUS processes, offshore geological storage sites are still limited in numbers and capacities. In 2020, green hydrogen projects towards brown and blue hydrogen options have been projected to become cost-competitive by 2030. However recent cost increases of green hydrogen projects have put this anticipated target for 2030 increasingly in doubt (see again [Chapters 2.2](#) and [3](#)).

Figure 16: Map of announced low-emissions hydrogen production projects, 2024



Source: IEA (2024) in line with the CC BY 4.0 License

In contrast to the EU, Japan, Australia, the U.S., and other countries, China's H₂ development plans appear to still rather be modest and being balanced with various other energy policies for its future primary energy mix despite declared to play an important role in it. Beijing targets just 5% hydrogen by 2030 and 10% by 2050 of its final energy consumption. By 2035 it aims for comprehensive H₂ energy industry formation. Like other countries, it views hydrogen as a pivotal energy storage option for intermittent solar and wind power, to decarbonize steelmaking and other energy-intensive industries as well as an option for more flexibility in its national electricity system. By 2030, Beijing plans nearly to triple its solar and wind power capacities up to 3.3 TWh. In contrast to the EU, China has not focused just on green H₂ based on renewables since 2020. It is also developing other colorful energy options such as blue H₂ or pink H₂ (based on nuclear power) (Umbach 2023b).

While China's H₂ overall development is projected to grow rather incrementally by 11-20% by the end of this decade, it might speed up during the 2030s and further grow up to 90 Mt by 2060 to achieve its net-zero-emissions target. It has already 30% of the global installed solar capacity driven by significant cost reduction and subsidies, which has made Europe's green energy transition ever more dependent on China (IEA 2022c; IEA 2024a; Brown 2022; Kühl 2024; Xue 2024; Umbach 2023).

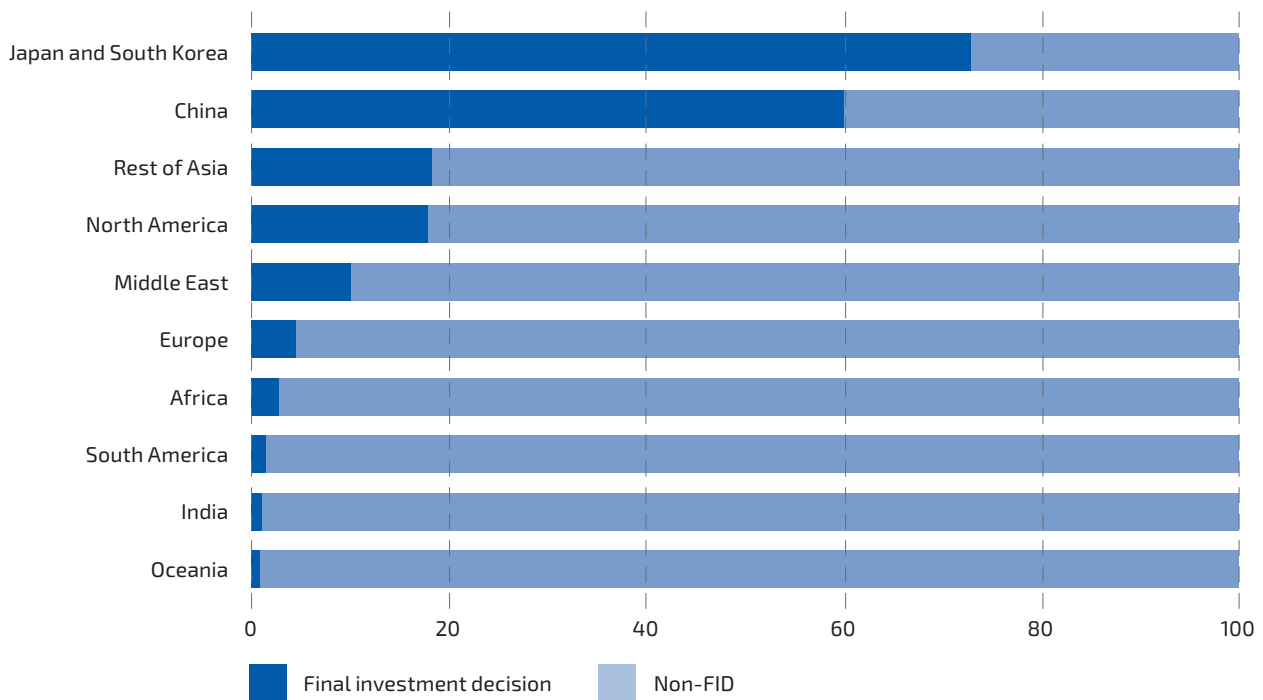
Beijing also seeks to strengthen its market share of global electrolysis capacity. It accounts for more than 40% of global FIDs in electrolyser capacity and is home to 60% of global electrolysis manufacturing capacity (IEA 2024a). Electrolysis has been the most expensive and rather inefficient production option – costing on average two to three times more than steam-methane reforming (even by including CCUS). Around 20-40% of the energy used in the

production process is lost in the present technology generation. Electrolysers have also a rather short lifespan (normally around 10 years), which makes them a costly solution to use. New Chinese electrolyser technologies indicate that Chinese alkaline electrolysis systems have decreased costs to just about US\$ 343/kWh – a third of about US\$ 1,200/kWh in Western countries (Arnold 2022; Umbach 2024b). It could result in an even higher import

dependence on green technologies – including electrolysis technologies and capacities. China's planned hydrogen technology exports to the global market also benefit from its strategic global control of expensive and scarce CRMs, particularly for its booming electrolyser capacity. It needs especially nickel, rare earths, and platinum group metals (PMG) such as platinum, iridium, and ruthenium (World Bank Group 2022; Butler, Denis-Ryan 2024).

Figure 17: Global hydrogen investments by countries

Asia leads in hydrogen investments by status (%)



Source: Financial Times/Hydrogen Council (2024)

Furthermore, despite being at the forefront and being in the driver's seat, most European H₂ projects lack final investment decisions (FIDs – comparing particularly with Japan, South Korea, and China – see Figure 17) due to the lack of regulatory clarity and European-wide standards in regulations as well as an uncertain demand. Industry experts have already warned in 2022 that the EU might miss its green hydrogen targets by 2030 due to too different national H₂ standards within the EU, which are also globally a barrier to the development of

international hydrogen trade. Those different national standards include different rules and framework regulations on carbon intensity as well as certification systems. They also need to “standardize processes, minimize costs and maximize transparency” on a global level as clear objectives (IEA 2023b). As an IEA study warned, if those barriers won't be overcome by defined international or regional standards (such as in the EU), the present market fragmentations and investment risks will continue and hamper the implementation of planned H₂ projects and faster decarbonization of the world's industries. In 2023 only 7% of the worldwide announced low-emission H₂ projects are under construction or have already passed an FID decision due to those barriers (IEA 2023b). On the positive side, many countries have increased their investment in future hydrogen options and updated their older hydrogen strategies (IEA 2023a; IEA 2024a). The IEA has also warned that the overall global investments in hydrogen storage are not sufficient for the global demand and storage needs (IEA 2024a).

Green hydrogen is still facing technological challenges across the entire supply chain, beginning with CRMs for electrolyser capacities and production and storage to transport and end-use have prevented a faster expansion of production and an international hydrogen trade (BNEF 2024a; BNEF 2024b; Palladino 2024). Already in 2020, some experts had warned against considering hydrogen as another “silver bullet”-solution due to the present inefficiency of electrolysis and the need to convert H₂ into synthetic fuels and feedstocks (Umbach 2020a; Umbach-Pfeiffer 2020). It includes some 45-60% loss of the electricity used to produce the complex and capital-intensive hydrogen in the entire supply chain process. By turning electricity into hydrogen, it could lose alone about 25% of its energy. The energy stored in H₂ is around 60% less compared with LNG due to the lower volumetric energy density of the presently available technology (Umbach 2023b; Umbach 2024b).

In addition to new Chinese electrolysis technology developments, also in Australia (a potential green energy superpower in the forthcoming decades

– Umbach 2021c) a new capillary-technique has been developed for the electrolysis process which splits seawater to produce green hydrogen. It should allow to increase its efficiency of the overall effect method to increase from 75% up to 95%. If successful, it could make green H₂ cost-competitive to blue hydrogen five years earlier than 2030 as previously forecasted. The first electrolysis gigafactory is projected to begin its operation in 2025. It could confirm that technological progress might lead to a downward pricing trend of electrolysis in the mid-term perspective (Bersle 2023).

Experts from the aviation industry hope that a hydrogen retrofit of a regional airliner could already be in service in 2025/26. Instead of a radical redesign of an aircraft and powering aircraft by electrical power from fuel cells, hydrogen-powered aircraft will have engines burning hydrogen (Chew, Sagun-Trajano 2024).

A potential game changer could be 'white (natural) hydrogen (Pironon, de Donata 2023; Berse 2023; Fischer 2023; Wetzel 2020; Cookson 2024; Honsel 2024). Reportedly, larger white hydrogen resources have recently been found in France and Albania. As demonstrated in Mali, the African country has proven natural hydrogen, which does not have to be produced in an energy-intensive way but can be extracted directly technologically and up to a fifth of the cost. In the first phase, 45 wells are expected to produce around 16,000 t of hydrogen per year (Prinzhofer, Cisse, Diallo 2018). It is possible that such a 'white hydrogen' could also be directly extracted in other countries and then become a global 'game changer'. So far, however, there had been no active search for it until recently. An analysis by the Federal Institute for Geosciences and Natural Resources (BGR) from June 2020 lists up to 10 places worldwide (such as Oman, Russia, Canada, the USA, and the Philippines) where high hydrogen concentrations of 30-99% have so far been found by chance. However, no orders of magnitude have yet been found in the geological subsurface that can even be compared with those of large commercial natural gas fields (Franke, Blumenberg, Pein 2020; Patonia, Lambert 2024).

The maritime hydrogen transport sector: Imports of H₂ derivatives, energy efficiency dimensions and the geopolitical risks of unstable maritime routes

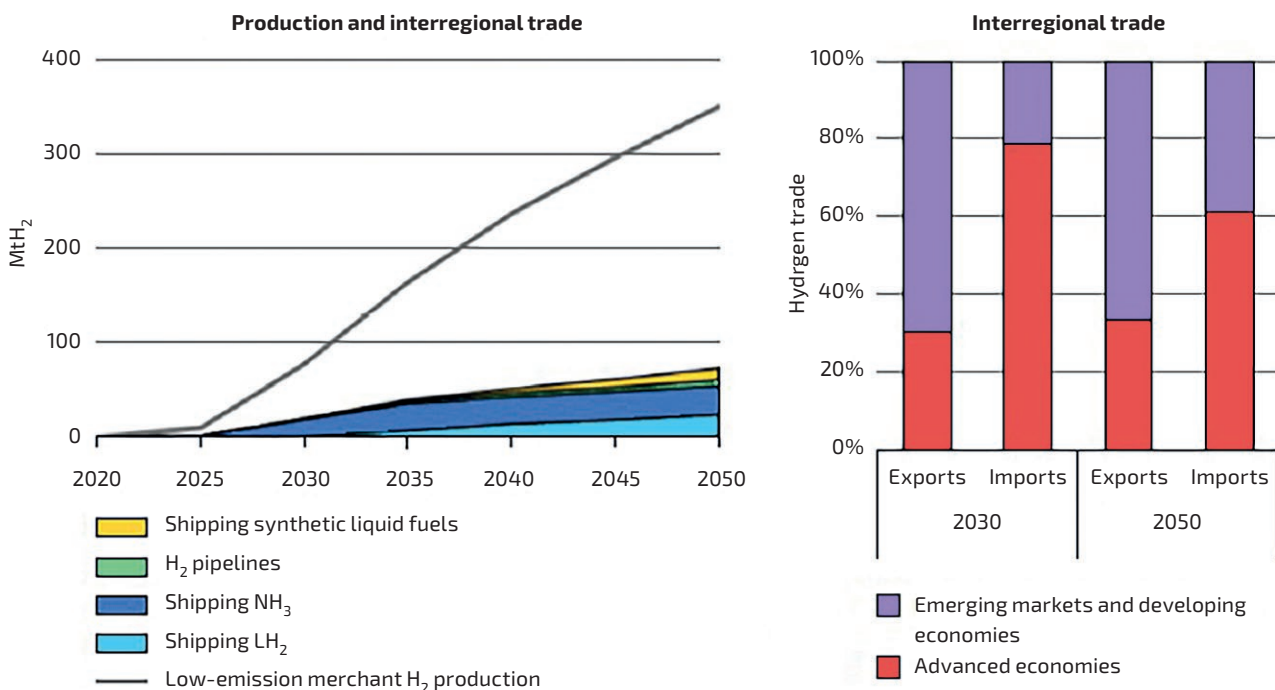
Hydrogen as a low-carbon fuel can be transported as liquid hydrogen (LH₂), ammonia (NH₃), and liquid organic hydrogen (LOHC) carrier over varying distances. Some 400 Mt of the forecasted 660 Mt have been projected to meet the EU climate goals for long-distance maritime transport. Seaborne Transportation is the most cost-competitive option for distances more than 2,500 km (Kneebone, Piebalgs 2023; Umbach 2024b).

Like Liquefied Natural Gas (LNG) versus natural gas, liquid hydrogen is easier to store than hydrogen itself but is also more technologically challenging than LNG as it must be cooled and kept at -253°C

(LNG: -162°C) or it boils off. The liquefaction of hydrogen transported over long distances could lose more than 30% of the energy content of hydrogen.

Other projections have suggested that hydrogen lost for boil-off and fuel use for propulsion via a 9,000km shipping tour could be up to 40%. The boil-off could be as high as 9 times compared with the loss in LNG shipping. A fully loaded LNG carrier transports about 72,000 t of LNG, which is some 1 TWh of energy. In comparison, one needs 2.5 Liquid H₂ (LH₂) carriers to transport 1 TWh in the form of LH₂. The world's first shipment of LH₂ took already place from Australia to Japan in February 2022 (Umbach 2023b).

Figure 18: Global production of low-emission merchant hydrogen and interregional trade (NZE Scenario)



Source: IEA (2023) in line with the CC BY 4.0 License

Notes: Mt H₂ = million tonnes of hydrogen; LH₂ = liquefied hydrogen; NH₃ = ammonia. Interregional trade is based on regions modelled in the NZE Scenario. Trade in LOHC is not explicitly modelled in the NZE Scenario.

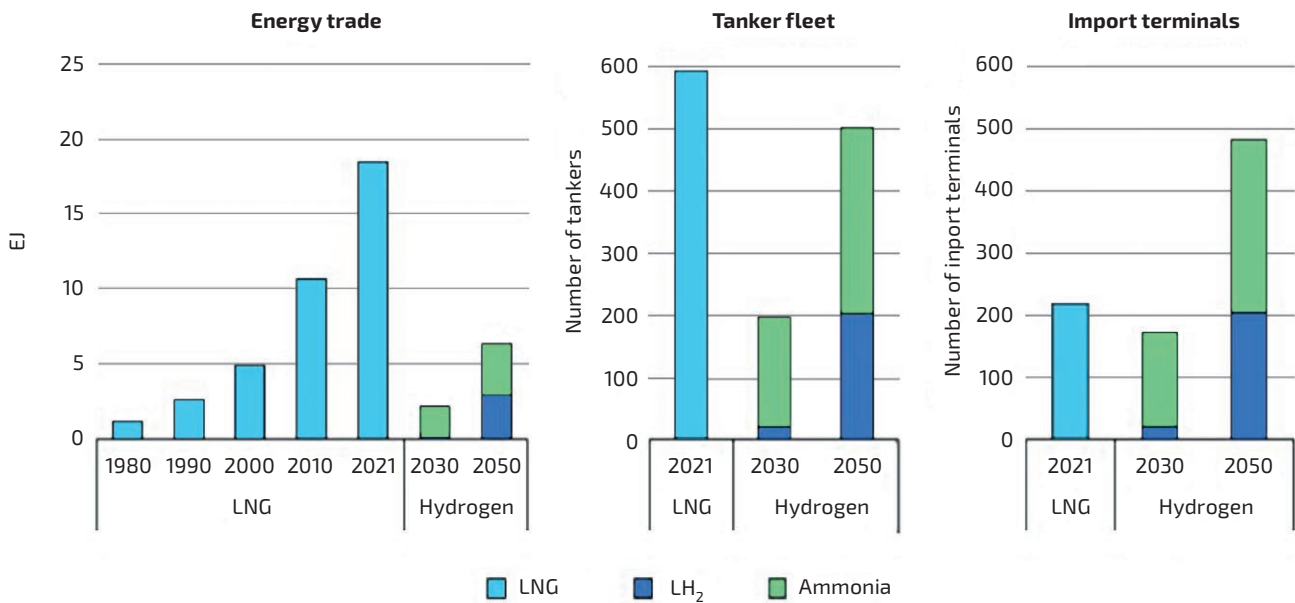
Some 16% of global merchant hydrogen supply is shipped as LH₂ or ammonia in 2025, with more than 65% of exports coming from emerging economies in the NZE Scenario.

The delivery and regasification at the receiving H₂ import terminal could consume another 5% of the energy content of the cargo. Japan, Australia, Saudi Arabia, and potential hydrogen importers and exporters pin great hopes particularly on ammonia as a low-carbon fuel. In June 2020, Japan – which imports 90% of its energy demand – unveiled a public-private investment of US\$ 104 bn to build H₂ and ammonia supply chains. Ammonia has the benefit that needs to be cooled just at -33°C (and not -253°C as liquid hydrogen) and can use already existing shipping ammonia options (RANE 2024a). To some extent, green ammonia is already competitive with fossil alternatives in 2022 due to the gas price explosion (Lex 2022; Wee 2023). By 2050, the IEA has forecasted in its 'New Zero Emissions (NZE)' scenario that around 20% of the 400 Mt of low-emissions

consumed global hydrogen equivalent might be traded internationally (see also Figure 18 and Figure 19).

Japan also wants to help Southeast Asian countries replace some coal consumption with ammonia as it allows reducing carbon emissions from coal-fired plants without retiring them. But co-firing a power plant with 20% ammonia and 80% coal will emit more CO₂ than combined-cycle gas turbines, which are widely used to generate electricity from gas. A higher co-firing rate of 50% ammonia or more is still considered as too expensive in comparison with other low-emission technologies. In contrast to many other countries by focusing almost exclusively on electromobility, Japan also hopes to have 800,000 hydrogen vehicles on the road by 2030 (IEA 2023a; IEA 2024a).

Figure 19: Interregional trade and infrastructure for shipping low-emission H₂ compared with LNG trade



Source: IEA (2023) in line with the CC BY 4.0 License

Notes: EJ = exajoile; LNG = liquefied natural gas; LH₂ = liquefied hydrogen; For the LNG tanker count, small and medium-sized tankers, icebreakers and bunkering vessels are not included. Hydrogen traded as an LOHC is not explicitly modelled in the NZE Scenario.

While hydrogen shipped as LH₂ or NH₃ in 2025 in the NZE Scenario is equal to one-third of today's LNG trade in energy terms, their lower density requires almost as many tankers.

The ever-increasing maritime trade, including fossil fuels (like oil and LNG), has been the backbone of global trade and the global economy. The future shipping of hydrogen and its derivatives will further increase the international shipping and expansion of maritime transports via critical Sea Lanes of Communication (SLOCs) and Choke Points of narrow sea channels (such as the Strait of Hormuz, Bab-el Mandeb, the Sues Canal, the Malacca Strait, and others) (EIA 2024). During the last decades, increasing piracy at the eastern coast of Africa and other maritime regions as well as the recent Houthi attacks on international shipping via and near the Bab el-Mandeb have highlighted how vulnerable the maritime transport of oil, LNG, and other goods is for regional and even global stability of the worldwide and European trade (Umbach 2018b). Iran's hardline and powerful Revolutionary Guards, for instance, have

repeatedly threatened to close the vital Strait of Hormuz if the U.S. is threatening the national economy and political stability of Iran. It could block the regional oil and LNG exports to the world markets and lead to a more dangerous escalation with severe global economic and energy impacts as some 35% of the global maritime oil trade moves through this strait. Another example of the acute geopolitical risks of maritime transport is the recent disruption in the Red Sea by the Houthi attacks. They caused a loss of US\$ 7 bn for just Egypt's state budget last year (El-Tablawy, Wahba 2024). The forecasted expansion of the global hydrogen trade will further increase the geopolitical risks on unstable SLOCs and Choke Points. Around 50% of all maritime trade in clean technologies, for instance, already passes through the Strait of Malacca and other important global Choke Points (IEA 2024f).

4.2 Geopolitical Risks and Vulnerabilities in a Hydrogen Era

The last years have shown how the geopolitical landscape can change very rapidly and profoundly with huge implications for stable supply security when market concentration, manipulation, and asymmetric interdependencies are overlooked (IEA 2024d; Fels 2024).

An important pre-condition for providing green hydrogen from RES, up to 20% of the global energy demand by 2050, the electrolysis of hydrogen conversion requires sufficient water and electricity supply. A worldwide expansion of, and shift to, hydrogen as a major instrument of decarbonisation in the international energy system will inevitably result in new geopolitical winners and losers as well as new challenges for energy supply security. This, in turn, results in varying geopolitical implications for a 'green' or 'blue' hydrogen future in Europe and the rest of the world (IRENA 2022; Pflugmann, de Blasio 2020):

- New Rising Import and Geopolitical Dependencies:** Import and external (over)dependencies leave Europe vulnerable to market instabilities and geopolitical risks and blackmail as Germany's excessive gas pipeline dependence has been highlighted as a historical lesson. High energy and electricity prices of the EU (and Germany as the largest economy in Europe) – up to three times compared with the U.S. and even higher towards China – are hurting the industrial and overall competitiveness and have undermined European political solidarity. In the new world of a geopolitical *Zeitenwende* (change of an era) and fragmented globalisation with worldwide supply chain disruptions, resilience of supply security and stable imports will play a much more important role in the future. Accordingly, the EU needs to rebalance its ambitious energy and climate agenda with industrial competitiveness, cost efficiency, and resilience of supply chains. Consequently, it needs to build up more green hydrogen production and electrolysis capacity and

decrease its energy import demand than in the old world of liberalised global markets (Lotze et al. 2023)⁷, when the old assumption of "it's the economy, stupid" was still prevailing in Western democracies.

- A Renewable Hydrogen Future:** In a 'Green Hydrogen' future, Russia could be a loser of the EU's and global decarbonisation efforts. Unlike Australia, Africa, and the Middle East and Northern Africa (MENA) region, Russia does not have comparable cheap and abundant solar and wind power capacities, though theoretically, it could be a 'blue hydrogen' superpower when sufficient costly hydrogen infrastructures could be built (see Figure 20 and Figure 21). However, it had never shown a greater interest at any hydrogen exports until its Ukraine invasion in 2022 because they have not been considered as much profitable as its traditional gas exports to Europe, according to Russian energy experts and their domestic debates (Umbach 2021d).

Whether renewable hydrogen will be regionally concentrated (such as today's gas markets) or be more decentralised will largely be dependent on technology, the existence of enabling infrastructure, and future market structures. Renewable hydrogen is also dependent on and constrained by the space available for RES-based electricity generation and the country's population density (e.g. in Germany). Another factor could be sufficient water supply, especially in countries where water is a scarce resource (e.g. Africa, the Middle East, South America, and Asia, including in many regions in China). Other countries may have access to vast RES, the space to expand electricity generation, and sufficient water supply but are unable to build the required infrastructure for the production, transmission, and distribution of RES. The bigger the country, the more expensive it is to build the needed infrastructure (such as in Russia, India, China, and the US). In this light, one of the first analysis of the geopolitical implications of a green hydrogen revolution identified

Figure 20: Hydrogen export champions and resource endowment

	Group	Resource endowment		Infrastructure potential	example countries
		Renewable energy resources	Renewable freshwater resources		
1	Export champions with vast renewable energy and water resources, as well as high infrastructure potential	++	+	+	Australia, United States, Morocco, Norway
2	Renewable-rich, but water-constrained nations with high infrastructure potential	++	--	+	Saudi Arabia, potentially China
3	Renewable-constrained nations with high infrastructure potential	-	+	+	Parts of the EU, Japan, South Korea
4	Resource-rich nations with high infrastructure potential	+	+	+	Turkey, Spain, Thailand
5	Resource-rich countries with low infrastructure potential	+	+/-	-	Most parts of South America

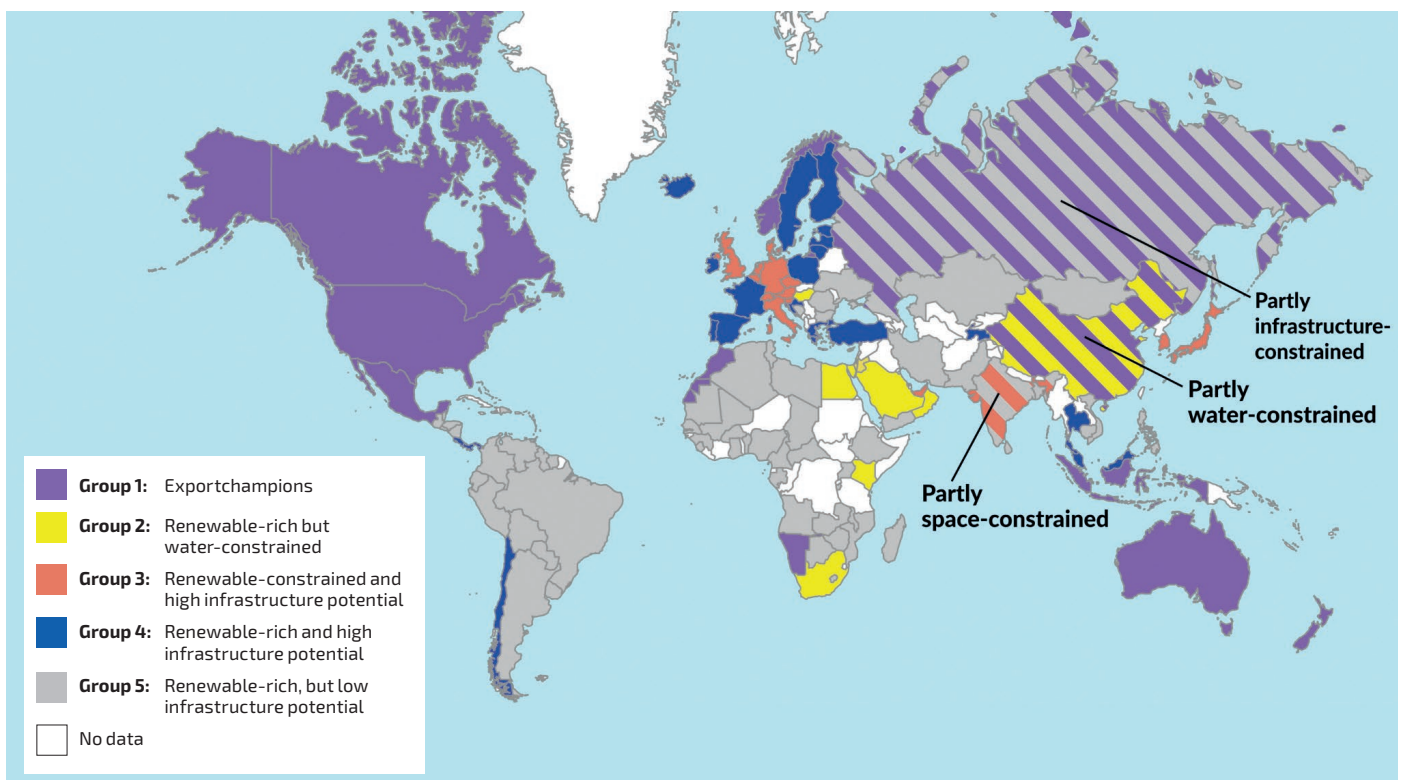
Source: GIS/Belfer Center (2020)

7 An analysis based on two different scenarios concludes, for instance, a doubling of the electrolysis capacity from 29GW in an unrestricted global hydrogen market up to 60GW in a resilient energy scenario by taking geopolitics more into account – see Lotze et al. (2023).

the US, Australia, Morocco, and Norway as future potential export champions and the real geo-economic as well as geopolitical winners. The EU might be a leading technology supplier with a high infrastructure potential but will be constrained in its efforts to expand RES due to its limited space and high population density as well as the water scarcity in some member countries (Pflugmann, de Blasio 2020; Umbach 2020c).

Europe and Southeast Asia might become net importers of renewable hydrogen from new energy export champions (such as Australia and Morocco with their strong cost positions and access to large import markets). Against this background, the EU needs to develop hydrogen supply security strategies with clear long-term diversification objectives to bolster the resilience of its imports and supply chains.

Figure 21: The global renewable hydrogen world



Source: GIS/Belfer Center (2020)

While the EU and Germany still prefer the expensive 'Renewable Hydrogen' option rather, many other countries (i.e. China, India, Japan, South Korea, and others) will not only pursue the more expensive options in the next decade, as their large fossil fuel reserves for cheaper blue hydrogen production provide offers more commercial profitability at least in the short-term and mid-term perspective for the transition period. Although production costs are expected to decline by 2030, large-scale demand through upscaling and mass production will still be

required to render blue hydrogen cost-effective and affordable.

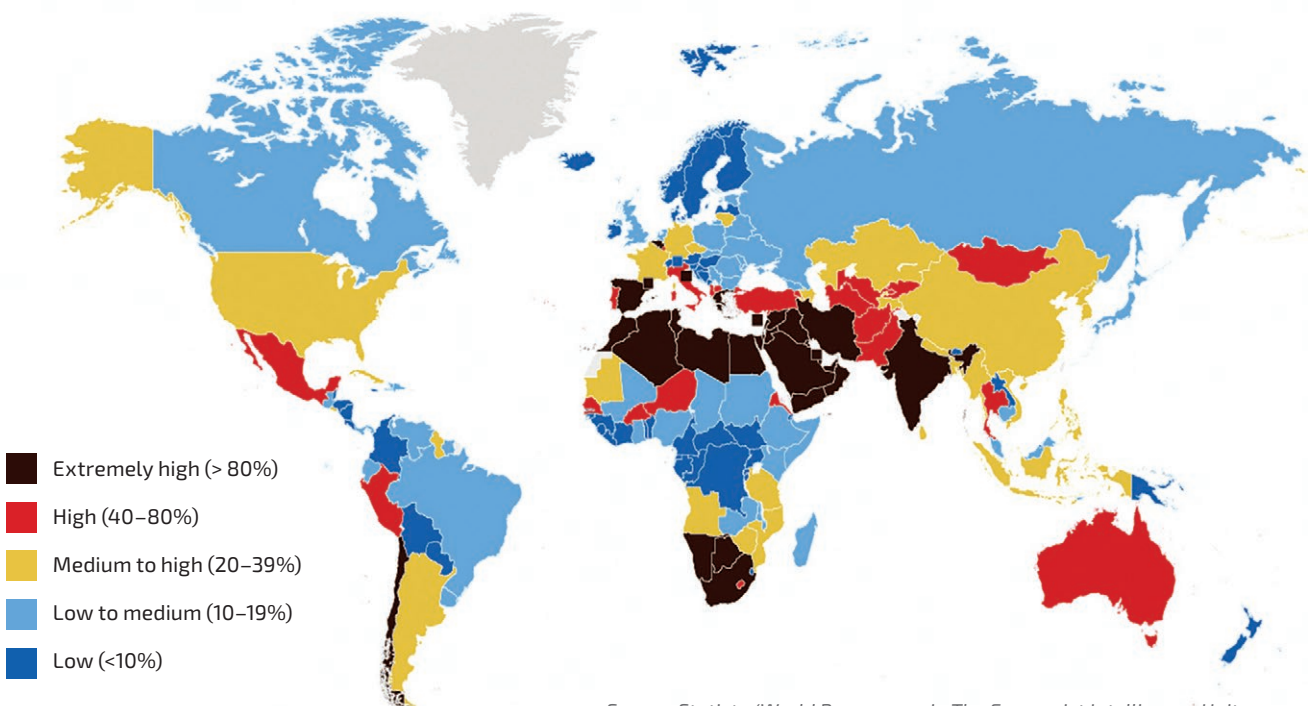
Given the rising hydrogen industry rivalry with China and worldwide tendencies of economic nationalism, the EU, Australia, and the US must also protect their industry stakeholders from unfair competition and foreign takeovers in an era of fragmented global markets and a new wave of resource nationalism (McCormick, Hodgson 2024).

- Water Scarcity – A Challenge for the Hydrogen Revolution?:** Green hydrogen can be produced at best in the sunny EU's southern member states such as Spain, Italy, and Greece as well as in North Africa such as Morocco. But all MENA- and African countries are facing huge water scarcity problems. Any additional use of larger water reserves for green hydrogen production could exacerbate the already deteriorating water security and hamper agriculture production in Africa, Latin America, and other countries – particularly when they do not have any coastlines (RANE 2024b; RANE 2024c). Therefore, many H₂ projects incorporate desalination plants. But they are also expensive, energy-intensive, and could cause other environmental problems on the coast and territorial waters.

According to the U.S. Department of Energy, 33 projects of the planned hydrogen hubs are in highly-water-stressed regions such as Southern California, Colorado, Kansas, and New Mexico as well as Texas (Volcovici 2023; Chu 2024). Globally, even more than 70% of proposed green hydrogen projects are in water scarcity regions like the Middle East and Africa. As a result, extensive environmental impact reviews of groundwater use and conservation efforts are needed as desalination plants could worsen water pollution by solids, chlorides, and sulfates as well as damage the ecosystem. Despite the increasing global water shortages (see Figure 22) because of worldwide climate change, international investments are still insufficient to cope with growing water problems in many countries (RANE 2024d).

Figure 22: Where Water stress will be highest by 2050

Projected ratio of water withdrawals to water supply (water stress level) in 2050



Source: Statista/World Resources via The Economist Intelligence Unit

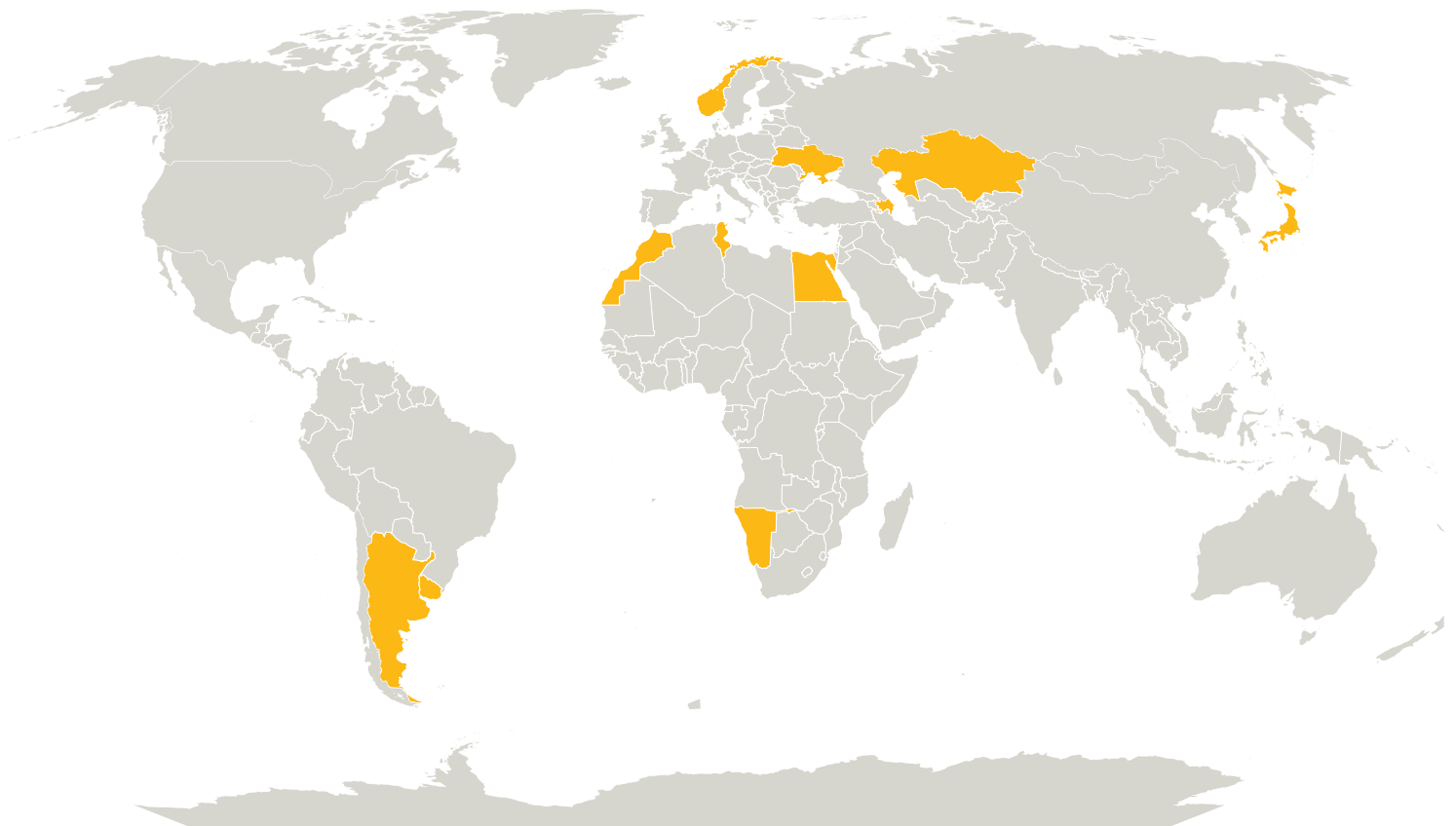
4.3 Hydrogen Partnerships

Originally back in 2020, Ukraine and Morocco played the most prominent role in the German and EU hydrogen strategies as part of their hydrogen and energy foreign policies (BMWK 2020; European Commission 2020a; Umbach 2021; NWR 2024b). Countries with large, non-populated, unused or underdeveloped land, abundant RES, and relatively low domestic hydrogen demand could benefit at most from the global hydrogen revolution and H₂ exports. But the EU also needs to balance its hydrogen import policies with its climate policies as well as its industrial competitiveness. The global hydrogen demand centers and H₂ net-importing countries could be supplied via pipelines or ships. Thus,

hydrogen partnerships between Europe and North African countries – as part of an already existing European-Mediterranean energy partnership –, for instance, could benefit both sides (Beckman 2021; BMWK 2024b; BMWK 2024c). Potential import corridors are depicted in [Figure 25](#).

The EU signed H₂ partnership agreements (see [Figure 23](#) and [Table 3](#)) with Morocco, Egypt, Namibia, and other countries. It has also offered Kenya, Mauritania, and South Africa to develop green H₂ by offering those countries financial and technical support for their H₂ development projects (Agora Energiewende 2024; Alsulaiman 2023).

Figure 23: EU's hydrogen partnerships (2022-2024)



Source: Dr. Frank Umbach illustration based on European Commission (2024)

Table 3: The EU's hydrogen partnerships

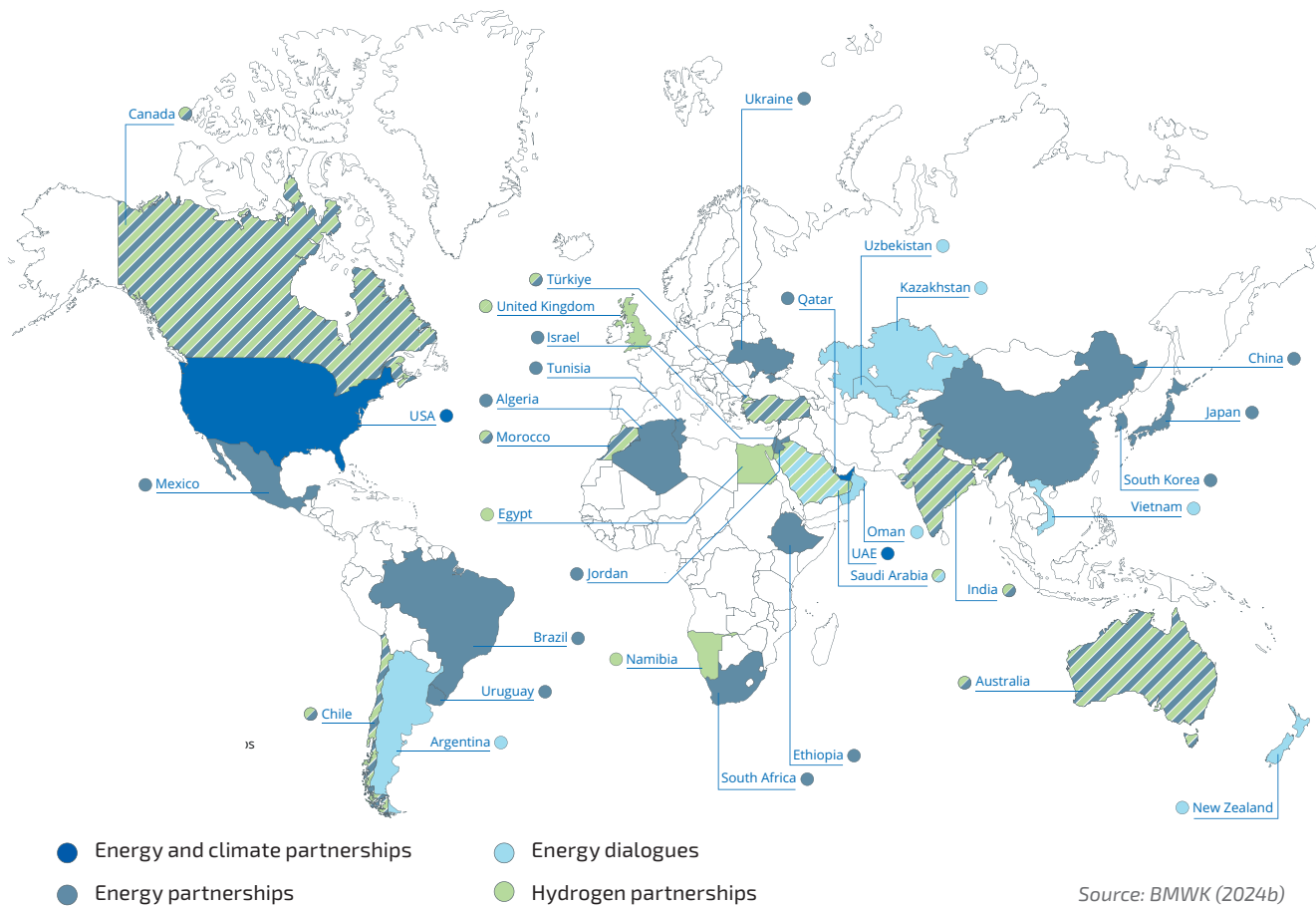
EU-Hydrogen Partnerships (2022-2024)
EU – Morocco MoU on Green Partnership was signed on 18 October 2022.
EU – Kazakhstan MoU on a Strategic Partnership on Sustainable Raw Materials was signed on 7 November 2022.
EU – Namibia MoU on Sustainable Raw Materials Value Chains and Renewable Hydrogen was signed on 8 November 2022.
EU – Egypt MoU on a Strategic Partnership on Renewable Hydrogen was signed on 16 November 2022.
EU – Japan Memorandum on Hydrogen was signed on 2 December 2022.
EU – Ukraine MoU on a Strategic Partnership on Biomethane, Hydrogen and Other Renewable Gases was signed on 3 February 2023.
EU – Norway Green Alliance was signed on 24 April 2023.
EU – Argentina MoU on Cooperation Related to Energy was signed on 17 July 2023.
EU – Uruguay MoU on Cooperation Related to Renewable Energies, Energy Efficiency and Renewable Hydrogen was signed on 18 July 2023.
EU – Azerbaijan MoU on Strategic Partnership in the field of energy, signed on 18 July 2022.
EU – Tunisia MoU to Promote Renewable Energies signed on 13 June 2024.

Source: Dr. Frank Umbach based on European Commission (2024)

But the EU needs to avoid a widespread impression in Africa and elsewhere (as documented by its failing Desertec project in North Africa) of promoting just H₂ export projects instead of supporting H₂ projects for the decarbonization of the energy mixes of African countries themselves as their energy companies are almost all bankrupt. Moreover, many countries in Asia, Africa, and South America are not just interested in green hydrogen projects but also blue ones – particularly those who have massively invested in natural gas and LNG (export) projects (Adeoye 2024).

The German government (see [Figure 24](#)) – more than other EU member states or the European Commission – has also supported and agreed to many bilateral hydrogen partnership agreements with African and Latin American as well as other countries (BMWK 2023a; BMWK 2024a; BMWK 2024b; NWR 2024b).

Figure 24: German hydrogen and energy partnerships



Hydrogen partnerships and long-term contracts with African and Latin-American countries are certainly an important instrument and necessary to diversify import dependencies to avoid overdependencies as in Germany's and the EU's past decades on Russia (Bouacida 2022; Nuttall 2023; Cantini 2022). However, neither of these instruments provides any real guarantee, especially in times of crisis with rapidly changing political framework conditions. Hydrogen partnerships assume a rule-based world order in which new governments in Africa, Latin America, and other parts of the world will respect existing and agreed contracts.

But the political and geopolitical realities meanwhile are different than four years ago. Neither opposition parties nor geopolitical powers such as Russia and China support a rule-based order neither at home nor abroad. Both are also willing to overthrow

governments with the financial and military support in Africa and elsewhere (as the use of the half-private Russian Wagner group has repeatedly demonstrated during the last decade).

Under these geopolitical pressures as well as fragmented global markets and supply chains, hydrogen partnerships will face many more uncertainties to translate into long-term sustainable trade and energy supply security for Europe. The EU has expanded its hydrogen 'partnership of equals' to countries in Africa and South America as part of its 'Hydrogen Alliance' during the last years. It shall prevent geopolitical dependencies, diversify its imports, and respect the decarbonization interests of its partner countries. In this regard, it seeks to avoid colonial mistakes and China's 'neocolonial resource grab' to promote its unilateral interests at the expense of its African partners. Instead, it favors a

mutual win-win benefit cooperation on an equal footing in Africa (Rikabi 2024; Agora Energiewende 2023; Gomes et al. 2024; Hank et al. 2023; Kapelier, Reuter, Ortmann 2023; Kathan 2022; Shabaneh et al. 2024).

Furthermore, negotiated and agreed bilateral hydrogen partnerships for joint (production) H₂ projects should not be equalized automatically with H₂ imports to Europe. Most of these proclaimed and negotiated hydrogen partnerships cannot translate directly into stable hydrogen exports from non-European partner countries as, ultimately, the private energy industry must sign commercial H₂

contracts based on commerciality and profitability. But even the newly agreed first import contracts need to be subsidized and supported by state funds and credits. Under certain circumstances, such partnerships and contracts could even lull politicians and industry into a false sense of supply security if they are not part of a comprehensive and strategically defined supply security strategy by including commerciality and profitability for the industry. Moreover, geopolitical risks are increasing in a non-rule world, in which the number of democracies is in a minority since 2016 and further shrinking almost every year.

4.4 Geopolitical Risks of the EU's Main Hydrogen Import Routes

In the previous [chapters 2](#) and [3](#), we have drawn attention to the newest global and European studies and analyses, which have decreased the global and European hydrogen demand and supply. This could also decrease the future EU hydrogen import demand to less than 10% if an integrated European hydrogen system with a cost-optimal system design can be implemented as a new study has concluded (Fleiter et al. 2024). Furthermore, those studies have also concluded and recommended that for both economic and geopolitical reasons, Europe should rely on its own green hydrogen production as much as possible. Thus, the Scandinavian countries (particularly Norway, Denmark, and Finland) may cover a larger part of Germany's and the EU's imports. EU member states had already disputed the scale of its future hydrogen imports as some EU member states already warned since 2020 not to become too import dependent again as the EU has been historically a major energy importer primarily from unreliable suppliers like Russia (with its gas pipeline exports) and the Persian Gulf states (with its oil supplies during the oil crisis

in the 1970s), which have weaponized the European import dependencies in the past (Simon 2021).

However, the basic conclusion of favoring "energy independence" and "energy self-autonomy" (without being able to achieve them completely) as well as the intention of strengthening the EU's industrial competitiveness will have to be balanced with cost considerations and its international trade interests as well as climate protection policies. Thus, the inherent conflicts between the three major objectives of the 'energy trilemma' will further increase in the EU's energy policies as well as globally. Its hydrogen policies are no exception in this regard and need to balance these three strategic objectives and the risks and trade-offs more strategically in the new geoeconomic and geopolitical environment (Dejonghe 2023; Giuli 2022; Ansari, Pepe, Gehrung 2023).

In general, hydrogen pipeline imports up to 3,000 km are considered cheaper and more energy efficient than maritime transport.⁸ But maritime transport

8 2,500-3,000 km distance has been a rule of thumb for gas pipeline vs. LNG shipping imports. Some studies for hydrogen imports have estimated a higher commerciality for pipeline imports even up to 5,000 km (Wietschel et al. 2024). But up to now, no hydrogen pipeline is planned or discussed beyond around 2,000 km (IEA 2024b). Furthermore, no safety and security experiences (e.g. hydrogen leaks and losses etc.) are available for long-distance onshore and offshore pipelines (IEA 2024b).

options may become more cost-competitive over time and the scale of the worldwide expansion of the hydrogen demand and use.

From a geopolitical point of view, in contrast to worldwide oil and gas production, green hydrogen production won't be so much concentrated in a few suppliers and exporting countries and, instead, offers much more import diversification options. The newly forecasted decreased global and EU hydrogen demand also offers a perspective of a reduced hydrogen import demand from outside Europe. Therewith, it could also reduce the geopolitical risks from unstable imports from outside Europe. In addition to the net-exports of the Scandinavian countries Denmark, Sweden, and Finland to net-importing EU-member states (like Germany), non-European hydrogen exports to the EU will primarily be supplied from Norway as the EU's main gas supplier today and its closest energy partner (as a stable democracy and market economy).

The EU also needs to consider maintaining an adequate mix of hydrogen imports via pipelines and shipping. While pipeline supplies are mostly a more cost- and energy efficient transport option up to 3,000 km, the shipping option for imports also guarantees supplies in the case of disruptions as hydrogen transport ships can deliver supplies from other exporters even during a (geo)political crisis. Thus, ships can be re-routed at short notice in contrast to unflexible pipeline transports (as the German gas supply crisis had highlighted when Russia stopped all pipeline exports in August 2022 and when Germany had still no LNG-import terminals). Hence, shipping of hydrogen (or LNG) imports serve the criteria of 'crisis stability' as part of energy security concepts.

In general, imports from other democratic countries with a stable market economy (such as the G7 member states) are to be preferred from a geopolitical risk perspective – including the U.S., Canada, and Australia – at first glance. Thus, the EU and Germany as the largest EU hydrogen importer should give some priority to an expanded hydrogen production in its member states and Norway. But the following examples highlight that even in this case, new

geopolitical risks are involved which are different from previous times:

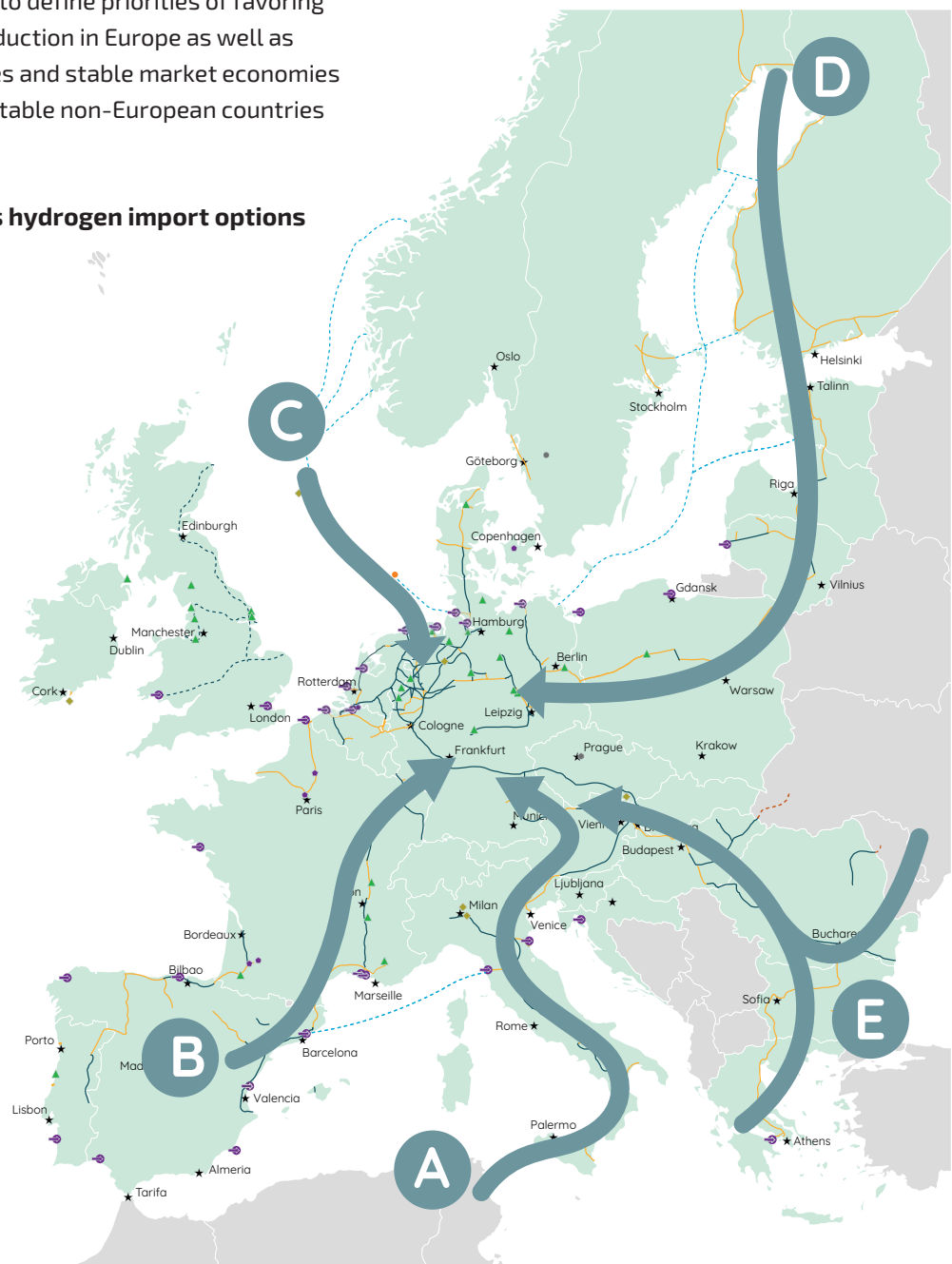
- **Norway** has been the most important energy partner of the EU for decades and has become even more important after Russia suspended its gas supplies via the Nord Stream gas pipelines at the end of August 2022 and alongside Western energy sanctions against Russia. With its potential for larger hydrogen exports in addition to its oil and gas supplies to the EU, it might become even more strategically important. As a stable democracy and market economy, which never really caused any troubles for the EU, it has been the perfect energy partner. However, since Russia's military invasion into Ukraine and becoming even more important for the EU, both Norway and NATO fear a deliberate Russian sabotage of its critical (maritime) energy infrastructures (CEIs) such as offshore and onshore energy production sites as well as undersea electricity and internet cables (Piebalgs, Schmitt, Umbach 2024). Any successful hybrid warfare and open sabotage of those CEIs could have major impacts on the EU's and UK's energy supply security. Hence, even a high import dependence on Norway could prove to be shortsighted and counterproductive for the EU's future energy and hydrogen supply security.
- The **U.S.** has become the most important LNG supplier of the EU already before the Ukraine war began. During the wintertime of 2022-2023, it was the only LNG producer worldwide that could significantly increase its LNG production and exports to the EU at short notice (Umbach 2023c; Umbach 2023d). It has strengthened both the transatlantic and security partnership between both sides. The European Commission has now offered the U.S. even more LNG imports to avoid a potential bilateral trade conflict across the transatlantic. By 2030, the U.S. has been forecasted to become the world's largest producer of hydrogen, which could also allow exports to Europe. But with the new Trump presidency and Europe's strategic security interests at close and stable transatlantic relations, even future stable hydrogen imports from the U.S.

have become uncertain as no one can exclude the possibility that Trump could use the long-standing EU's energy dependence and weaponizing it as a coercive diplomatic instrument in an escalating trade conflict with the EU (Liebing, Murphy 2024).

and potential hydrogen exporters. At the same time, it needs to become more pragmatic and not restrict those imports by overloading the energy and hydrogen partnerships with too many own demands and requirements which are often perceived as another "neo-colonial agenda" of Europe under the cover of a green energy and climate policies (Ansari, Pepe 2023; Ansari, Pepe, Gehrung 2023).

In this light of potential geopolitical risks, the EU needs in principle to diversify its imports regardless of who the exporters are (Ansari, Pepe 2023b) as a basic requirement of its import strategy. On the other hand, it needs to define priorities of favoring green hydrogen production in Europe as well as other G7 democracies and stable market economies over often more unstable non-European countries

Figure 25: Europe's hydrogen import options



Source: European Hydrogen Backbone (2024)

While the EU also has favored close hydrogen partnerships with Canada and Australia, those partnerships are equally uncertain for different reasons. Both countries have also a strategic interest in hydrogen exports to the EU (for commerciality and their own demand security as exporters). But Canada has no existing gas or hydrogen pipelines and export terminals in place at its eastern Atlantic coast of the country. Building completely new ones is very expensive and Canada has not made any investment decision up to now as it will only be realistic with long-term contracts which European companies have not agreed on – neither for Canadian LNG nor future hydrogen exports to Europe (Atlantik-Brücke Canada, KAS-Canada, NANOS-Research 2023).

As a green energy and technology superpower in the forthcoming decades, Australia has become an ever more important strategic trade partner for the EU, including for CRMs, joint green technology collaboration, and potential hydrogen exports (Umbach 2021c; Morgan 2020; Fernyhough, Hume 2022). But currently, the Australian government is still focusing on its expanded LNG and CRM exports rather than fastening its green energy transition. Furthermore, the EU will face heavy competition for any hydrogen imports from Australia with its traditional LNG exports markets of Japan, South Korea, China, and other East and South Asian countries, whose geographical distance and transport costs are lower compared with EU importing countries.

In its declaratory policies, the EU hopes to promote some kind of “energy independence”, sustainable development and strengthen “value-based trade” in its hydrogen partnership diplomacy. But China's growing role and geoeconomic and geopolitical influence in Africa, the Gulf region, East Asia, and even South America as part of its Belt-and Road-Initiative (BRI) as well as the worldwide shrinking

number of real democracies, put the EU ambitions for focusing on “value-based partnerships” increasingly into doubt. It highlights a major lack of attention and analytical in-depth analysis: a critical geoeconomic and geopolitical review of the rapidly changing *global* energy and economic markets as well as the *global* critical supply chains.

Most of the EU's assumptions still rest on the old world of rule-based global governance institutions and priority given to economic interests on all government sides (except for Russia). Despite its general recognition of its overall economic and CRM dependence on China, the systemic changes of increasingly fragmented markets are hardly addressed or even integrated in its policies often still based on best-case scenarios (European Commission 2020; European Commission 2022b; BMWK 2024b). An exception is the Commission's first “Economic Security Strategy” in 2023 (European Commission 2023e) – though hitherto with only limited impacts on the EU's overall common as well as national economic and energy policies of its member states.

Similarly, many academic publications on the EU's and Germany's future hydrogen import routes and identified hydrogen partnership countries are often focusing (and thereby almost exclusively) on techno-economic dimensions with costs analyses and national socio-economic and political instabilities as well as related geopolitical risks in the individual hydrogen exporting countries in the MENA-region, Africa and Latin America (Wietschel et al. 2024; Fleiter et al. 2024; Agora 2023; Alsumailan 2023; Rikabi 2024; Steiß et al. 2022; Nunez et al. 2024; Piria, Raffaele et al. 2022; SCI4climate NRW 2021; World Energy Council 2021).

No doubt, these detailed analyses have enriched our understanding of the complexities and pre-conditions for any hydrogen exports to Europe (such as the hydrogen demand and interests of the EU's potential hydrogen partner and exporting countries alongside



their own decarbonization strategies and goals, related and often overestimated export volumes and their wider economic-political objectives (Transport & Environment 2024). But the systemic geoeconomic and geopolitical changes of nationalistic as well as protectionist policies of the major powers (China, Russia, India, the U.S., etc.), leading to fragmented global markets, trade conflicts, and geopolitical priorities and trump multilateral policies and organizations, are hardly addressed or even integrated as systemic factors. Thus, many conclusions are worthwhile for an era of international relations, which has already gone. If that is all, the general call for more resilience, diversification, and energy security sounds like paying lip service without fully understanding or being willing to understand the fundamental changes that have already taken place in the global markets. This changing geoeconomic and geopolitical landscape is fastening to upset the traditional underlying European assumptions of how world markets and international relations are functioning today.

Originally, the EU and German hydrogen strategies had identified Ukraine and Morocco as the most important potential exporters of green hydrogen (BMWK 2020; European Commission 2020; Umbach 2021a; Gotev, Simon 2022). But as the Ukraine war continues and a sustainable peace agreement is uncertain, the country may not become so fast a major green hydrogen supplier for the EU. Despite these uncertainties, Germany and Ukraine have pushed forward their collaboration on hydrogen projects (NWR 2024b). Also, the European Bank for Reconstruction (EBRD) and the Ukrainian state company Gas Transmission System Operator of Ukraine (GTSOU) have pushed forward their cooperation on hydrogen development since July 2021 (NGW 2021).

At the same time, various studies and political initiatives by the European Commission and particularly Germany have increasingly focused on potential hydrogen imports also from the MENA-region (including the Gulf-countries), Africa, and Latin America (Stamm, Strohmaier 2023).

Hydrogen Import from the MENA-Region

The Gulf- and the entire MENA-regions have been considered geopolitically rather as unstable. Traditional and new security challenges are mixed with national ambitions and a militarization and regional increase of military capabilities. The Israeli-Palestinian conflict and the Saudi-Iranian rivalry as well as the strategic interests of the major worldwide powers like Russia, China, and the U.S. have determined regional policies since the 1970s and the worldwide oil crisis. For few years, the political rapprochement between Israel and some Arab countries (the United Arab Emirates, Bahrain, Morocco, and Saudi Arabia in perspective) alongside the Abraham Accords in 2020 have offered new cooperation perspectives. But Iran, Russia, and some other countries in the region itself have not been interested in such a rapprochement which would come at the expense of their geopolitical and geoeconomic influence in the region. Iran's supported Hamas terrorist attack on Israel in October 2023 has shattered all hopes for more cooperation between Arab countries and Israel for the time being. Despite a rapprochement between Iran and Saudi Arabia, the underlying conflict and regional competition won't change in the foreseeable future.

The regional oil, LNG, and potential hydrogen exports remain dependent on unstable regional SLOCs and three vulnerable Choke points (Strait of Hormuz, Bab-el Mandeb, and the Suez-Canal), whose passing traffic with a rising maritime trade will further increase. But in contrast to many other potential African and Latin American countries, the Gulf states have the financial powers and like Saudi Arabia also the political will to become first-movers (Shabaneh et al. 2024; BMWK 2022; Ellinas 2022; Brown 2021; Ratcliffe 2021). The latter one is at the forefront to become the world's largest ammonia exporter and help to scale up an expanded global hydrogen trade, including with H₂ derivatives. More than 60% of the re-enabled energy projects in the Middle East and North Africa are planned for hydrogen production and exports (Urbasos 2023). The first test supply of ammonia from the United Arab

Emirates had already taken place in 2022. However, the geopolitical risks for any hydrogen imports to Europe will remain rather high. Furthermore, the MENA region may have an interest in making green iron and steel itself as well as for exports as green hydrogen exports may prove to be too inefficient and costly for European imports (Basirat, Nichols 2023).

This rather bleak geopolitical assessment also concerns the North African countries, though Algeria has been an important gas pipeline supplier to Italy and Europe for decades, while Morocco is an important electricity exporter to Spain. But the bilateral conflict between Algeria and Morocco about the Western Sahara has also complicated Germany's and the EU's hydrogen partnership with these countries and regions (MIPA-Institute 2022; Crisis Group 2024; Fasanotti 2022; RANE 2021). Furthermore, Algeria appears primarily interested in future blue rather than green hydrogen exports given its gas export and gas infrastructure interests. Economic, financial, political, investment, and regulatory uncertainties as well as regional assertiveness and autonomy need to be added to the multifaceted challenges for a closer European hydrogen partnership with these countries (Lampert, Walter 2024; Aboushady, Faus Onbargi 2023).

Hydrogen Imports from Sub-Saharan African Continent

The African countries have certainly a huge potential for producing green hydrogen (Nuttall 2023). But the economic, social, political, and other conditions also vary between the regional states (Oyewo et al. 2023; ECDPM 2024; Obineme 2023; Stamm et al. 2023; Altenburg, Kantel 2024). Also, African countries have different interests and defined priorities such as exports of their fossil fuels. Several African countries have just become LNG exporters for the first time (Adeoye 2024). Some 2 bn people do not have any clean cooking fuels (IEA 2024d). On the other hand, Europe has learned some lessons from the previous experience with the Desertec project by

taking more decarbonization and hydrogen interests of the African countries into account by avoiding any "neo-colonial" attitudes.

But any major investment in African countries with their favorable conditions for green H₂ needs to come from outside due to the financial constraints of almost all African energy companies. Thus, the 'Africa Green Hydrogen Alliance' with its six members Egypt, Kenya, Mauritania, Morocco, Namibia, and South Africa needs some US\$ 450-900 bn of investments by 2050 (BMWK 2023a; BMWK 2024b; BMWK 2024c). But the investment conditions are very different and have often become more difficult – also partly to Russia's and China's geopolitical interventions, including using private security companies (like Russia's Wagner Group) for coup d'etats and defending pro-Russian and Chinese (clan) governments (Lee, Wittman 2023; Sukhankin 2023; RANE 2023; Patton 2024; Adeoye, Pilling 2024).

The example of the civil war and change of power in Mali 2020 has also highlighted the challenges of its geopolitical risks for the EU's future hydrogen import dependency (Hook, Adeoye 2024) and the wider risks for any foreign investors (Pinto 2020; Editorial Board 2020; Glencorse, Kondo 2020; Abboud, Seddon 2021). At that time, Mali was the only country that produced natural white hydrogen. After France, which at times was actively involved in the fight against the "Islamic State" in Mali with up to 5,000 men, the Bundeswehr provided the largest troop contingent there with up to 450 soldiers. But at the end, both German and French troops had to leave Mali.

There are also plans for the construction of a hydrogen pipeline from Mali via Senegal up to Morocco. Large wind and solar farms are then also to be built along the route, adding green H₂ from electrolysis plants to the white hydrogen. But the realization is only realistic if there is considerably greater regional stability. For example, the Trans-Saharan gas pipeline from Nigeria via Niger to Algeria, which has been in the planning stage for a long time, has not yet progressed due to political instability, because the risk

for private investors has been considered too high and the protection of such a 4,300 km long pipeline as too costly. Other African countries, like South Africa, face an energy and electricity crisis, which demands other priorities in their energy policies (Gaventa 2020; Mathekga 2023).

Given the vulnerable Choke Points at the eastern coast of Africa (Bab-el Mandeb and Suez Canal) and the regional piracy problems as well as the Houthi attacks on Western shipping in regional waters, the geopolitical risks of the SLOCs and the transport costs due to shorter distance of the maritime import routes from Africa's western coast are and will remain lower.

Beyond, by taking historical experiences into account, green, blue, or white hydrogen could be a curse and a blessing at the same time, as Africa's wealth of resources has repeatedly been a source of corruption and conflict for national as well as local political power rivalries, instability, and Islamic terrorism. But joint hydrogen partnerships and projects also offer new economic perspectives for the regional states as well as international trade and mutual hydrogen cooperation.

Imports of Hydrogen and its Derivates from South America

In addition to the African continent, South and Latin America have also attracted a wider and growing interest as a potential export region for Europe's hydrogen import demand. The most interest from Europe, as well as from other countries for hydrogen cooperation has been directed towards Chile, which promises to have the lowest production costs of green hydrogen and a rather low domestic demand. It can capitalize on its abundant natural and renewable energy resources as well as its largely decarbonized electricity mix. According to the IEA, Latin America could produce more than 7 Mtpa of hydrogen with a carbon intensity below 3 kg CO₂-eq/kg H₂ (3-4 times lower than using unabated natural gas) by considering the requirements of several existing

regulations around the world (EWI 2023a; EWI 2023b; EA 2024a; SCI4climate NRW 2021; Wietschel et al. 2024). It also offers excellent conditions for hydrogen derivatives and the export of ammonia and methanol. The latter can be used for producing Sustainable Air Fuels (SAF) for long-distance flights of airlines, which do not have any alternative in contrast to smaller airplanes and shorter distances (where electrification and batteries offer a more cost-efficient technology solution). In addition to Chile, Brazil offers the greatest potential for decarbonizing its steelmaking and fertilizer production (Gomes et al. 2024).

But as in the case of Africa, the EU's hydrogen cooperation with Latin America is facing numerous socio-economic and financial constraints, electricity supply shortages, weak governance institutions, and political instabilities in the region – partly also due to water scarcity (IEA 2024a). The important regional mining industry is already rivaling the agriculture sector for sufficient water supply. Green hydrogen production can even fuel those local conflicts and undermine public acceptance. Beyond, maritime transport would either be dependent on an import route via the Choke Point Panama Canal or a longer route along the western coast of Brazil and the Atlantic to Europe. The Panama Canal must already cope with insufficient water levels to use it for an entire year as well as by new recent threats of US President Trump to take re-control over the canal because of "exorbitant prices" to American shipping and naval vessels (Wendling, Horton 2024). But both routes have also a longer distance compared with any imports from western Africa. In contrast to the MENA-region and Africa, Latin America's regional stability promises still to be better. Hence, the geopolitical risks of any regional instability are being considered lower despite many national instabilities and investment risks.



Take aways from the expert workshops:

Industry

- The future hydrogen economy will result in completely new industrial value, supply, and logistics chains.
- Green hydrogen is still facing technological challenges across the entire supply chain, beginning with CRMs for electrolyser capacities and production and storage to transport and end-use.
- Geopolitical risks are often still underestimated and difficult to integrate into already existing business plans.

Academia & Think Tanks

- Rising conflicts in the 'energy trilemma' with its three competing objectives of affordability, reliability, and sustainability. But balancing in the right way becomes ever more challenging and needed.
- The global and European expansion of hydrogen will lead to new import dependencies and geopolitical risks.
- Many geopolitical risks resulting from a growing hydrogen import dependence are not different from those of the previous and current fossil fuel import dependencies.
- However, enhancing the resilience of energy security demands holistic thinking and new energy security concepts as well as more investments in safety and security, including of the critical hydrogen infrastructures.

- Diversification of imports is needed more than ever – even regardless of which hydrogen exporting country.

Politics

- The future EU policies will pay much more attention to the new guiding principles of industrial competitiveness, cost-efficiency, and resilience of energy security and import diversification.
- New uncertainties arise with the new U.S. presidency of Trump for transatlantic economic and security relations as well as global governance, in which also new trade conflicts cannot be excluded. They raise critical questions for both the EU's present LNG as well as a potential future hydrogen import dependency from the U.S.

Take Aways from the study:

Rising geopolitical risks and vulnerabilities

- The EU's future green hydrogen import demand and supply security depend not just on its own production and electrolyser capacities, but also on whether sufficient hydrogen volumes will be available in the exporting countries – and, there-with, on the worldwide global demand-supply balance.
- The creation of a hydrogen economy and huge electrolysis capacities demands a further increase in the mining, refining and processing of CRMs.
- EU needs to re-balance its future imports of Chinese extracted and refined CRMs as well as cheaper green technologies for a faster decarbonization and green energy transition with the need for an enhanced resilience of a stable supply of hydrogen and electrolysis technologies as well as a domestic production capacity.
- The future shipping of hydrogen and its derivatives will further increase the international shipping and expansion of maritime transports via unstable SLOCs and Choke Points.
- The present cost difference between green and blue hydrogen could even increase in the forthcoming years and further slow the expansion of green hydrogen as the global LNG supply will enter again at least for a decade a global over-supply beginning in 2026/27. It may also lead to worldwide lower LNG and natural gas prices which could further delay the prospect of green hydrogen becoming cost-competitive with 'blue hydrogen' by 2030 into the future.

Expert workshops

- Hydrogen partnerships and long-term contracts with African and Latin American countries are certainly a useful instrument and necessary to diversify import dependencies. However, neither of these instruments provides any real guarantee, especially in times of crisis with rapidly changing framework conditions.
- Negotiated and agreed bilateral hydrogen partnerships for joint (production) H₂ projects should not be equalized automatically with H₂ imports to Europe. Most of these proclaimed and negotiated hydrogen partnerships cannot translate directly into stable hydrogen exports from non-European partner countries as, ultimately, the private energy industry must sign commercial H₂ contracts based on commerciality and profitability.
- New studies have indicated that just 10-15% percent of the EU's rather decreased hydrogen demand needs to be imported, primarily from Norway as the EU's main gas supplier today and its closest energy partner as a stable democracy and market economy.
- The worldwide systemic geoeconomic and geopolitical changes of nationalistic as well as protectionist policies of the major powers (China, Russia, India, the U.S., etc.) – leading to fragmented global markets, trade conflicts, and geopolitical priorities and trump multilateral policies as well as organizations – have been hardly addressed or even integrated up to now as systemic factors in Academic studies of the EU's future hydrogen import policies.

5. Geoeconomic and Geopolitical Implications for the Global and EU Energy Transition

Written by Dr. Frank Umbach (CASSIS)

5.1 Impacts of rapidly changing global energy markets and geopolitical developments

The global energy transition to a non-fossil fuel age, determined by the interplay between the geopolitics of fossil fuels and renewables, is a challenging, risky, and vulnerable process by itself. An unprecedented pace of the global and regional energy transition is accompanied by a high degree of unpredictability, “tsunamis of innovation” and non-anticipated disruptive developments and strategic implications. Given the fact that almost every aspect of the complex energy system is changing simultaneously, it is becoming less predictable and has upset traditional assumptions of the global energy markets and energy security. The unfolding global energy transition and the digitalization of energy systems are prompting existing long-standing energy security paradigms to be reviewed, rethought, and redefined (Umbach 2021b).

A simplistic, non-balanced, and naive liberalization of global markets has weakened the national security of Western democracies because of non-diversified import dependencies – ranging from energy supply insecurity to supply chain vulnerabilities in medical equipment, medicines, semiconductors, telecommunication, and CRMs that could be exploited for geoeconomic and geopolitical leverage. During the past decades, trade and commerce have largely been disentangled from security. Governments and

businesses have prioritized markets over security, hoping that economic liberalization and interdependence would guarantee peace. Alongside, economic, trade, and foreign as well as security policies have largely been separated from domestic policies and the nature of political regimes.

Moreover, the global energy markets are fundamentally changing and are increasingly influenced by geopolitical factors and developments. The global energy markets have become much more fragmented and are increasingly influenced by the global geoeconomic rivalry between the U.S. and China as well as by a systemic global conflict between Western democracies and the “axis of resistance” (China, Russia, Iran, North Korea, and Yemen). In contrast to countries like Japan, neither the EU nor Germany and most other member states had a real economic security strategy until 2022 (European Commission 2023a).

In addition, Russia's military invasion of Ukraine has fuelled the geopolitical rivalries between Western democracies and nationalist, autocratic-dictatorial powers such as Russia and China, which both have declared themselves as “non-status quo powers” by changing existing borders and incorporating territories of other countries (Ukraine in 2014) or even an

entire independent state (Ukraine, Taiwan). They are willing to change a rule-based world order even by using coercive military means. Russia has initiated a hybrid warfare against EU member states which includes the sabotage of critical (energy) infrastructures (CEIs) such as subsea electricity and internet cables (Piebalgs, Schmitt, Umbach 2024). Resilient energy security concepts need to be adopted and include both rising cyber and physical sabotage attacks on those CEIs.

All these goeconomic and geopolitical developments will heavily influence the EU's and global hydrogen policies in the years and decades to come. The building of hydrogen infrastructures, for instance, will add new targets for attack both within Europe and in hydrogen exporting countries as well as for maritime hydrogen transport. Anticipating rising hydrogen imports need to anticipate not just potential geopolitical and investment risks in the EU's hydrogen partnership countries but also to consider the broader geopolitical risks of new hydrogen supply chains of fragmented markets both on a regional as well as global level. The future security of critical hydrogen infrastructures is already a topic of the EU's energy security agenda and will be part of the forthcoming revised and updated "EU Energy Security Strategy" of 2014, which is currently being pushed by the new European Commission and the Polish EU Presidency.

Beyond the Ukraine war and Russia's upsetting of the existing European security order, China has become the most important mid- and long-term challenge for the EU's goeconomic influence and its worldwide industrial competitiveness. China has not only caught up technologically but is beginning to outstrip the EU and even the United States (Gaida et al. 2024; IEA 2024d). Beijing's subsidy policies for its domestic market as well as for its export markets and its unfair trade and competition policies have led to a fragmented globalization and more protectionist policies on the EU side. Hence energy supply security, resilience of supply chains, and "strategic autonomy" play a much more important role in the EU than in the past. Beijing tries to control the most important disruptive technology supply chains on the world markets and has a dominant

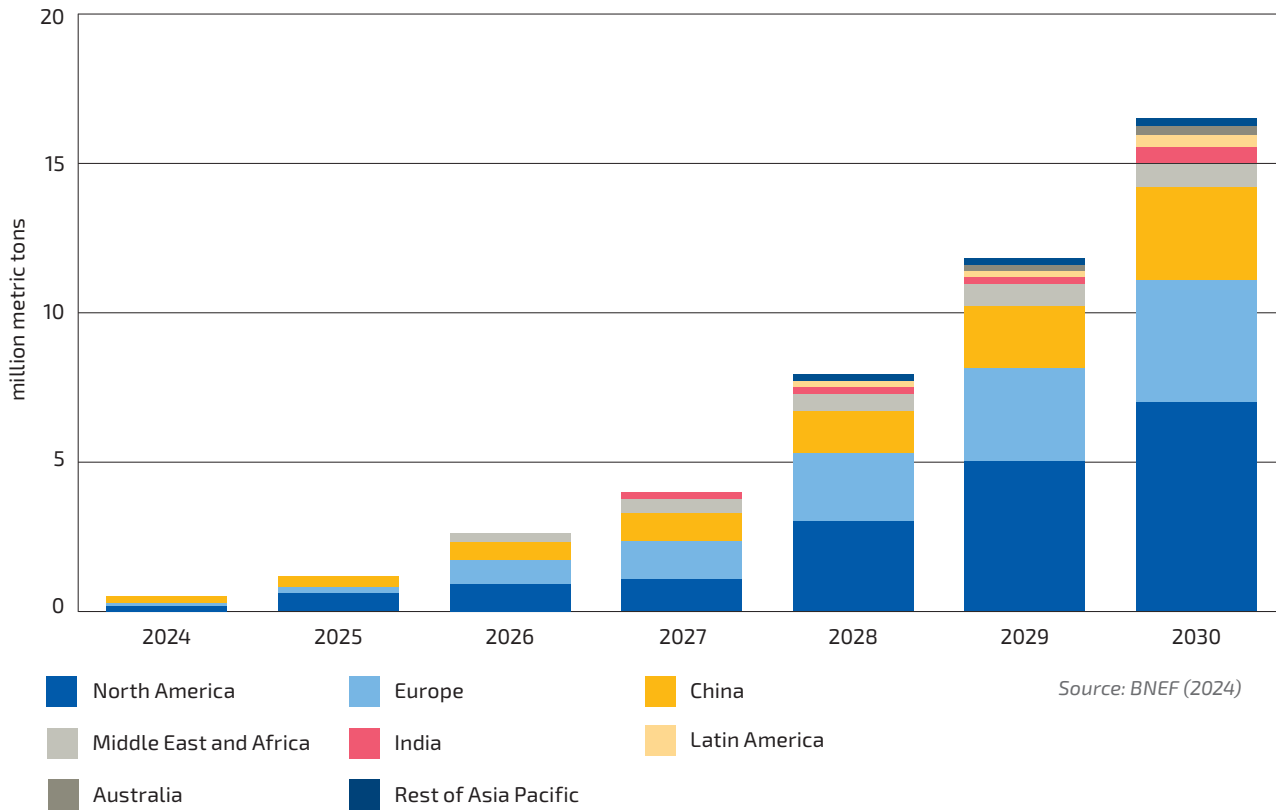
global position in the global CRMs supply chains both on the world-wide extraction as well as refining and reprocessing stage.

At present, China also controls about 40% of the global electrolyser market and even 60% of the worldwide manufacturing capacity (IEA 2024a). For the EU, it creates another conflict for its strategic objectives: If the EU would restrict cheaper Chinese electrolyser technology (by additional import tax like for electric vehicles and solar cells) for enhancing resilience and de-risking, it would simultaneously slow down the expansion of its planned growth of its electrolysis capacity. Thereby, the U.S. may already surpass Europe in its leading role (after China) at the global electrolysis market by 2030 (see [Figure 26](#)). Whether the U.S. may still be able to do it, has become more uncertain with the new U.S. Presidency of Trump. While the expansion of the U.S. hydrogen growth may also slow down, energy companies already involved in the hydrogen business as well as federal states having invested themselves in hydrogen projects will not give up their commercial business interest in the expansion of U.S. hydrogen projects.

In Europe, the enforced shift to more security and defence spending implies that in the forthcoming decade less subsidies and funding might be available for the EU's energy and climate policies (Kurtyka 2024; Walstad 2024) – including for its ambitious hydrogen plans and targets. It could also threaten the targets for decarbonizing the EU's energy-intensive industries like steel and aluminum. Both industries are also strategically and geopolitically important for the EU's defence industry as otherwise it would become almost completely dependent on weaponry imports from other countries and undermine its self-declared objective of achieving "self-autonomy". In the new geopolitical landscape and with the EU intention to raise its defence budgets significantly to become "ready for war" (so German Defence Minister Pistorius), the EU needs to discuss more openly and publicly which industries are also strategically important (such as the steel and chemical ones) not just for jobs and the European industrial competitiveness, but also for Europe's security and defence policies and by taking over

Figure 26: Global clean hydrogen production

North America Leads Clean Hydrogen Production this decade



more responsibilities and a fair 'burden sharing' within NATO. The outcome of those debates will also determine the EU's future decarbonization plans and its hydrogen demand.

The study has shown that the future of hydrogen will not just have energy and economic dimensions but – as a cross-cutting topic – it will also have wide-ranging implications for its foreign and security policy. Global competition for technologies,

control of supply chains and CRMs (Umbach 2018; Umbach 2020d) as well as supply security concerns will increase and determine the future geoeconomic cooperation as well as the worldwide geopolitical rivalries during the next decades. The additional global demand for renewables for expanding worldwide green hydrogen will also have enormous implications for an already rapidly rising worldwide consumption of CRMs (World Bank Group 2022).

5.2 Impacts on the EU's ambitious Hydrogen Policies and Targets

In this new geopolitical context, the study has analysed the changing parameters and specific geopolitical risks related to the EU hydrogen policies and its forecasted high hydrogen import dependency. It has critically reviewed the EU's hydrogen policies and targets by 2030 and highlighted and explained

the factors why those targets have become unrealistic. Rising costs of green hydrogen projects in Europe and globally as well as a decreased European and global demand due to new, more cost-efficient alternative technology options (such as electrification of the transport and building sectors

and even in hard-to-abate energy-intensive industries – see again [chapter 3.5](#)) have increasingly determined its hydrogen policies during the last two years. They also explain why the share of FIDs of the worldwide planned hydrogen projects is still so with just 11% in 2024 (see [Figure 27](#)).

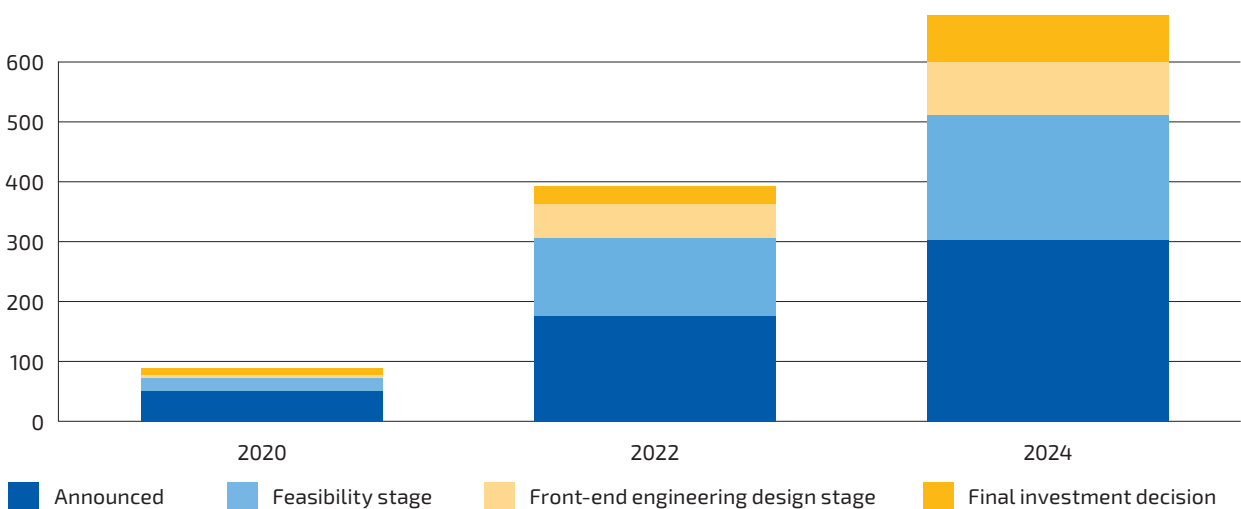
But rising costs for green hydrogen and the entire energy transition also raise the question of public acceptance. The EU's and Germany's need for fast-tracking the modernization, digitalisation and expansion of the ageing electricity grid networks demands huge investments as fast as possible to avoid any bottlenecks of electricity supply as otherwise no additional heat pumps and EVs can be connected to the grid without causing any electricity blackouts. According to a new study, Germany needs alone around EUR 650 bn for modernizing and digitalization of its electricity grids by 2045 – much more than previously estimated (Bauermann, Kaczmarczyk, Krebs 2024).

The European and global gas and electricity price explosions in 2022 have already highlighted the risks to the competitiveness of the European industries and waning public support for unpopular crisis

measures. Also, high hydrogen costs – alongside other energy transition costs – could translate into much higher energy and particularly electricity bills. They could make hydrogen projects politically more difficult to accept and support for larger parts of societies and decrease governmental decarbonization efforts. In this regard, the projected higher costs of green hydrogen compared with older analyses even in mid- and longer-term perspectives could threaten a fast European and worldwide decarbonization. Hence, the EU's new focus on much more cost-efficient technology options will become ever more important in times of increasing financial constraints. In this context and contrast to widespread assumptions, the repurposing of existing infrastructures is not always the cheaper solution: repurposing an LNG terminal with ammonia, for instance, costs an additional 11-20% of the investment cost of a new one. A hydrogen storage tank to replace an LNG tank can also be 50% more expensive (Kneebone, Piebalgs 2023; Umbach 2024b). These examples highlight that the global and European green energy transition will be very costly and that those costs are often underestimated in public and political debates.

Figure 27: Only 11% of global hydrogen investments have reached a final investment decision

Global clean hydrogen investments by status, \$bn



Source: Financial Times/Hydrogen Council (2024)

Against this background, the EU needs to find an adequate balance between its geoeconomic and geopolitical interests with resilient energy supply security (based on the guiding requirement of diversification of its hydrogen supplies) and cost-efficient hydrogen imports. It will be particularly challenging for Germany as the EU's largest hydrogen consumer as well as importer and facing one of the highest hydrogen wholesale prices and production costs within the EU and in the world compared with its economic competitors (U.S., China, Canada, Scandinavian countries, and other – Wietschel et al. 2024).

The EU's hydrogen import dependence, even by considering a decreased overall demand as well as import demand, does not suggest that the

traditional energy supply security risks are diminishing as the result of its shrinking oil, pipeline gas, and LNG imports. But the future geopolitical challenges will be added by new energy security risks linked with new import dependencies on CRMs, green technology supply chain and hydrogen as well as multiplied cyber security vulnerabilities (as the result of electrification, digitalization, and AI of large industry, transport, and building sectors). In this light and the new geopolitical environment, the EU must prioritize resilience of energy (supply) security and flexibility in the new energy markets but also balance this priority with cost-efficient measures to maintain and strengthen its industrial competitiveness.

5.3 Green versus Blue Hydrogen

Green hydrogen in Europe is presently at least two times more expensive than blue hydrogen (including CCS/CCUS). During the last years, green hydrogen costs (incl. for electrolysis) have increased instead of decreased as previously forecasted. The original estimate that green hydrogen will become cost-competitive with blue hydrogen around 2030 is now equally unrealistic.

The present cost difference between green and blue hydrogen could even increase in the forthcoming years and further slow the expansion of green hydrogen by another development as new analyses of the global gas and volatile LNG markets have forecasted, that the global LNG supply will enter again at least for a decade a global oversupply beginning in 2026/27 (IEA 2024d; IGU 2024a; IGU 2024b; BNEF 2024; NGI 2024). According to the IEA, the global LNG export capacity will increase by some 50% by Qatar, African exporters, and the U.S. (regardless of Trump's energy call again for "Drill baby drill!") (IEA 2024d). It may also lead to worldwide lower LNG and natural gas prices which could further delay the prospect of green hydrogen

becoming cost-competitive with 'blue hydrogen' by 2030 into the future.

But if less-costly blue hydrogen expands faster, it will be detrimental to climate change even by using CCS or CCUS as methane gas (up to 80 times more dangerous than CO₂) may increase along its entire supply chain (Mar, Quitzow 2024; Shafiee, Schrag 2024). However, the environmental impact of green hydrogen production can also vary depending on the source of renewable energy used for electrolysis as new life-cycle analyses concluded (Hamed et al. 2023). It highlights the inherent contradictions in the 'energy trilemma' and the conflicts of the three competing objectives affordability, reliability, and sustainability: For geopolitics, it has the impact that Europe would remain largely dependent on the same exporters as for its volatile LNG imports and increase its dependency on those exporting countries into the mid-term transition period. In comparison, green hydrogen imports can be much more diversified for the EU member states in the mid- and longer periods. But in the short- and medium-term, they remain the most expensive import option,

contradicting the EU's new focus on its future industrial competitiveness and the criteria of affordability.

For the import of derivative commodities produced using green hydrogen, such as low-emissions ammonia (which could account for up to 45% of global shipping fuel demand by 2050), low-emission methanol (used as Sustaining Air Fuel), and steel and iron, the EU needs to develop specific import

strategies, certification, standardisation, and regulatory frameworks as well as enhance its international collaboration with hydrogen partner countries (IRENA 2024; Wee 2023; Wietschel et al. 2020). It will also create numerous new safety and security risks and demand related heavy security investments to ammonia infrastructures (such as ammonia crackers in EU importing countries like the Netherlands, Belgium, France, Spain, Germany, and others), classified as new CEIs (Widdershoven 2023).

5.4 Electrolysis versus Electrification in the Energy-Intensive Industries

The decarbonization of the hard-to-abate energy-intensive industries will remain the most uncertain development due to the unknown technological innovation and whether new technologies (both on the sides of electrolysis as well as electrification) will also be cost-efficient solutions. Not every new technology will enter the markets. At present, China offers the most cost-efficient electrolysis with the highest quality and is dominating the worldwide manufacturing capacity. Chinese alkaline electrolysis systems cost significantly less than Western ones (Arnold 2022; Harris, Temple-West 2024).

From a cost and technological perspective, a sector-specific solution might be beneficial in this context. Electrification versus green hydrogen use in energy-intensive industries should be seen as complementary pathways rather than one excluding the other one. Even hybrid heat supply using electrification and hydrogen could offer cost-competitive options.

Given the high costs of green hydrogen and the newest forecasts that the costs will not decrease so much as previously estimated, the EU needs to subsidize technology innovation for both new electrolyser capacities as well as for new heat electrification in the hard-to-abate energy-intensive

industries for decreasing the overall future costs of green hydrogen production.⁹

Against this background, it can be concluded that (1) while hydrogen is not a 'silver bullet'-solution to solve all energy transition problems, it remains imperative for the decarbonization of the hard-to-abate energy-intensive industries (complemented by new heat electrification technologies), and longer-distance shipping and air flights; (2) geopolitical risks will not end with renewables, the decarbonization, and the green energy transition in the forthcoming decades. They will rather increase as a result that the traditional dependencies won't disappear by 2050, and, simultaneously, numerous new ones have already emerged in a new goeconomic as well as geopolitical landscape and fragmented global markets. They will enforce a resilient and holistic understanding of the future energy as well as hydrogen supply security; and (3) a hydrogen era will be very costly which demands an honest political and public debate in the context of the EU's increasing financial constraints, a lower global and European hydrogen demand, and the need for cost-efficient technology solutions and strengthening the EU's industrial competitiveness without giving up its climate policy and other sustainability targets.

⁹ To the development perspectives of electrolyser technologies see also Wet et al. 2024.

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Abbreviations

BImSchG	Federal Immission Control Act (Bundes-Immissionsschutzgesetz)	MENA	Middle East and Northern Africa region
BNEF	Bloomberg New Energy Finance	NECP	National Energy and Climate Plan
CAPEX	Capital Expenditures	NWR	German National Hydrogen Council (Nationaler Wasserstoffrat)
CCfDs	Carbon Contracts for Difference	OPEX	Operational Expenditures
CCS	Carbon Capture and Storage	PCI	Projects of Common Interest
CCUS	Carbon Capture, Use and Storage	PEM	Polymer Electrolyte Membrane Electrolyser
CRMs	Critical Raw Materials	R&D	Research and Development
ECA	European Court of Auditors	REDIII	Renewable Energy Directive III
ECB	European Central Bank	RES	Renewable Energy Sources
EHB	European Hydrogen Backbone	REEs	Rare Earth Elements
ENNOH	European Network of Network Operators for Hydrogen	RFNBO	Renewable Fuel of Non-Biological Origin
EU	European Union	SAF	Sustainable Aviation Fuels
FID	Final Investment Decision	SLOCs	Sea Lanes of Communications
GHG	Greenhouse Gas	SMR	Steam Methane Reforming
IEA	International Energy Agency	SOEC	Solid Oxide Electrolyser Cell
IPCEI	Important Projects of Common European Interest	TCO	Total Cost of Ownership
LH₂	Liquid Hydrogen	TRL	Technology Readiness Level
LNG	Liquefied Natural Gas	TSO	Transmission System Operator
LOHC	Liquid Organic Hydrogen Carrier	WACC	Weighted Average Cost of Capital

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Appendix

Important insights into the EU strategy and national strategies of all member states

EU:

Investment into hydrogen technologies rises

In the EU a local production of 40% or more of the required technology for the EU 2030 climate and energy objectives is aimed at. Up to EUR 5,400 m can be allocated to 41 hydrogen technologies along the value chain including the generation, storage, transportation, distribution, and end-users' applications. EUR 3,000m is dedicated to support hydrogen related technology projects (EU Hydrogen strategy 2020; IEA, 2021; IEA 2022a; IEA 2023a).

Austria:

Increasing hydrogen production to reach climate neutrality by 2040

Austria focuses on several guiding principles in its hydrogen strategy. This includes the usage of climate neutral hydrogen (including also hydrogen from natural gas and CCS) to reach climate neutrality. They aim at a gradual conversion of the natural gas grid and using hydrogen directly on the hard to decarbonize¹⁰ industries. Hydrogen is planned to be used by chemical and steel industries, aviation and shipping (Federal Ministry for Climate Action, Environment, Energy, Mobility, Innovation and Technology 2022).

Belgium:

Becoming a transport and transit hub

Belgium lays down the foundations of its hydrogen strategies based on 4 pillars. The first pillar is positioning Belgium as an import and transit hub for renewable hydrogen molecules and derivatives with planned import quantities of 20 TWh in 2030 to be used partially to satisfy local demand. Strengthening Belgium's leadership in hydrogen technologies is the second pillar in the Belgian hydrogen strategy. Third, building a resilient market for hydrogen molecules (and potentially hydrogen derivatives) against insecurity of supply due to national or international disruptions. Infrastructure development is necessary to achieve the third pillar through operating a hydrogen connection with Germany by 2028. Cooperation and collaboration with neighbouring countries and international partners is crucial and is considered the fourth pillar (Belgian Federal Public Service Economy 2022). Hydrogen is planned to be used by industry and building sectors (IEA 2022a).

Bulgaria:

Established hydrogen roadmap, still no official hydrogen strategy

The integrated Energy and Climate Plan of Bulgaria for the period 2021-2030 includes the development of hydrogen projects (Ministry of Energy 2020). Additionally, there is a National Roadmap for

¹⁰ Sectors or processes that are challenging to transition to low-carbon alternatives due to their reliance on high energy density fuels, specific chemical reactions, or infrastructure that currently depends on fossil fuels

Hydrogen Development that has been established with the goals of developing efficient deployment of green hydrogen in industry, energy, and transport, enhancing research and innovation, fostering education and training for new jobs and informed consumers, and encouraging cooperation. Hydrogen will be mainly used by the petrochemical, chemical, and hard to decarbonize industries, as well as the transportation sector (32 GWh by 2030 planned according to the integrated Energy and Climate Plan) (Ministry of Energy 2020; Ministry of Innovation and Growth 2023).

Croatia:

Increase hydrogen consumption and renewable hydrogen production by 2050

The Croatian hydrogen strategy states that renewable hydrogen production capacities will be developed through national projects and supporting infrastructure development. Hydrogen is planned to be used by industry, transportation, electricity, and heating sectors (Ministry of Economy and Sustainable Development 2022).

Cyprus:

No hydrogen plan

Czech Republic:

Hydrogen will be used as fuel, feedstock, and for storage

The hydrogen strategy by the Czech Republic is structured around 4 pillars, that include low-carbon hydrogen production and accordingly R&D, demand in different industries (especially the chemical and transportation sectors) as fuel and feedstock, as well as hydrogen transport and storage (Ministry of Industry and Trade 2021; IEA 2021). Hydrogen is planned to be used by chemical industry and transportation sector (IEA 2021; Ministry of Industry and Trade 2024).

Denmark:

Scaling electrolyser capacity for green hydrogen

Denmark has not yet published a hydrogen strategy. However, the country has the objective to provide a 4–6 GW of electrolysis capacity by 2030 (Danish Energy Agency 2023). In 2023, EUR 170 m are approved to support renewable hydrogen production (IEA 2023a).

Estonia:

Hydrogen projects pilots in force only possible between 2031 to 2035

The Estonian hydrogen roadmap is considered the pilot phase (2021–2023) of a 3 phases hydrogen deployment plan. It prioritizes policy development, research and development, pilot project implementation, and enhancing the availability of renewable energy. Estonia plans to have built 3–5 hydrogen refueling stations by 2030 with a capacity of 2,000 tonnes of hydrogen annually. Estonia plans that the period between 2031 to 2035 can possibly witness hydrogen projects pilots in force. Hydrogen is planned to be used by industry and transportation sectors (Ministry of Climate and the Ministry of Economic Affairs and Communications of the Republic of Estonia 2023).

Finland:

Provide 10% of the EU clean hydrogen target

Finland's hydrogen strategy is briefly presented in Finland's national climate and energy strategy of 2022 and Finland's Integrated National Energy and Climate Plan Update. The national strategy establishes a target of hydrogen electrolysis capacity of 10% of the EU clean hydrogen target. A target of 0.2 GW electrolysis by 2025 is not achieved (Ministry of Economic Affairs 2024). The primary focus of the strategy is on developing a domestic hydrogen value chain, with secondary emphasis on the potential for hydrogen exports. Hydrogen is planned to be used by the industry and transportation sectors (Organisation for Economic Co-operation and Development 2023; Ministry of Economic Affairs and Employment 2024).

France:**Second largest installed electrolyser capacity by 2030**

France published its national hydrogen strategy in 2020, which seeks to position France as a leader in three key areas of the decarbonized hydrogen sector. It aims to produce 680,000 tonnes of low-carbon or renewable hydrogen annually through an installed electrolyser capacity of 6.5 GW by 2030. Second, the strategy places a strong emphasis on advancing research and development to drive innovation in hydrogen technologies. The third key area is industrial and transport sector decarbonization (Ministry of Ecological Transition and the Demographic Challenge 2020b). Hydrogen is planned to be used by industry, in refining and the transportation sector (IEA 2021).

Germany:**Reaching climate neutrality by 2045**

Germany's national hydrogen strategy pinpoints key targets and measures to achieve climate neutrality by 2045. Starting with hydrogen market ramp-up acceleration and installation of electrolyser capacity of 10 GW by 2030. Additionally, the strategy focuses on developing essential hydrogen infrastructure. A hydrogen core grid of 9,040 km (60% repurposed, 40% newly built) by 2032 is planned (FNB Gas 2024).

Germany positions itself to lead in providing hydrogen technologies by 2030, along with establishing suitable regulatory frameworks (BMWK 2023a). Currently, there are EUR 550m approved to support steel production decarbonization (In force) and Carbon contracts for difference (CfD) to support achieving carbon-neutral industries (supporting both renewable and "blue" hydrogen (In force) (IEA 2023a). Hydrogen is planned to be used by the industry, refining, shipping, aviation, electricity and the transportation sector (IEA 2021).

Greece:**Focus on infrastructure and 3.8 GW electrolyser capacity by 2030**

Greece published its national energy and climate plan (NECP) as a roadmap for its energy transition, where country's hydrogen plan is highlighted. However, Greece does not have a separate hydrogen strategy published. The NECP emphasizes that it is important to develop alternative fuels infrastructure including hydrogen refueling infrastructure. It also highlights that Greece plans an installed electrolyser capacity of 3.8 GW by 2030. Hydrogen is planned to be used by the transportation sector (Ministry of Environment and Energy 2023).

Hungary:**Scaling low-carbon hydrogen production and decarbonizing industry**

The hydrogen strategy by Hungary has four priority objectives to be achieved by 2030. The first objective is producing large-scale quantities of low carbon hydrogen and decentralized carbon-free hydrogen, which involves producing 20,000 tonnes of low-carbon hydrogen and 16,000 tonnes of carbon-free (i.e. green) hydrogen annually. The second objective is industry decarbonization using hydrogen. Third, speeding up the shift to green transportation through consuming clean alternatives and building 20 hydrogen refueling stations. The fourth objective is to provide infrastructure support for storage and the reconstruction of existing infrastructure (Government of Hungary, 2021). Hydrogen is planned to be used by industry, electricity and transportation sectors (IEA 2021).

Ireland:**Export potential and infrastructure development**

Ireland's hydrogen strategy prioritise the production and expansion of renewable hydrogen, where surplus renewables from grid connected electrolysis will be used to produce hydrogen before 2030. Ireland plans to become a net exporter of renewable hydrogen from offshore wind. Domestic hydrogen demand is estimated to be between 4.6 to 39 TWh by 2050. Additionally, the strategy focuses on enabling infrastructure, where natural gas pipeline repurposing will be implemented whenever possible. Hydrogen is planned to be used by industry, transportation, shipping, and aviation sector, as well as exports (Department of the Environment, Climate and Communication 2023).

Italy:**Consume 0.25 million tons annually of green hydrogen by 2030**

The Italian hydrogen strategy; national energy and climate plan (NECP), sets a target to consume 0.25 million tons annually of green hydrogen by 2030 (Italian Ministry of the Environment and Energy Security 2024). Second, Italy has planned EUR 3,640m in hydrogen investments (Gandiglio & Marocco 2024). Third, in 2023, EUR 450m are approved to support renewable hydrogen production projects in brownfield industries (IEA 2023a). Hydrogen is planned to be used by industry, shipping, refining sectors (Ministry of economic development 2020).

Latvia:**No clear hydrogen plan**

According to Latvia's national energy and climate plan (NECP), hydrogen is viewed as as a future alternative fuel to replace fossil products (Ministry of Climate and Energy 2024).

Lithuania:**Produce 129,000 tons of green hydrogen per year**

The Lithuania hydrogen guidelines is published in 2024. The country's hydrogen guidelines highlight three goals for hydrogen deployment by 2030. First, a target of 1.3 GW electrolyser capacity by 2030. Second, building 10 hydrogen refueling stations. Third, producing green hydrogen equivalent to 129,000 tons annually (Minister of Energy of te Republic of Lithuania 2024). Previously, the country proposed hydrogen roadmap prepared to the government by Baringa. Lithuania is characterized by a relatively significant presence in manufacturing of fertilizers and substantial demand for fuel for heavy transport relative to the country's size. Therefore, it is necessary to replace fuels in these sectors with cleaner alternative fuels, where hydrogen is a solution in this case. Hydrogen is planned to be used by refining, transportation, fertilizers industry (Baringa 2022).

Luxembourg:**Hydrogen usage in hard to decarbonize sectors**

Luxembourg prioritizes energy efficiency and direct electrification. However, hydrogen will be used initially in hard to decarbonise sectors. The hydrogen demand potential ranges between 125,000 and 300,000 tonnes annually. Hydrogen is planned to be used by industry and transportation sectors (Ministry of Energy and Spatial Planning 2021).

Malta:**No hydrogen plan**

Malta has no hydrogen strategy and its NECP has hardly mentioned any information on hydrogen plans. Additionally, it is stated that the country's geology and topology hinder hydrogen and geothermal energy production as there is no significant thermal gradient or any water bodies. However, Malta has the objective of enhancing the connection of energy supply between Europe and third countries on within the Mediterranean, this can be through the hydrogen-ready natural gas pipelines (Ministry for the Environment, Energy, and Regeneration of the Grand Harbour 2023).

Netherlands:**Large scale hydrogen production and infrastructure development**

The Netherlands published its Climate Agreement which includes hydrogen objectives by 2030 and 2050. The main objective is producing large volumes of green hydrogen. The development of necessary hydrogen infrastructure is another important focus as well as building 50 refuelling station by 2025 and 300,000 fuel cell vehicles by 2030 (Ministry of Economic Affairs 2019). Moreover, in 2022, EUR 784 m were approved in subsidies to support electrolyser projects (IEA 2023a). Hydrogen is planned to be used by the industry, buildings, refining, shipping, aviation, electricity, transportation sectors (IEA 2021).

Poland:**Focusing on energy, transport, and industry**

The Polish hydrogen strategy published in 2020, sets targets to boost hydrogen supply to reach 2 GW of electrolysis. The strategy focuses on three key areas of hydrogen use: energy, transport, and industry, alongside its production, distribution, and storage, emphasizing the need for a stable regulatory environment (Ministry of Climate and Environment 2020). Further, in 2023, EUR 158 m are dedicated to support renewable hydrogen production in the refining sector (IEA 2023a). Hydrogen is planned to be used by the transportation sector and the industry (Ministry of Climate and Environment 2020).

Portugal:**Building 50 to 100 hydrogen filling stations by 2030**

Portugal published its hydrogen strategy in 2020, which seeks to provide incentives and stability for the energy sector. The strategy sets the goal of installing 2 - 2.5 GW of electrolyser capacity by 2030 to significantly increasing hydrogen supply. Second, the strategy includes targets as building 50 to 100 hydrogen filling stations by 2030. This is accompanied by promoting the country's industrial policy around hydrogen and other renewable gases (DGEG 2020). Hydrogen is planned to be used by industry, electricity, transportation sectors (IEA 2021).

Romania:**Generate 282 kt of green hydrogen and 7 kt of clean hydrogen by 2030**

Romania published its hydrogen strategy and action plan in 2023, setting targets to scale up hydrogen production and integrate it into key sectors of the economy. First, Romania targets to produce annually 282 kt of green hydrogen and 7 kt of clean hydrogen by 2030, to advance industries that are hard to decarbonize and to create a clean transportation sector. Furthermore, a key aspect of the strategy is advancing hydrogen technologies and integrating them into the economy by supporting research and innovation. Hydrogen is planned to be used by industry and transportation sectors (Ministry of Energy 2023).

Slovakia:**Targets EUR 59.6 m of planned investments by 2026**

Slovakia's hydrogen strategy, as well as its national energy and climate plan outline general hydrogen goals. The plan promotes the development and use of hydrogen technologies, as well as planned investments of EUR 59.6 m by 2026 (Ministry of Economy 2023).

Slovenia:**No hydrogen plan****Spain:****Aiming for 25% industrial hydrogen consumption**

Spain's hydrogen roadmap and its NECP updated in September 2024, sets the goal of installing 12 GW (4 GW previously) of electrolyser capacity by 2030, aimed at significantly boosting hydrogen production (Ministry for Ecological Transition and the Demographic Challenge 2024). Second, it prioritizes infrastructure development, including the construction of 100-150 hydrogen refueling stations to support the transport sector. Third, Spain aims for 25% of its industrial consumption to be supplied by hydrogen (Ministry for Ecological Transition and Demographic Challenge 2020a). In line with these targets, Spain estimates a total of EUR 8.9 bn in investments dedicated to renewable hydrogen projects. Additionally, in 2023, EUR 450 m was specifically approved to support renewable hydrogen production within the steel industry (IEA 2023a). Hydrogen is planned to be used by chemical industry, refining, shipping, aviation, electricity, transportation sectors (IEA 2021).

Sweden:**No official hydrogen plan**

Sweden national hydrogen strategy is under development (draft) and has not been officially approved (European Union Agency for the Cooperation of Energy Regulators 2024). The Fossil Free Sweden initiative in 2015 aims to bring together actors as firms and regions to make Sweden fossil free. The initiative proposed a hydrogen roadmap (Fossil Free Sweden 2021).

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Center for Advanced Security, Strategic and Integration Studies (CASSIS)

University of Bonn
Römerstraße 164
53117 Bonn, Germany

Board of Directors

Prof. Dr. Volker Kronenberg
Prof. Dr. Wolfram Hilz
Prof. Dr. Ulrich Schlie

Managing Director

Dr. Enrico Fels

Phone: +49 (0) 228/73 62995

cassis@uni-bonn.de

<https://www.cassis.uni-bonn.de/en>

Institute of Energy Economics at the University of Cologne gGmbH (EWI)

Alte Wagenfabrik
Vogelsanger Straße 321a
50827 Cologne, Germany

Director

Prof. Dr. Marc Oliver Bettzüge

General Manager

Annette Becker

Phone: +49 (0) 221/650 853-60

<https://www.ewi.uni-koeln.de/en>

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H₂ Reality Check

Overall project management

Dr. Enrico Fels
Dr. Frank Umbach
David Isken
Svenja Paul

Executive Summary, Political Recommendations, Chapter 1, Chapter 2.2, Chapter 4 & Chapter 5

Center for Advanced Security, Strategic and Integration Studies (CASSIS)
Dr. Frank Umbach

Executive Summary, Chapter 2.1 & Chapter 3

Energiewirtschaftliches Institut
an der Universität zu Köln gGmbH (EWI)
Dr.-Ing. Ann-Kathrin Klaas
Dr. Philip Schnaars
Michael Diehl
Nada Fadl

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University of Bonn
cassis.uni-bonn.de

Institute of Energy Economics
at the University of Cologne gGmbH (EWI)
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