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Green hydrogen:
Energizing the path to net zero

Deloitte's 2023 global green hydrogen outlook

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Foreword

When it comes to tackling climate change, the world is rapidly moving from ambition to action. In just the past few years, private companies, research institutions, regulators, financiers, and governments have accelerated in the race to decarbonize organizations, supply chains, sectors, and, indeed, economies. This newfound zeal finds its motivation in the very crucible of innovation: necessity—the necessity of tackling climate change, the necessity for energy security, the necessity for geopolitical recalibration.

The calls for action have finally found voice. Deloitte's Turning Point analysis pointed to economic arguments for action on climate change—from a regional perspective and a global perspective. This economic and commercial perspective has highlighted the structural and transformative challenge of climate change and advanced the energy transition as a necessary condition for growth and sustainable development.

Globally, the movement toward net-zero is now broadly acknowledged, while debate continues around the pace and scale of change across industries and nation-states. Yet, the crescendo of attention to the common concern to humankind poised by climate change is juxtaposed with a narrowing window for action highlighted by scientists, the Intergovernmental Panel on Climate Change (IPCC), and the international community.

At its core, a shift in the energy mix will transform economies' production systems. In terms of scale, it truly can be that profound. The speed of transformation will be dictated by the calculus of physical and economic damages of climate change, alongside the costs to decarbonize, influenced by the interplay of the supply and demand of old and new energy. In the end, the constant is an inevitability of change.

While the greatest energy mix switch will be toward electricity from renewable sources, 15% to 30% of future energy needs is likely to be satisfied by hydrogen, a function of sectors that may not be able to electrify easily (hard-to-abate sectors) and of the creation of additional demand from new products and services—for example, green steel. In the context of the timeframe for the world to achieve net-zero, hydrogen, and in particular green hydrogen, gains significant currency.

Using projections from Deloitte Economics Institute's Hydrogen Pathway Explorer (HyPE) model, this report offers a comprehensive analysis of the development of renewable hydrogen to energize the global economy toward net-zero by 2050. The development of green hydrogen is a key element in the transition pathway from a high-emissions intensive energy system to a net-zero economy by 2050.

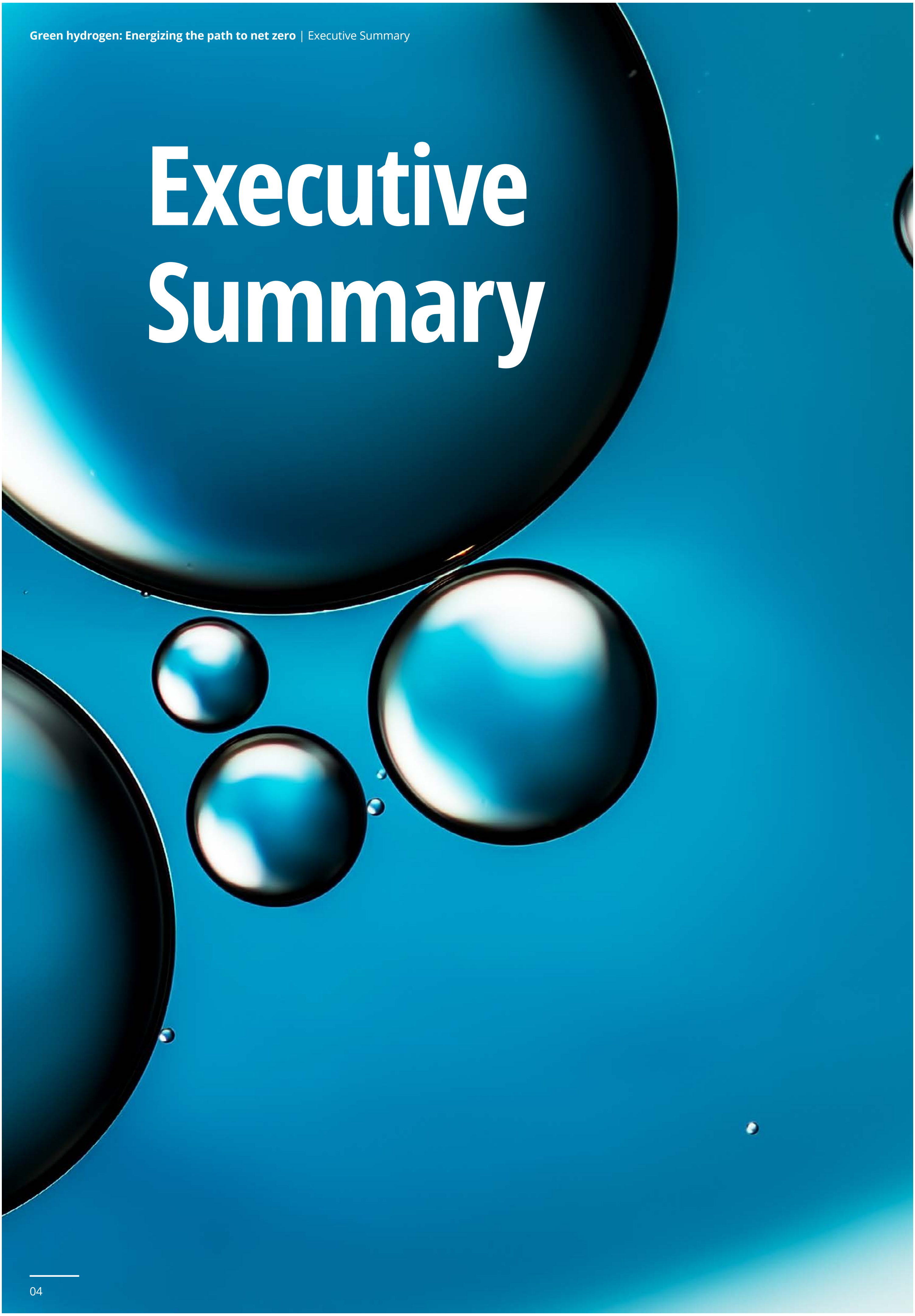
The significance of Deloitte's analysis—a US$1.4 trillion market by 2050 in which green hydrogen comprises some 85% of the hydrogen market, with 20% traded around the world—is twofold: first, this trade is critical to the lowest-cost decarbonization of the world economy; second, the production and export of green hydrogen can offer a global sustainable development realignment for developing and emerging economies across Africa, Latin America, and the Pacific, alongside countries such as Australia and the United States and regions such as the Gulf States.

This report is not a prediction—it is a plausible scenario of how this new energy transition could unfold based on some of the latest, credible data, assessments, and regulatory and policy developments.

As the global economy searches for new sources of value and a new growth path for sustainable economic development, green hydrogen can provide a pathway of hope and prosperity. Please join us on this global project of decarbonization and write the chapter to unlock the green hydrogen economy together.

Jennifer Steinmann
Global Sustainability &
Climate Practice Leader
Deloitte Global

Executive Summary



The critical role of clean hydrogen on the way to climate neutrality

Governments, executives, researchers, and other parties around the world are looking to accelerate the ongoing energy transition to reach carbon neutrality. Aligning economies with the targets laid out in the Paris Agreement—limiting global warming to well below 2 °C, while pursuing efforts to limit the increase to *1.5* °C[1]—requires replacing legacy systems powered by fossil fuels with low-carbon energy sources such as renewables.

Evan as electrification leveraging on low-carbon technologies such as renewables clearly appears as an essential solution, it still faces real barriers, particularly when it comes to decarbonizing hard-to-abate sectors such as heavy industry and transport. Activities such as high-temperature heating, feedstock supply for chemicals, or heavy-duty freight are indeed hard to fully electrify. Besides, if wind and solar power continue to expand as prices fall, network stabilization issues can arise with the need to take into account their variability.

Clean hydrogen is now clearly recognized as a potential breakthrough technology to overcome these limits.[2] Hydrogen is a versatile molecule,[3] which can be used directly via fuel cells or for electricity generation, and as feedstock to produce more suitable derivatives—such as ammonia, methanol, or sustainable aviation fuels (SAF)—to specific industrial and transport applications.

Hydrogen supply currently almost entirely relies on natural gas reforming and coal gasification, which are highly carbon intensive (more than 1 Gt of CO_2 emissions per year). The real breakthrough is the potential of *clean* hydrogen to decarbonize current supply and develop new end uses at scale.[4] *Green* hydrogen, produced from renewable electricity via electrolysis, is the most promising and truly sustainable technology. *Blue* hydrogen, produced via natural gas coupled with carbon capture and storage, can also be labeled "clean" provided it meets stringent methane emissions and carbon capture standards.

Deloitte's outlook, leveraging a data-driven and model-based quantitative analysis, explores the emergence of a carbon-neutral, inclusive clean hydrogen economy in the coming years. This outlook relies on Deloitte's Hydrogen Pathway Explorer (HyPE) model (see Appendix) and proposes a vision for a fast-tracked development of the clean hydrogen economy, highlighting the associated challenges and bottlenecks. It showcases a steady market growth, from US$642 billion in annual revenue in 2030 to US$1.4 trillion per year in 2050, a recognized milestone to reach climate neutrality.

The emerging green hydrogen economy: Deloitte's outlook

To achieve climate neutrality by 2050, the clean hydrogen market capacity can grow to 170 million tons (MtH_{2eq}) in 2030 and to 600 MtH_{2eq} in 2050. Demand is expected to initially build on the decarbonization of existing industrial uses of hydrogen (95 MtH_{2eq}), most notably for fertilizer production.[5] The net-zero transition then underpins rapid demand growth, cementing hydrogen's role as a versatile solution for decarbonization. By 2050, industry (iron and steel, chemicals, cement, and high-temperature heating) and transport (aviation, shipping, and heavy road transport) respectively can account for 42% and 36% of total clean hydrogen demand. Overall, this outlook shows clean hydrogen delivering crucial carbon emission reductions. Decarbonizing current and developing new end-uses, it can abate up to 85 $GtCO_{2eq}$ in cumulative emissions by 2050, more than twice global CO_2 emissions in 2021.

While demand is expected to quickly ramp up in industrialized economies, clean hydrogen can also represent a major sustainable growth opportunity for developing countries, leading to the progressive structuring of a truly global market. Yet, materializing a new major industry within less than three decades presents an unprecedented challenge along the still-nascent value chain.

Projects initially depend on public support to break even, as illustrated by the first major government programs such as the United States Inflation Reduction Act, the Australian Clean Energy Finance Corp., the European Union Fit-for-55 package and Important Projects of Common European Interest (IPCEI) funding program, and Japanese demand-side research and development (R&D) support programs. Indeed, the production cost of conventional carbon-intensive hydrogen does not sufficiently reflect its impact on climate. Government's support may be needed until clean, and especially green hydrogen catches up in terms of costs, leveraging on economies of scale and tightening CO_2 pricing. The breakeven point can be reached by 2030 for ammonia, 2035 for gaseous hydrogen, 2045 for methanol, and 2050 for SAF. Therefore, with time, green hydrogen can stand on its own feet. By 2050, the global hydrogen market can reach maturity as supply capacities massively scale up to meet the demand, underpinned by new end uses in industry and transport. The market growth is expected to allow spot markets to dominate price formation, improving resilience and channeling investments to the most competitive geographical areas.

Deloitte's modeling results show that green hydrogen can dominate the supply mix from the beginning, reaching 85% of market share in 2050 (above 500 MtH_{2eq}). Blue hydrogen can help to build up demand in the early stages, facilitating the emergence of the hydrogen economy in regions that can leverage natural gas reserves such as the Middle East, North Africa, North America, and Australia. Production peaks in 2040 at almost 125 MtH_{2eq} (30% of supply), after which blue hydrogen is set to gradually be crowded out by more competitive green hydrogen and tightening environmental constraints on unabated methane and CO_2 emissions.

Global trade connects the dots

Throughout this outlook, global trade between major regions can represent almost one-fifth of total volume, reaching about 110 MtH_{2eq} in 2050. The most common products are hydrogen derivatives—ammonia, methanol, and SAF—which are easier to transport over long distances. Ammonia also can become a medium for transporting hydrogen, implying conversion and re-conversion steps. By 2050, four regions collectively account for about 45% of global hydrogen production and 90% of trade: North Africa and Australia have the highest export potential (44 MtH_{2eq} and 16 MtH_{2eq} respectively) compared to their domestic demand. They are followed by North America (24 MtH_{2eq}) and the Middle East (13 MtH_{2eq}). South America and sub-Saharan Africa can also actively take part in global trade, with some 10% of traded volumes. On the import side, Japan and Korea facing resource and land-availability constraints, can heavily depend on global trade, importing 90% of their demand between 2030 and 2050. Europe, China, and India can produce substantial amounts of hydrogen but also are likely to rely on imports throughout the transition.

In 2050, global trade between major regions can generate more than US$280 billion in annual export revenues in 2050. The main recipients include North Africa (US$110 billion per year), North America (US$63 billion), Australia (US$39 billion), and the Middle East (US$20 billion). Free and diversified trade can significantly reduce costs, improve energy security, and foster economic development in developing and emerging markets. Export revenues from clean hydrogen can help today's fossil fuel exporters offset declining revenue from oil, natural gas, and coal.

Redirecting investments from fossil fuels to clean hydrogen

Creating the pathway to net-zero compliance in 2050 as it is materialized in this outlook is estimated to require over US$9 trillion of cumulative investments in the global hydrogen supply chain, including US$3.1 trillion in developing economies. The figures may sound daunting, but average annual investments over this 25-year period, are actually less than the US$417 billion spent on oil and gas production in 2022. If governments and companies can redirect spending on oil and gas to clean hydrogen, this seems to be a manageable endeavor. Deloitte's outlook suggests that China, Europe, and North America—the main consuming regions, also accounting for more than half of production—invest US$2 trillion, US$1.2 trillion, and US$1 trillion, respectively. Significant funding should also be raised in developing and emerging economies, including about US$900 billion in North Africa, US$400 billion in South America, and US$300 billion each in Sub-Saharan Africa and Central America. In these regions, the development of the green hydrogen economy can be a unique opportunity to attract foreign investment.

Future-focused policy action

Decisive policy support can help to scale up the clean hydrogen economy and ensure that, especially, green hydrogen plays its needed role on the path to climate neutrality. To date, more than 140 countries (collectively responsible for 88% of global CO_2 emissions[6]) have adopted net-zero targets. However, clean hydrogen projects announced worldwide would provide a collective production capacity of only 44 MtH_{2eq} by 2030, one-quarter of this demand scenario. Targeted policy support for clean hydrogen may be crucial to help ensure that early projects, such as pilot and head of series, can compete on a level playing field, enter the market, and trigger economies of scale.

Policymakers should focus attention on three components:

Laying the foundations for a climate-oriented market. Policymakers can lay out national and regional strategies to boost the visibility and credibility of development prospects. A robust and shared certification process for clean hydrogen can ensure transparency and avoid technological lock-ins. International cooperation is a critical piece to help mitigate political friction and ensure a level playing field.

Creating a business case. Policymakers can use targeted instruments (for example, mandates, direct subsidies, Carbon Contracts for Difference, fiscal incentives, public guarantees, and creating targets or markets for hydrogen-based products) to reduce the cost difference between clean and fossil-based technologies. Long-term offtake mechanisms, such as Germany's H2Global project[7], can substantially mitigate project risks, bridge the gap between price and willingness to pay, and strengthen price stability.

Ensuring long-term resilience. National strategies should aim for diversification all along the value chain, from trade partners to equipment and raw material suppliers, to help avoid costly bottlenecks during the ramp-up and bolster market resilience. Extensive public support should also be dedicated to infrastructure design to transport (pipelines and marine roads) and store (strategic reserves) clean hydrogen commodities. Governments should aim to strike international cooperation to strengthen synergies between energy, climate, and development policies including promoting strong regional integration.

Introduction. Deloitte's outlook on the global clean hydrogen market

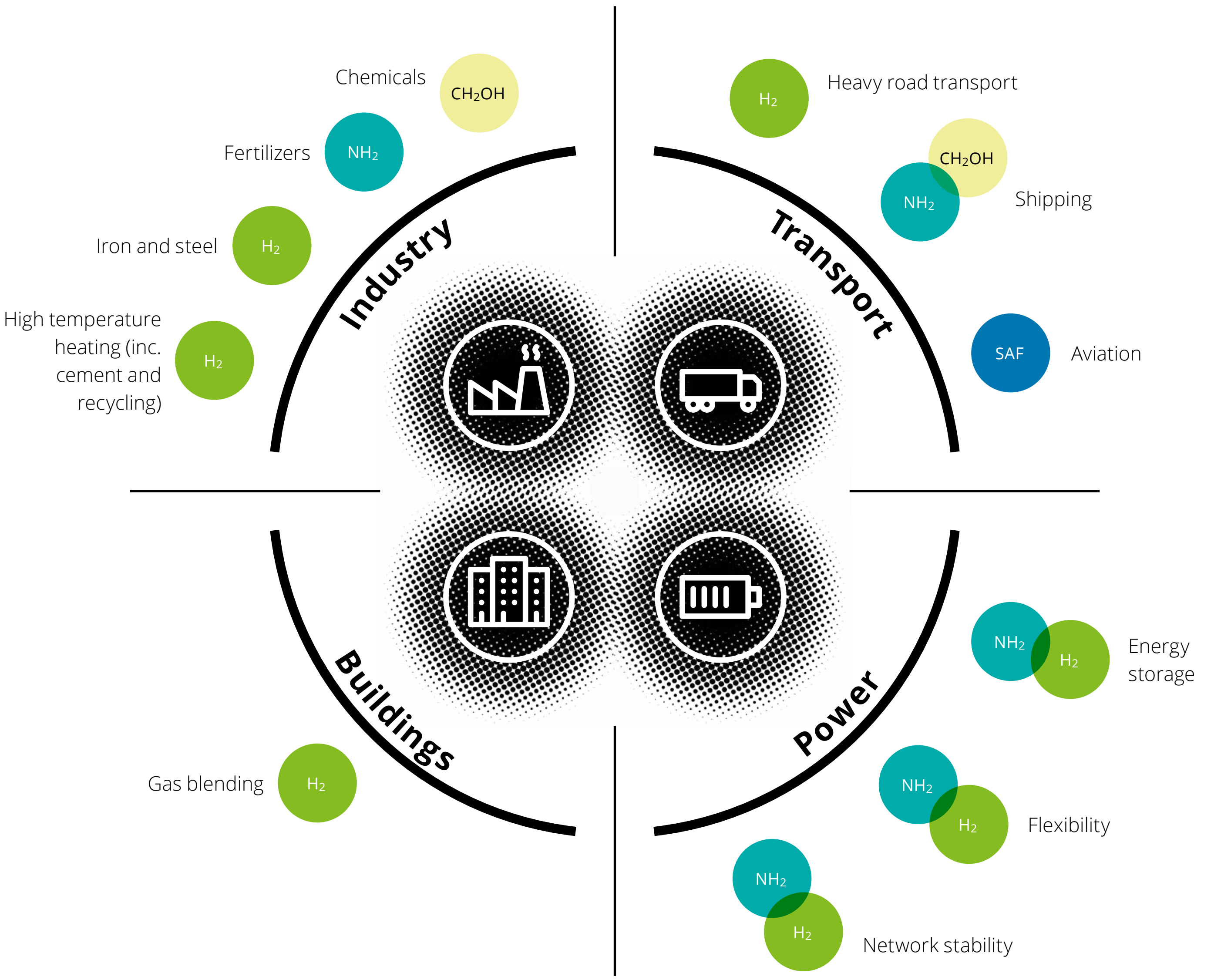
Nearly 200 parties signed the Paris Agreement in December 2015, aiming to limit global warming to well below 2 °C, while pursuing efforts to limit the increase to 1.5 °C—a target that requires achieving worldwide greenhouse gas (GHG) emission neutrality by no later than 2050.[8] But decarbonizing the global economy likely cannot happen without technological change, both on the energy supply side—via the large-scale development of renewables[9]—and end-use shift toward low-carbon energy carriers.[10,11] While electrification is central to much of the shift, decarbonizing hard-to-abate sectors may require solutions beyond electrification.

Clean hydrogen could prove as one of the key elements of decarbonization, helping to overcome the limits of electrification to decarbonize sectors such as industry or heavy-duty transport.

Biomass—for instance to produce biogas— is unlikely to take over clean hydrogen, but both can complement for industrial applications such as high heat for metallurgy, or feedstock use for chemicals industry.

Hydrogen is a versatile molecule—not to mention the most abundant in the universe[12]—that can be used both as feedstock and energy source in a variety of applications (figure 1). Various uses call for pure hydrogen (H_2), others for derivative molecules produced from clean hydrogen, such as ammonia (NH_3),[13] methanol (CH_3OH), or sustainable aviation fuels (SAF).[14] Derivatives are easier to store and transport and can, in the case of ammonia, be converted back into pure hydrogen, offering inexpensive maritime transport options.[15]

Figure 1. Identified main end uses of clean hydrogen and its derivatives in a climate-neutral energy system



Source: Deloitte analysis based International Energy Agency (IEA)[16], International Renewable Energy Agency (IRENA)[17] and Hydrogen4EU.[18]

Hydrogen production technologies

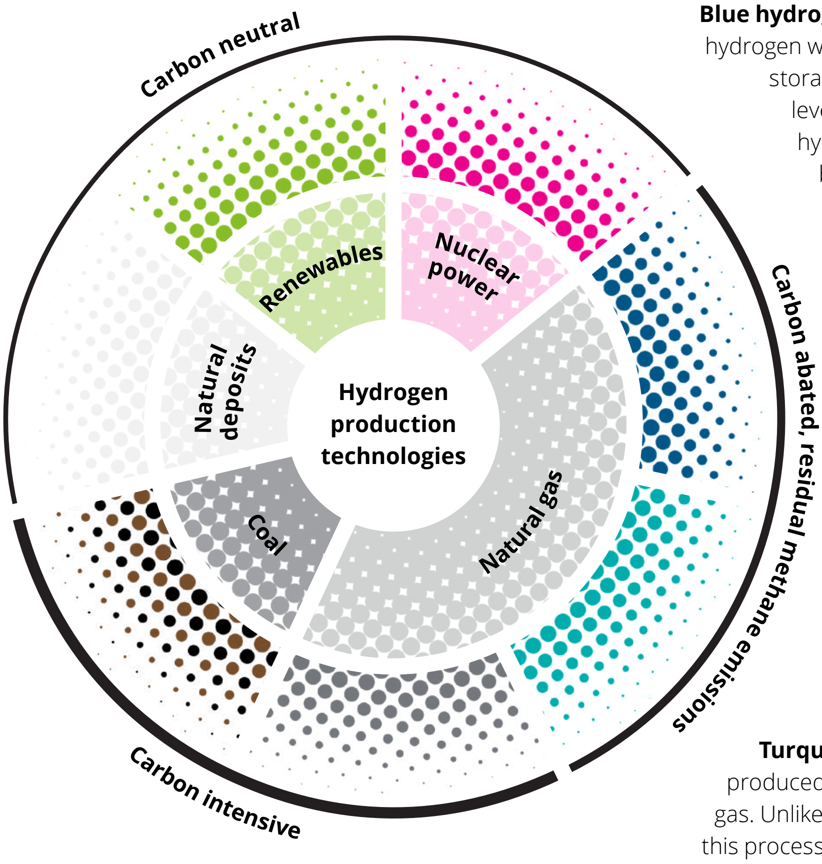
Several technologies already exist to produce hydrogen, with new technologies in various stages of development. The new technologies mostly focus on making the production process zero- or low-emission. The industry uses colors to help differentiate technological families of hydrogen, distinguishing between carbon-intensive (grey and black/brown) and clean (green, blue, turquoise, white, and pink) hydrogen.[19]

Green hydrogen is produced from electrolysis using renewable electricity (e.g. solar and wind). It is amongst the least carbon intensive technologies for producing hydrogen and releases no direct emissions. It can easily be scalable and is expected to become highly cost-competitive with growing deployment, similar to what was observed from renewable energies' development over the past decade.

Pink hydrogen is produced via electrolysis of water using nuclear power. This process is also carbon-neutral. Nuclear power may face social acceptance and scale-up issues and/or could be dedicated in priority to baseload electricity production.

White hydrogen refers to natural stockpiles of hydrogen which can be extracted from drilling in underground wells. The endowments are negligible with compared to global needs.

Blue hydrogen complements grey hydrogen with carbon capture and storage (CCS) technology. By leveraging on current grey hydrogen infrastructures, blue hydrogen can help rapidly build up the demand for clean hydrogen. However, even in the long-run, this technology will hardly achieve carbon neutrality due to residual emissions (the highest carbon capture rate is currently estimated at around 95%) and upstream methane emissions.



Black or brown hydrogen refers to the gasification of coal, the most polluting technology with 20 $kgCO_2/kgH_2$ of emissions released during the process.

Turquoise hydrogen can be produced via pyrolysis of natural gas. Unlike grey or blue hydrogen, this process releases solid (and not gaseous) carbon, which can be either used as feedstock for other industrial processes (without releasing it into the atmosphere as CO_2 down the value chain) or stored permanently. Therefore, direct carbon emissions are avoided. Nevertheless, this technology is to date expensive compared to alternatives, has not proven to be scalable yet, and would also need to deal with the upstream methane emissions.

Grey hydrogen relies on natural gas reforming (via steam methane reformation, auto-thermal reformation of methane or methane gas-heated reforming), the most widely adopted technology today. Carbon emissions associated with SMR ($9kgCO_2/kgH_2$), and upstream methane emissions resulting from natural gas supply, make grey hydrogen an emission-intensive process.

Unlocking clean hydrogen's decarbonization potential may require clean production technologies consistent with net-zero emission targets. Currently, electrolysis based on renewable electricity is recognized as the most promising and sustainable technological solution for producing green hydrogen. Though there is a long way to make that happen: Nearly all of today's 95 MtH_{2eq} global hydrogen-equivalent[20] production is based on fossil fuels, primarily through steam reforming of natural gas (grey hydrogen) or gasification of coal (brown or black hydrogen). This generates more than 1 Gt of annual CO_2 emissions—2.5% of global annual emissions, on par with the entire aviation sector. Coupling existing natural gas-based technologies with carbon capture and storage (blue hydrogen) can be an important interim step, with expectations of up to 95% reduction in direct CO_2 emissions for the most efficient processes.[21]

The emergence of a clean hydrogen market comes with opportunities and challenges at each stage of the value chain. Achieving carbon neutrality entails not only decarbonizing the current hydrogen supply but scaling it more than sixfold to help cover the new uses essential to the energy transition. This would demand an unprecedented ramping up of technological development (fuel cells, direct reduction for iron and steelmaking, and the processes for producing sustainable aviation fuel), manufacturing capabilities (electrolyzers, solar panels, and wind turbines), and infrastructure (production, transport, and storage facilities) while building new supply chains and establishing a global hydrogen trade.[22]

Large uncertainties remain on which pathway the global value chain follows,[23] depending on choices of supply technologies and associated leadership, production and consumption locations and resulting energy trade routes, and hydrogen applications. These decisions could create conflicts between the various stakeholders in the hydrogen economy, such as governments (energy security and industrial policy), energy suppliers and utilities, equipment manufacturers, consumers, and transport actors (shipping companies and port facility managers).

This report presents Deloitte's outlook on the emergence of a carbon-neutral, inclusive clean hydrogen economy in the years leading up to 2050. This outlook is based on the paradigm that the global economy reaches carbon neutrality by the middle of this century, with governments and companies proactively tackling financial and geopolitical matters, allowing free clean hydrogen trade to unfold in a diversified way, with the Global South playing an integral part. Such a level of ambition is likely necessary to fight global warming without delay while creating fair development opportunities and, with a diversified hydrogen value chain, improving global energy security and reducing the risk of supply chain disruption.[24]

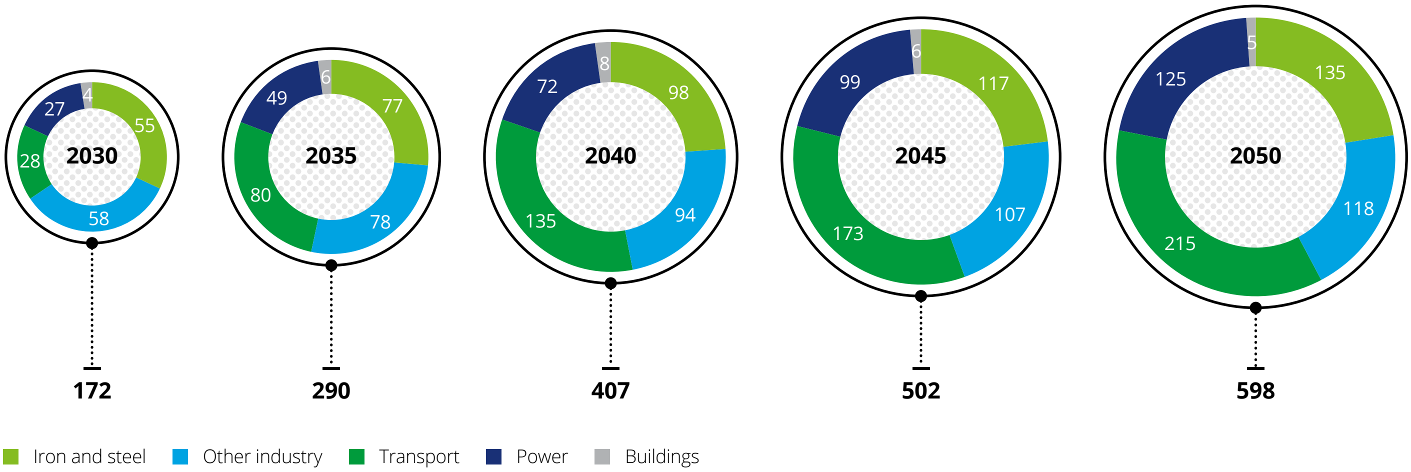
Leveraging a data-driven and model-based quantitative analysis, this outlook proposes a vision for a fast-tracked development of the clean hydrogen economy, highlighting the associated challenges and bottlenecks. It relies on Deloitte's Hydrogen Pathway Explorer (HyPE) model (see Appendix) to help provide a set of quantitative results on cost-efficient supply and trade flows, underlying economic indicators—detailed views on production costs, market revenues, and financing needs—and key policy actions needed to help achieve climate objectives in a robust and resilient fashion.

Part 1. Envisioning a 600 million metric ton market

Achieving net-zero greenhouse gas emissions by 2050 will likely require the development of a 170-MtH_{2eq} clean hydrogen market by 2030, growing to nearly 600 MtH_{2eq} by 2050. To put these numbers in perspective, in energy terms, 600 MtH_{2eq} is equivalent to more than 85% of the global electricity consumption in 2019 (22,850 TWh[25]). Currently, the clean hydrogen market cannot compete economically with fossil fuels, whose prices rarely include their environmental externalities.[26] Deloitte's outlook envisions the clean hydrogen economy emerging, through the policies put in place to achieve the ambitions to decarbonize the global energy system.[27]

Deloitte's outlook first envisions building demand on the decarbonization of existing industrial uses of hydrogen, notably for production of fertilizers, before turning to new uses (figure 2). Then, the industrial transformation to net-zero underpins fast demand growth for new end uses, underscoring hydrogen's role as a versatile tool for decarbonization. Overall, Deloitte's outlook sees pure hydrogen demand reaching nearly 390 Mt in 2050 (about two-thirds of the market in hydrogen-equivalent terms), followed by ammonia (more than 590 Mt of ammonia or 104 MtH_{2eq} in hydrogen equivalent terms), SAF (134 Mt or 80 MtH_{2eq}), and methanol (130 Mt or 25 MtH_{2eq}).

Figure 2. Evolution of clean hydrogen demand by sector, 2030 to 2050 (MtH_{2eq})

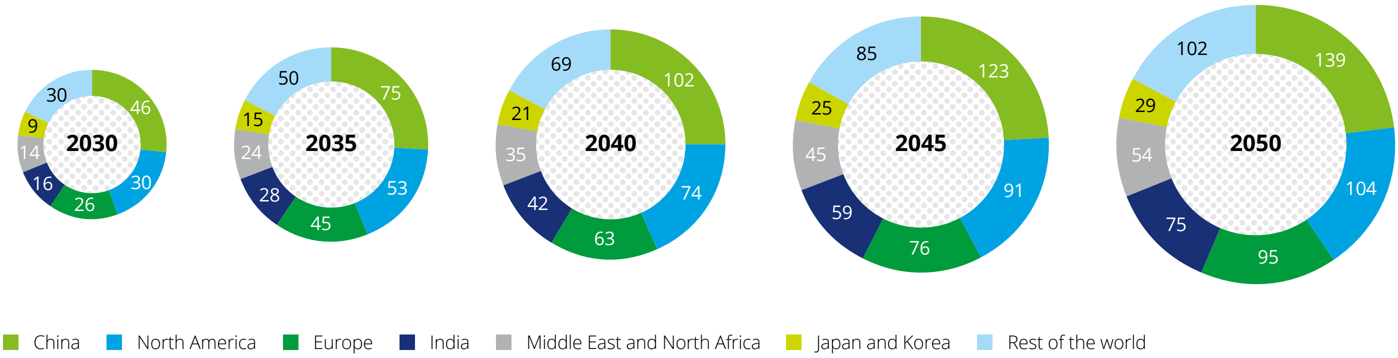


Source: Deloitte analysis

In Deloitte's analysis, hard-to-abate sectors can drive the bulk of long-term demand for green hydrogen.

- By 2050, demand for clean hydrogen in iron, steel and other **industry** tops 250 MtH_{2eq}, or 42% of total demand. Clean hydrogen can help to decarbonize current feedstock uses in the chemical industry, including producing ammonia for fertilizers and methanol for plastics and clothing. In the iron and steel sector, pure hydrogen can be used as a reduction agent in direct reduced steelmaking processes. Overall, pure hydrogen can also serve as an energy source for industrial applications dependent on high heat, including metallurgy (iron and steel), chemicals, textile fibers manufacturing, electronics, recycling, and oil refining.
- Full decarbonization of the **transport** sector will likely require 215 MtH_{2eq} of clean hydrogen by 2050, 36% of total demand for clean hydrogen. In Deloitte's outlook, derivatives can be particularly valuable to help decarbonize shipping (as ammonia and methanol) and aviation, where electricity and pure hydrogen may not be viable solutions. Pure hydrogen can be consumed in fuel cells or internal combustion engines in the road freight sector, complementing electric vehicles especially for long-haul freight requirements.
- Hydrogen can also play an important role in the **power system** for energy storage and flexibility services, requiring another 125 MtH_{2eq} by 2050 (about one-fifth of total demand). During excess supply periods (high solar irradiation or strong winds), hydrogen can be produced via electrolysis and stored to be converted back to electricity in excess demand periods, providing downward and upward flexibility to the power system.[28]
- The injection of hydrogen into the existing natural gas transport and distribution network can be a potential solution to slightly lower the carbon footprint of gas consumption in **buildings**. However, Deloitte's outlook suggests a limited role for blending as electrification rapidly displaces natural gas consumption in this sector, in a net-zero environment. Moreover, hydrogen transport and distribution require a strict safety protocol,[29] while the efficiency of heating buildings via hydrogen is limited.[30] For these reasons, it is expected that hydrogen demand in buildings remains marginal (5 MtH_{2eq} in 2050, below 1% of total needs).

Figure 3. Regional demand for clean hydrogen and its derivatives, 2030 to 2050 (MtH_{2eq})



Source: Deloitte analysis

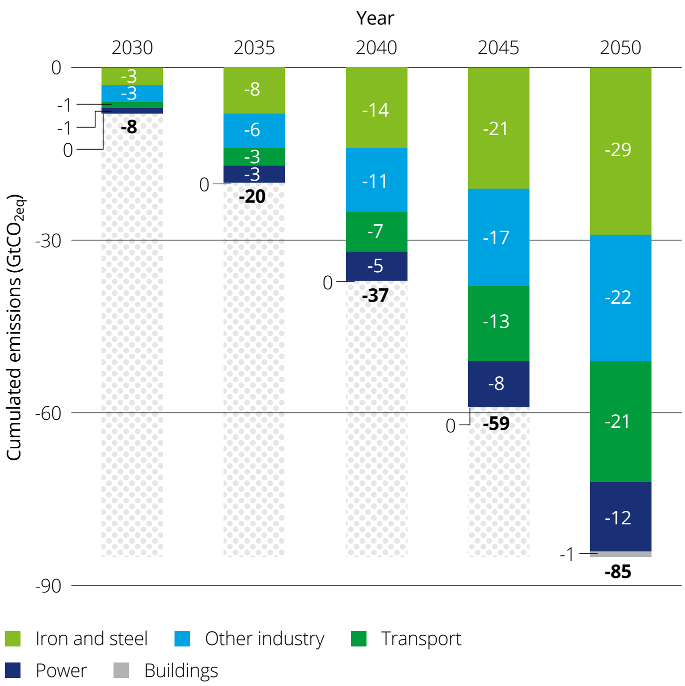
As climate change becomes a global imperative, with all major economies looking to decarbonize their end uses, clean hydrogen demand will likely skyrocket around the world, leading to the formation of a truly global market (figure 3). While demand initially takes off in industrialized economies, the hydrogen value chain can be a major sustainable growth and decarbonization opportunity for developing countries as well. Clean hydrogen can allow leapfrogging fossil fuels in the power system and fostering local production for both domestic consumption and exports.[31]

Developing countries can take advantage of their natural resources to help develop their own ecosystems, address a growing local demand driven by the transition toward climate neutrality, and integrate it into the global value chain by exporting the surplus of their domestic production to other regions. Moreover, future clean hydrogen value chains can go far beyond direct production or consumption aspects. Developing countries can benefit from the economic development opportunities of hydrogen transport, critical materials supply for electrolyzers, solar panels and wind turbines, or hydrogen processing/conversion plants.

Conversely, successful economic development should be a precondition to helping achieve net-zero in emerging markets. Reaching net-zero emissions, including the widespread use of clean hydrogen, may demand a conscious long-term strategy rather than a one-off approach. In Deloitte's outlook, investments would be necessary in both advanced and developing economies. A green colonialism mindset with developing countries providing only raw materials to the hydrogen economy[32] would be counterproductive, especially since the energy transition could likely be delayed in these regions—and globally.

Overall, Deloitte's results show that the uptake of clean hydrogen can deliver crucial CO_2 reductions in final demand, abating up to 85 $GtCO_{2eq}$ in cumulative greenhouse gas emissions by 2050 (figure 4) by decarbonizing current and developing new end uses.[33] To put this value in perspective, remaining on track with the 1.5 °C global warming objective would likely require limiting cumulative emissions to no more than 400 $GtCO_2$ between 2020 and 2050. Hydrogen can play a paramount role in sectors where emissions are hard to abate; while iron, steel and other industry represents only 42% of hydrogen demand between 2030 and 2050, clean hydrogen accounts for 60% of total cumulative emission reductions in this sector.

Figure 4. GHG emissions abatement unlocked by clean hydrogen, 2030 to 2050



Source: Deloitte analysis

Climate policy helps shape the market

Costs are one of the fundamental drivers of the clean hydrogen uptake—and, early on, an obstacle to overcome. Clean hydrogen is currently more expensive to produce and transport than its fossil-based competitors (figure 5). According to Deloitte's analysis, the production cost of green pure hydrogen ranges between US$2.50 and US$5/kg in 2025, at least US$1.5/kg more than grey hydrogen. Most critical clean hydrogen technologies—including electrolyzers and storage—are still at an early stage while legacy alternatives—such as steam methane reformers and coal gasification plants—benefit from decades of infrastructure and deployment.

As with other abatement technologies, economies of scale can, over time, reverse the current ranking of costs. The sharp decline in the cost of renewable electricity is a case in point. Sparked by public support, mass deployment of wind and solar power plants triggered a virtuous cycle of learning by doing: Between 2010 and 2021, production costs fell dramatically for solar (88%), onshore wind (68%), and offshore wind (60%).[34,35] Subsidies and advocacy are likely needed to do the same for clean hydrogen.

In a nascent market, uncertainties about market outlook can undercut private investments. The need for economies of scale to help reach economic viability points to a dilemma: Uncertainty about the uptake of demand for clean hydrogen may hold back investment in production or transport, while limited availability of clean hydrogen and the cost gap to carbon-intensive alternatives could deter widespread switching to clean hydrogen technology on the end-use side.[36] It therefore may require governments to make conscious policy decisions to help support the uptake of a green hydrogen economy and give visibility to stakeholders on both the market's production and end-use sides.

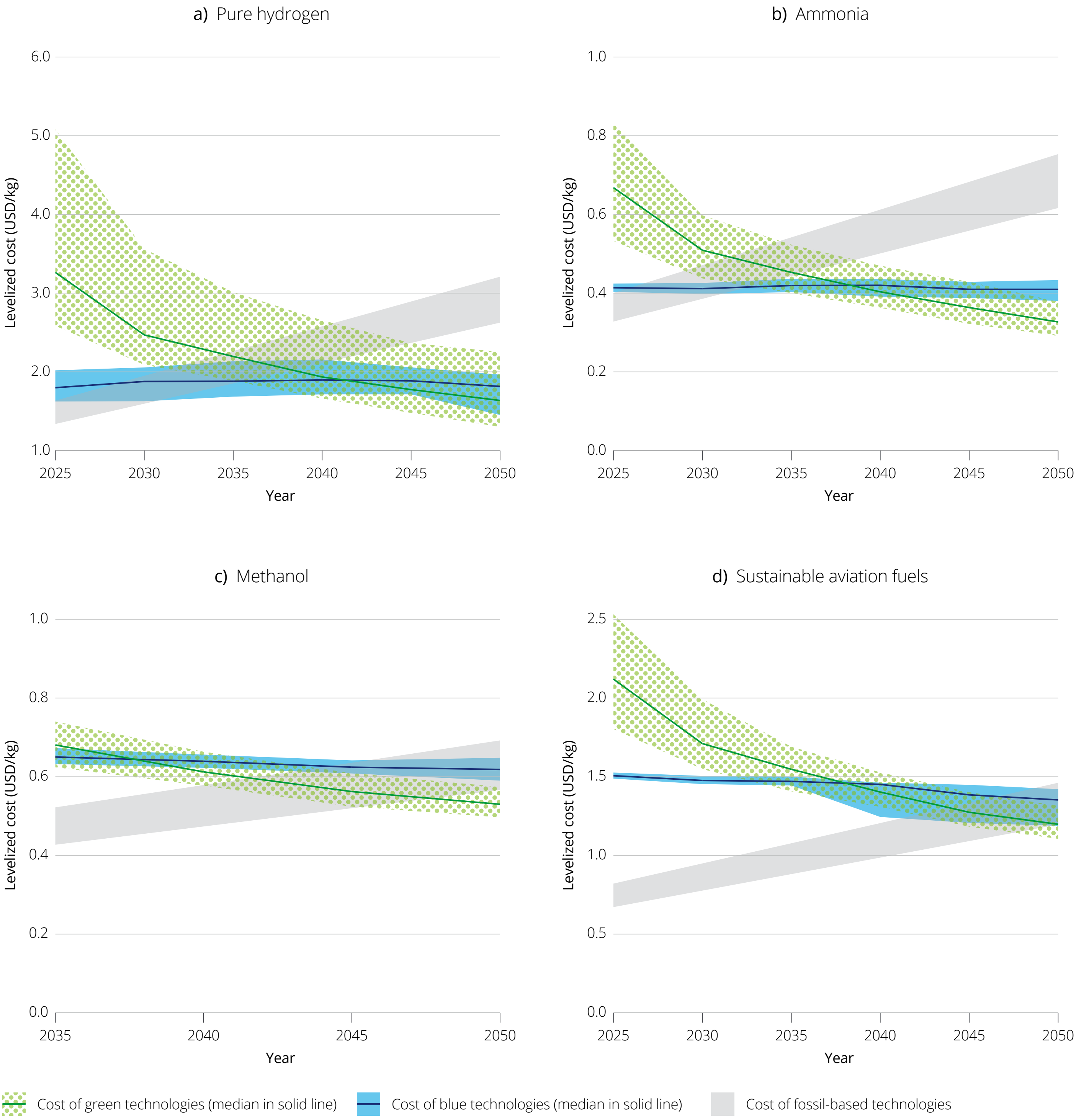
Deloitte's modeling results suggest that the green hydrogen economy could benefit from policy actions and regulatory support at least until the mid-2030s to help develop solutions at the necessary scale. Targeted policy support for clean hydrogen may be crucial to help ensure that early projects, such as pilot and head of series, can compete on a level playing field. For instance, the US Inflation Reduction Act provides a tax credit of up to US$3/kg for green hydrogen (US$1/kg for blue hydrogen), more than closing the cost gap with existing technologies. The EU's hydrogen-related Important Projects of Common European Interest (IPCEI) program (direct subsidies) and German H2Global instrument (offtake contracts with public support) are other examples of public support. Deloitte's pathway shows clean hydrogen can stand on its own, with the breakeven point reached before 2035 for pure hydrogen and ammonia, by 2045 for methanol, and by 2050 for SAF.

Governments should also play a role in providing a clear and reliable vision to private actors. Stringent climate regulation (for example carbon pricing, green fuels standards, carbon contracts for differences, and quotas for green fuels in transport or green materials) and ambitious decarbonization targets, including milestones with a timeline for the hydrogen economy (such as electrolysis capacity and number of charging stations) are crucial to anchor expectations and facilitate investments.

Gradually tightening climate standards, including clean hydrogen certification, can play a role in helping to continuously shrink the environmental footprint of fossil-based production processes. Residual methane and CO_2 emissions from blue hydrogen production should fall below sustainability thresholds, as already implemented by the European Union, the United Kingdom, and the United States. The natural gas industry's ability to rapidly adopt best available technologies in terms of carbon capture and storage (CCS) and curbing methane emission can be critical for blue hydrogen deployment. In this outlook, sustainability thresholds reach zero in the second half of this century, in compliance with climate targets.

Deloitte's pathway shows clean hydrogen can stand on its own, with the breakeven point reached before 2035 for pure hydrogen and ammonia, by 2045 for methanol, and by 2050 for SAF.

Figure 5. Outlook on production costs of clean hydrogen and its derivatives, 2025 to 2050



Source: Deloitte analysis; The production cost is computed here as LCOH (levelized cost of hydrogen), a methodology accounting for all capital and operating production costs in the levelized manner over a unit cost of produced hydrogen and its derivative (US$/kg). The green and blue areas represent the production cost distribution of 80% of clean hydrogen and its derivatives that can be produced in this outlook (solid lines representing the median).[37] The cost of grey pure hydrogen directly accounts for detailed modeling assumptions, while the cost of grey hydrogen derivatives (ammonia, methanol, and SAF) relies on average 2019 world market prices and a carbon price in line with the IEA's net-zero pathway. A 10% uncertainty range is added to the central estimate to account for market uncertainties.

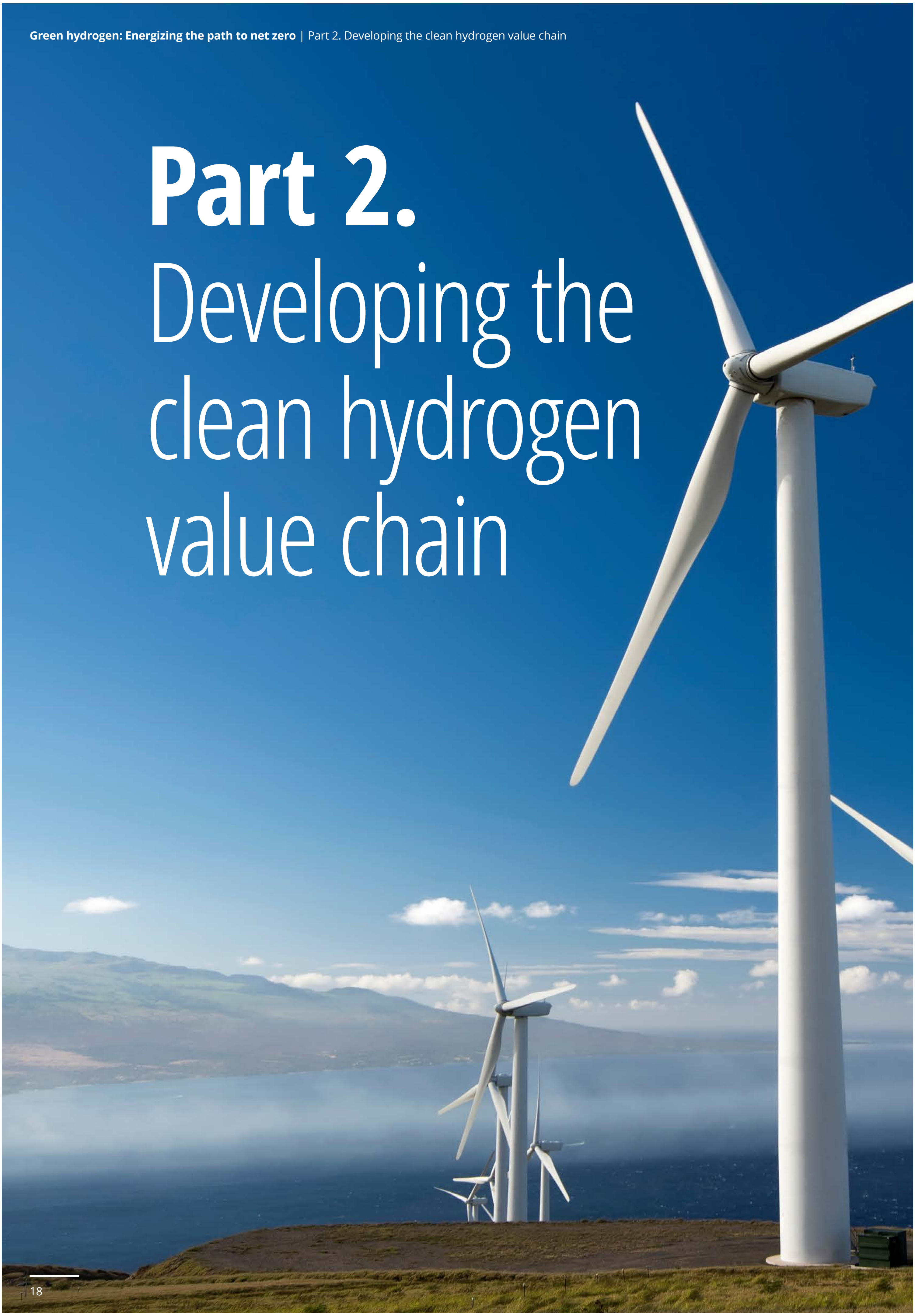
Sustainability thresholds for blue hydrogen certification

Hydrogen production will need to comply with environmental regulations to be certified as clean, an indispensable prerequisite for international trade. For blue hydrogen based on natural gas, carbon intensity of production should respect sustainability thresholds covering direct emissions—that is, efficiency of CCS technologies—and methane emissions associated with natural gas supply. Several regions and countries such as the European Union (EU Taxonomy[38]), United Kingdom (Low Carbon Hydrogen Standard[39]), and United States (Clean Hydrogen Production Standard[40]) have already implemented such standards. To date, one of the most stringent thresholds is the United Kingdom's standard, at 2.4 $kgCO_{2eq}/kgH_2$ in 2025.

In particular, methane emissions from natural gas supply should be of crucial importance in the certification of blue hydrogen and subject to investor scrutiny. The adoption of the best available technologies for upstream, midstream, and downstream methane leakage abatement should be a precondition for further use of natural gas in the next few years, and as such, for the deployment of blue hydrogen in a pathway that is compliant with climate neutrality objectives.[41] In Europe, this evolution could lead to a more than fourfold reduction in emissions related to the consumption of natural gas.

In Deloitte's outlook, global trade of blue hydrogen is bound by increasingly stringent sustainability thresholds that, together with a diminishing business case, eventually result in phasing out this technology. In practice, compliance with the United Kingdom's standard is retained as the initial condition to trade clean hydrogen (see details in Appendix). This threshold is assumed to decrease linearly to reach zero in the second half of this century. Residual direct emissions and methane leakages are incompatible, in the long term, with climate neutrality.

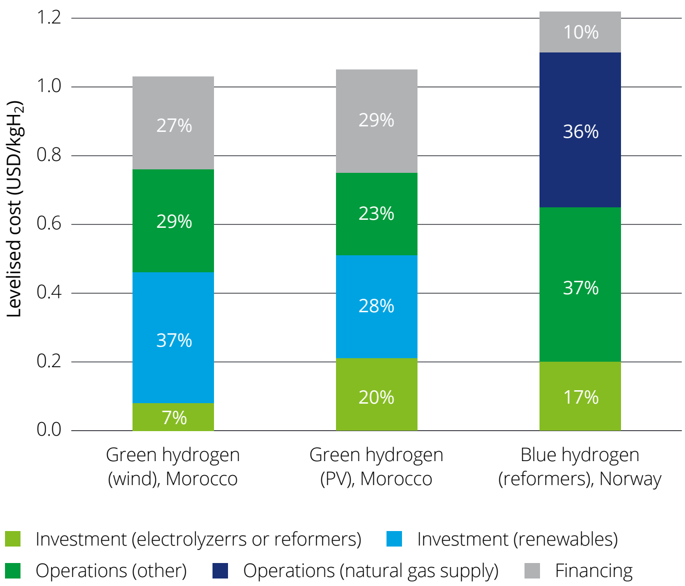
Part 2. Developing the clean hydrogen value chain



The rapid creation of the global clean hydrogen market is an unprecedented challenge, entailing the decarbonization of the entire current hydrogen supply and according to Deloitte's outlook, a more than sixfold increase in new uses over the next three decades. On the demand side, switching to hydrogen may require fundamental shifts in industrial and transport technologies such as fuel cells and SAF production, some of which can still have substantial potential for further improvement. On the supply side, the cost savings that mass deployment bring are still to be achieved.

Moreover, governments and companies should develop a large-scale global transport and storage infrastructure, including domestic transmission and distribution pipelines, international pipelines and vessels, seaborne terminals, and conversion and reconversion units including liquefaction and gasification units, ammonia synthesis, and cracking plants. Deloitte's pathway shows players harnessing technological progress and innovation across the whole value chain. Only a massive scale-up of related infrastructure, including renewable energies and electrolyzer manufacturing, complemented by sustained research and development (R&D) can help enable clean hydrogen to play its desired role in the transition to net-zero.[42]

Figure 6. Illustrative breakdown of pure clean hydrogen production cost in 2050



Source: Deloitte analysis. The levelized production cost represents the average cost of building, operating, and financing a hydrogen supply technology. "Investment" costs only cover the depreciation of assets, while "financing" costs include interests and dividends payments over the asset lifetime. For green hydrogen, this analysis assumes electrolyzers are powered solely by off-grid renewable capacities, hence a crucial impact of load factors. As wind technologies have higher load factors than photovoltaic cells (PV), they require less electrolyzer capacity to produce the same amount of hydrogen. However, the cost of wind turbines is higher than solar panels. Hence, investments in installed capacities of electrolyzers and renewables are optimized to take advantage of local wind and solar irradiation patterns.

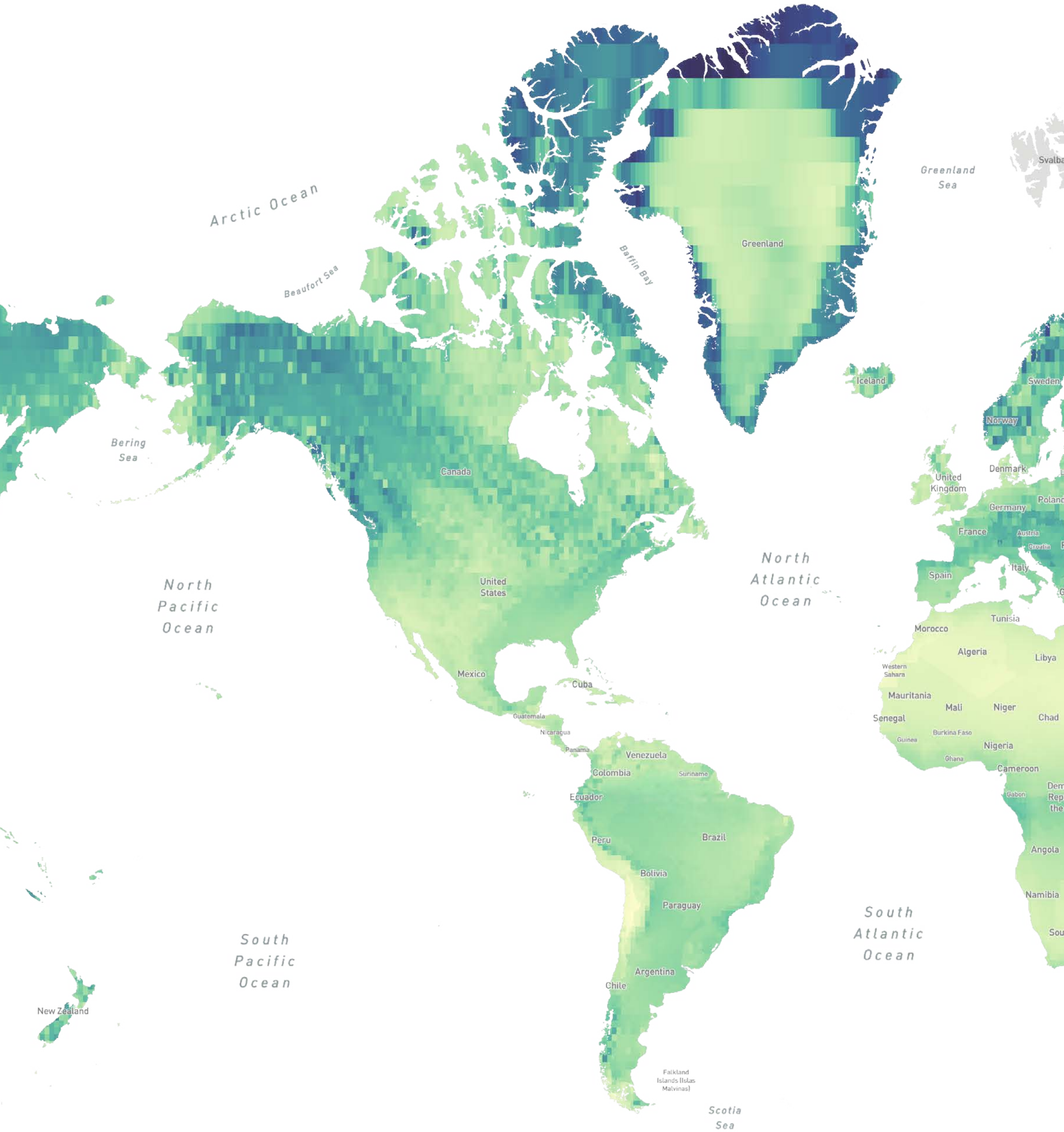
Assessing clean hydrogen supply opportunities

By 2050, the clean hydrogen supply potential exceeds demand by far. The potential of competitive supply—below US$1.5/kg of levelized cost, excluding transportation—of green hydrogen alone is likely expected to stand at 2,400 Mt, about four times the projected demand. Cost is one of the core drivers of competitiveness between regions and underpins trade opportunities. Geopolitical concerns, transport options, and costs also help shape the development of the global market.

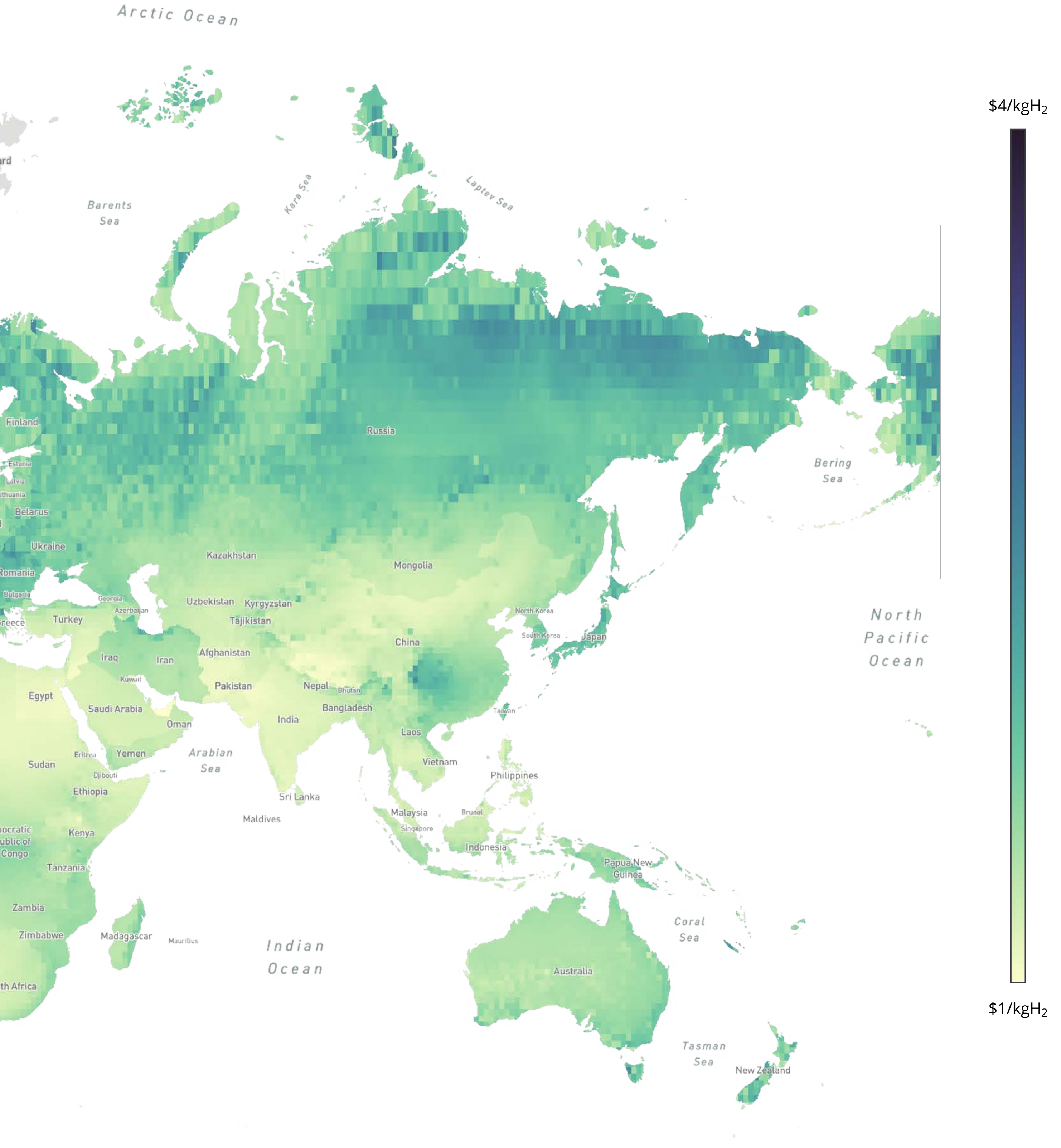
The production cost of clean hydrogen can be broken down into the following key elements (figure 6):

- **Green hydrogen is a capital-intensive industry.** Overall, capital expenditure typically accounts for 45% to 50% of levelized production cost, including 30% to 40% for the acquisition of solar panels or wind turbines to generate electricity[43] and 10% to 20% for electrolyzers. The relative share of renewables in levelized costs depends on each technology's load factors (higher for wind) and specific cost, along with the local renewable energy endowments—for instance, better wind or sunlight conditions increase the amount of electricity that a given installed capacity generates.[44] Installed electrolysis capacity requirements evolve accordingly. Operational expenditures account for an additional 20% to 30% of levelized costs.
- **Feed gas is one of the key drivers of blue hydrogen cost** and typically accounts for up to 40% of levelized costs. Natural gas producers may have a comparative advantage for blue hydrogen. From the perspective of financing a blue hydrogen project, natural gas supply—with the price incorporating the capital costs of exploration and production—is an operating expenditure—to be added to another 40% of non-related operating costs—that does not likely require upfront financing, hence a lower capital share than green hydrogen.
- **Financing costs could be paramount for a project's cost competitiveness.** The high capital intensity likely requires raising significant amounts of debt and equity, with the resulting financing cost putting upward pressure on hydrogen's levelized costs, typically 10% for blue hydrogen and about 30% for green.

Figure 7. Spatial distribution of levelized costs of green hydrogen, 2050



Source: Deloitte analysis


$4/kgH$_2$
$1/kgH$_2$
Arctic Ocean
Barents Sea
Kara Sea
Laptev Sea
Bering Sea
North Pacific Ocean
Arabian Sea
Indian Ocean
Coral Sea
Tasman Sea
Finland
Estonia
Latvia
Belarus
Ukraine
Romania
Bulgaria
Georgia
Azerbaijan
Turkey
Russia
Kazakhstan
Mongolia
Uzbekistan
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Afghanistan
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Philippines
Sudan
Eritrea
Yemen
Djibouti
Ethiopia
Sri Lanka
Maldives
Malaysia
Brunei
Singapore
Indonesia
Papua New Guinea
Kenya
Tanzania
Zambia
Zimbabwe
Madagascar
Mauritius
Australia
New Zealand

Nations producing natural gas—in 2020, more than 70% of proven reserves were held by Russia, Iran, Qatar, Turkmenistan, the United States, China, and Venezuela—may be obvious candidates to become major suppliers of blue hydrogen. The competitiveness of blue hydrogen largely depends on the outlook for natural gas markets in terms of price evolution, the development of new reserves, and consumption trends—such as for heating and power generation. In addition, the need to adopt best available methane emission reduction technologies, to comply with sustainability standards, places some of the most advanced countries (Norway, Australia, the United States, Canada, and some Middle East countries) ahead of the pack.

The widespread availability and falling cost of renewable energy production helps to ensure that green hydrogen can be produced virtually anywhere (figure 7), with developing economies gaining an edge—for instance, in 2050, producing green hydrogen in North Africa could cost one-quarter of European production. Benefiting from high-quality renewable energy endowments, Australia, Chile, Mexico, northern and sub-Saharan Africa, and Middle Eastern countries can present particularly attractive conditions to become major exporters of green hydrogen.

The manufacturing cost of green hydrogen equipment can drop in the coming decades, boosting the technology's competitiveness. While the installation cost of solar panels and onshore wind is expected to drop by 45% and 18%, respectively, between 2020 and 2050, the cost of electrolyzers (especially alkaline and proton exchange membrane (PEM) technologies[45]) decreases by two-thirds over the same timeframe, making green hydrogen production one of the most cost-competitive technologies by 2040. In 2050, levelized production costs could fall below US$1/kg$H_2$ in Chile, and below US$1.1/kg$H_2$ in north and sub-Saharan Africa, Mexico, China, Australia, and Indonesia.

Blue hydrogen technologies could see smaller cost decreases. The cost savings achieved through scaling-up and R&D on CCS technologies are, at least partially, offset by tightening environmental regulation—for example, the rising cost of unabated emissions, perhaps via carbon pricing. Overall, the cost of natural gas-based technologies is expected to remain flat between 2030 and 2050, with some of the lowest production costs (US$1.25/kg$H_2$ in 2050) expected in North America, mainly due to low-cost natural gas supply.

Financial conditions could favor some technologies or geographies.

- Reliance on natural gas, blue hydrogen technologies may suffer from sustainability concerns, reputational concerns, or lack of trust in the certification process. The technology could also present a risk of technological lock-in that could further delay the transition to carbon neutrality. In turn, blue hydrogen suppliers could be exposed to some of the various economic and financial components of transition risks, particularly the danger that projects become stranded assets. Environmental, social, and governance (ESG) investment rules and the potential pitfalls of aligning to different certification processes could also make it harder to obtain financing, at least in advanced and environmentally sensitive economies. Overall, in advanced economies, blue hydrogen projects may therefore be exposed to a risk premium.[46] In contrast, access to low-cost state financing for blue hydrogen could be facilitated in countries where national oil and gas companies dominate.
- Some of the most promising locations for green hydrogen projects may suffer from high country-related political risk. In practice, private investors and lenders expect higher rates of return to compensate for greater political risk. Thus, access to affordable finance can be a critical enabler for green hydrogen projects, and particularly those located in emerging markets with high political risk that may be otherwise prevented from tapping into their exceptional production potential (figure 8). International (as provided by export credit agencies or development finance institutions) and green finance can succeed in lowering the cost of capital for green hydrogen projects. By reducing country risk differences, these instruments can be particularly powerful in developing countries; they may be necessary for production projects to compete on a level playing field and to ensure a fair energy transition.[47]

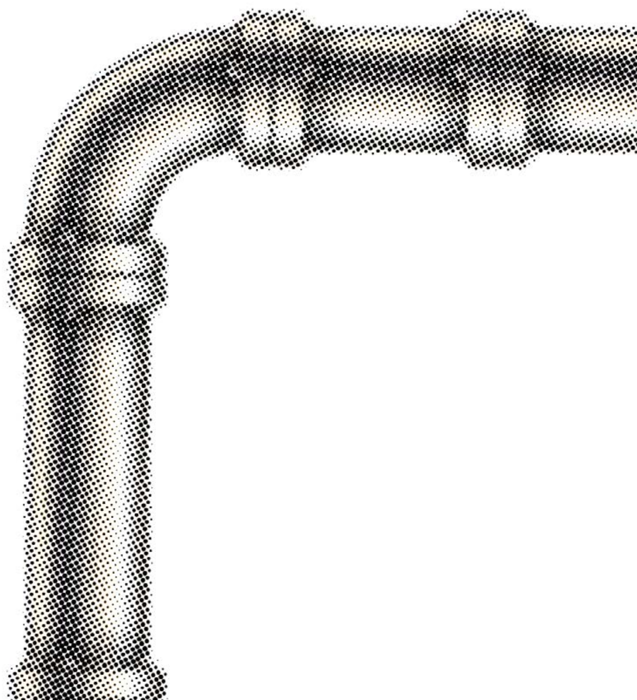
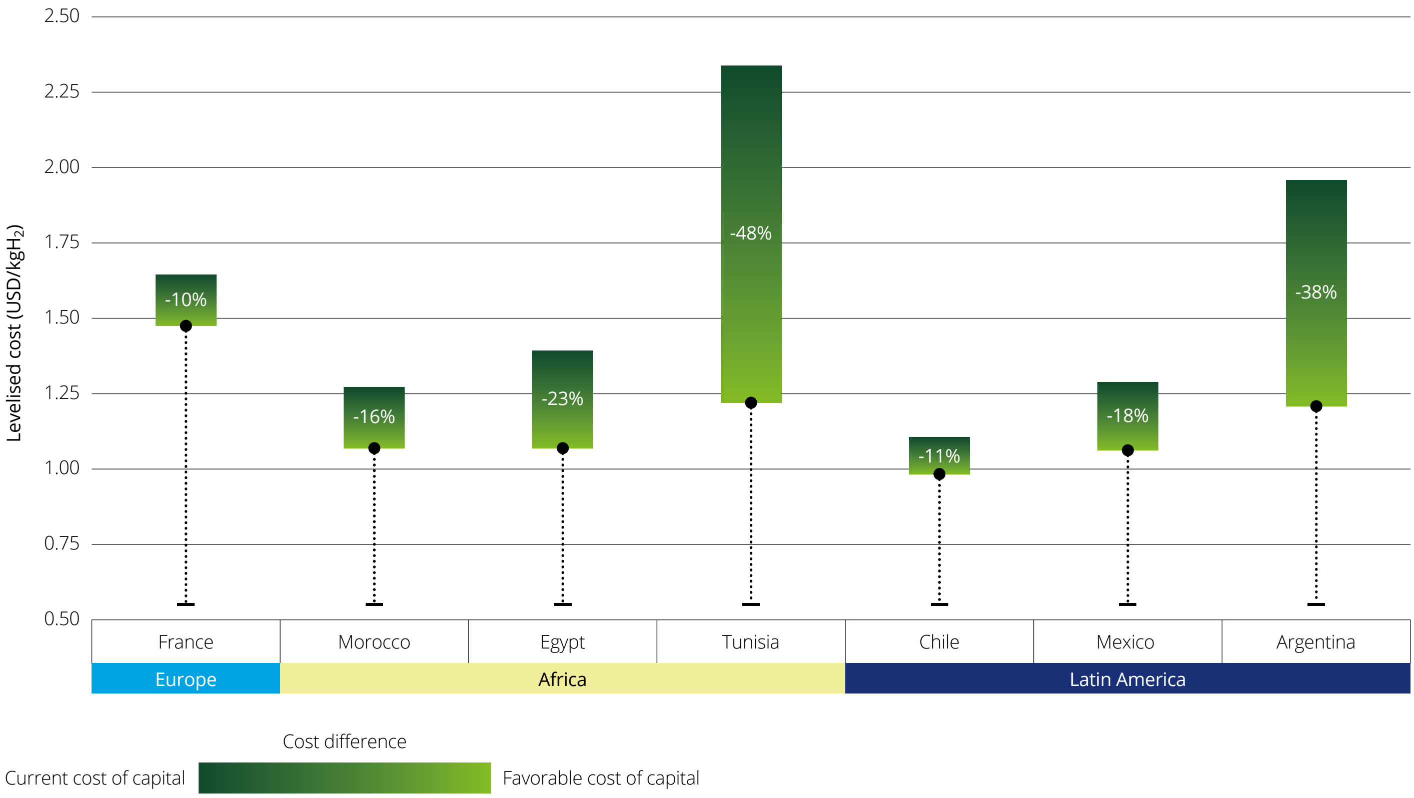
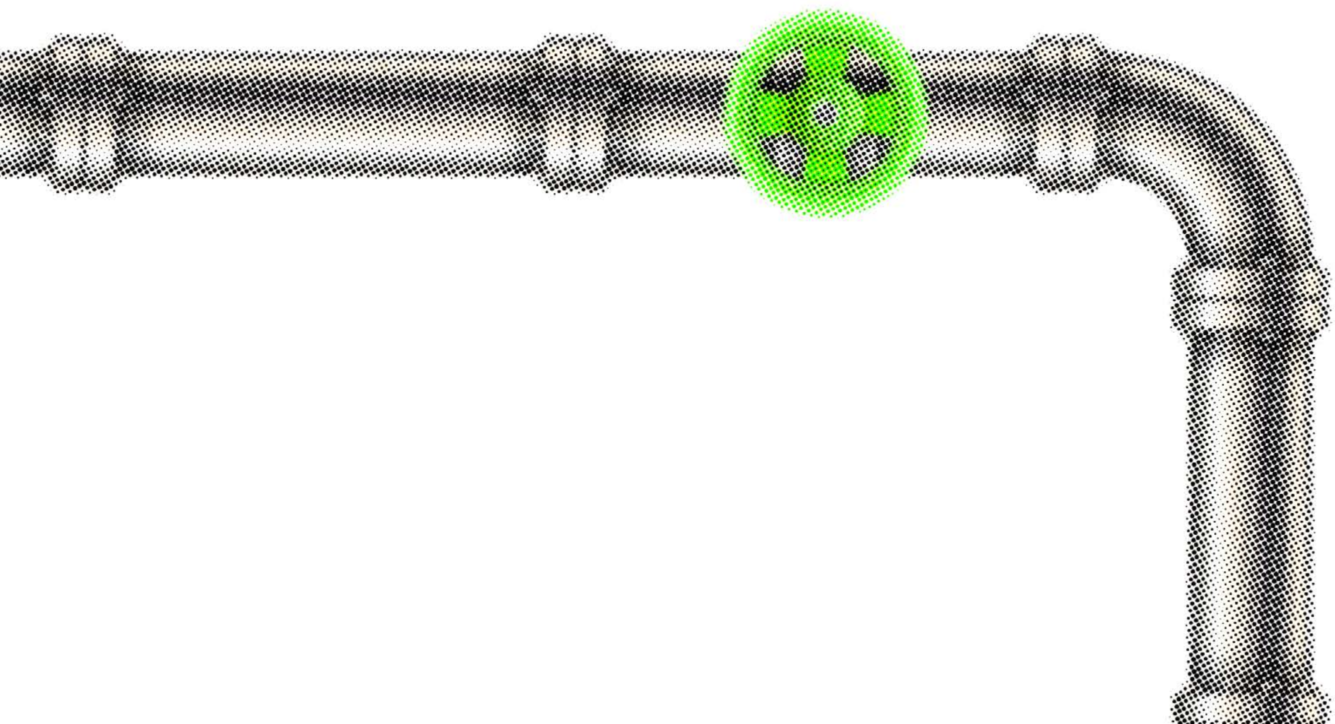


Figure 8. Illustrative sensitivities of levelized cost of green hydrogen with financing cost, 2050



Source: Deloitte analysis

Note: The (weighted average) cost of capital (WACC) represents the financing conditions accounting for the equity and debt pricing. The "current cost of capital" (WACC varying between 6% and 12%) setting is based on illustrative market outlook (i.e., accounting for differences in country risk), while the "low cost of capital" (WACC varying between 4% and 6%) assumes convergence of financial conditions between countries achieved by public support.



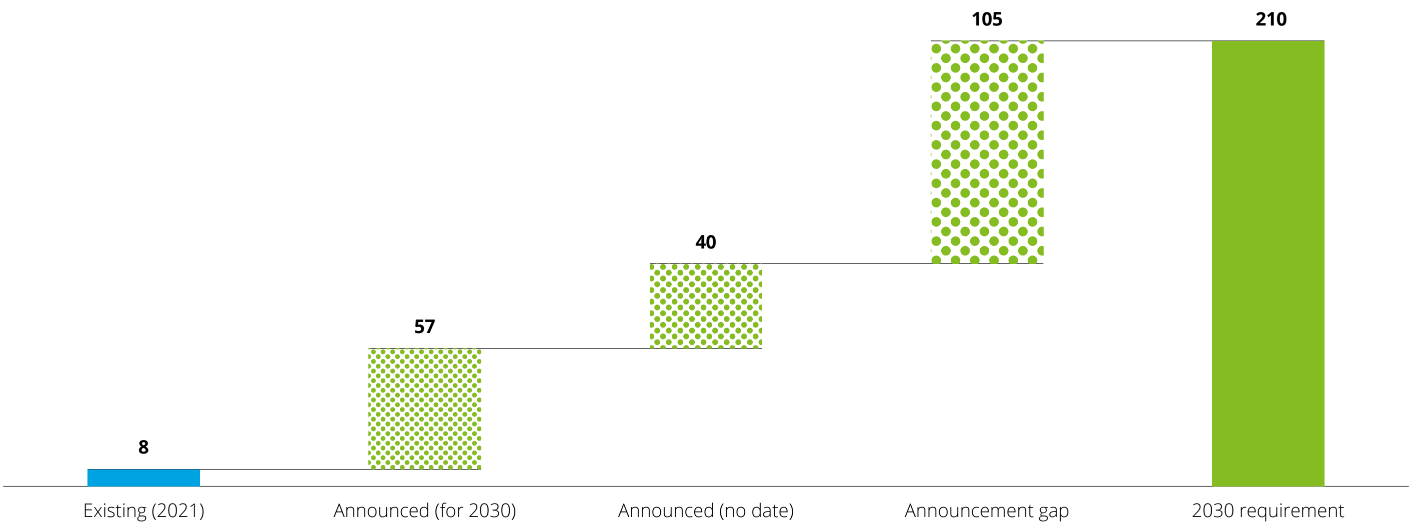
Overcoming bottlenecks for green hydrogen production

Land availability can be a challenge for some densely populated economies. Scaling up green hydrogen production may require large areas of land for the development of solar and wind installations for renewable electricity generation. Since PV and wind power have low energy density per surface area, land-availability requirements could be an obstacle to large-scale green hydrogen deployment in densely populated countries such as Japan, South Korea, and parts of Europe. Some highly industrialized countries may find it difficult to serve their entire hydrogen demand from domestic sources. For instance, Japan and South Korea both have less than 10% of their ground available to install renewable technologies.[48] By contrast, many developing countries can leverage large reserves of available, sunbaked land—for example, more than 80% of the territory in Algeria, Morocco, and South Africa.

Permitting processes for the installation of new renewable assets could prove a major bottleneck in some countries' production scale-up. Unlocking the rise of green hydrogen demands that permitting and validation procedures be simplified and shortened. This concern is particularly acute in Europe, Australia and the United States,[49] which would otherwise risk accepting a lower market share of global production in the long term.

In addition, the rise of green hydrogen should not be thwarted by limited manufacturing capacity for electrolyzers, PV panels, and wind turbines. In Deloitte's outlook, global electrolyzer manufacturing capacity may need to increase by more than 25-fold, to more than 200 GW per year in 2030, to reach a green hydrogen trajectory consistent with climate-neutrality goals. Similarly, global PV manufacturing capacity should increase from 250 GW per year in 2021 to 800 GW per year in 2030. In the same time frame, the installed capacity of wind should quadruple, with underlying manufacturing challenges as well. Anticipating the growth of the electrolysis market, industrial companies have already announced several projects that could bring the total manufacturing capacity to 65 GW per year in 2030.[50] China and Europe could lead the way, with 37% and 31% of the projects, respectively, announced to date. Even considering 40 GW of additional projects announced without target dates, a manufacturing gap of some 100 GW still may need to be overcome to help meet the projected demand in 2030 (figure 9). The level of industrial ambition must be further raised to accompany the creation of the green hydrogen economy.

Figure 9. Global electrolyzer manufacturing capacity required by 2030 (GW per year)



Source: Deloitte analysis based on International Energy Agency; the 2030 requirement is a low estimate based on linear deployment in the coming decade.

The fast-tracked adoption of new technologies can put increasing pressure on critical raw material supply chains. Green hydrogen relies on critical materials at two stages of the value chain: electricity generation via renewables and hydrogen production via electrolysis.

- Solar PV and wind power are some of the main drivers behind the rising demand for critical materials through the 2020s.[51] Solar consumes copper (about 2,850 kg/MW), while wind turbines require copper (about 8,000 kg/MW for offshore and 2,900 kg/MW for onshore), zinc (about 5,500 kg/MW), manganese (about 780 kg/MW), chromium (about 500 kg/MW), rare earths (about 220 kg/MW for offshore and 40 kg/MW for onshore), and molybdenum (about 115 kg/MW).
- The different technologies of electrolyzers have complementary critical material requirements (figure 10). This can offer protection against disruption in supply of some critical materials and can put strategic value on technology diversification. To date, one of the most widespread technologies is alkaline electrolysis, largely reliant on nickel, which faces no significant risk of reserve depletion.[52]
- Over the past decade, economically viable reserves of critical minerals have increased despite growing demand. However, ore quality has declined, raising challenges for extraction and processing costs, CO_2 emissions, and water consumption.[53] According to specialists, the supply from existing capacities and projects under construction will be insufficient to meet the expected demand in the long run. Significant investments are needed to avoid slowing down green technology deployment. Additionally, geopolitical tensions could arise from the increasing market concentration of the supply chain, prompting inquiries about its resilience. China dominates the mining of rare earths and graphite, and the processing of the critical material required by clean technologies: copper, lithium, nickel, cobalt, and rare earths. However, many western countries have also realized the sovereignty risks associated with such as concentration, and they are actively expanding mines and processing facilities.

Fortunately, water supply is likely not expected to be a strong barrier to green hydrogen. Green hydrogen production is based on water electrolysis, with between 9 kg and 11 kg of water required to produce 1 kg of hydrogen.[54] Therefore, about 5.0 to 5.6 billion cubic meters of water could be consumed annually to help produce the 500 Mt of electrolytic hydrogen envisaged in Deloitte's outlook in 2050, less than one-third of what the fossil fuel industry currently consumes each year.[55] Although green hydrogen production may trigger water conflicts in some arid and inland areas—especially in the Middle East and parts of Africa—desalination technologies could make it possible to recover sea water for electrolysis at a limited cost.[56]

Figure 10. Critical material content of key electrolysis technologies

Technology	Mineral	Content (kg/MW)
Alkaline	Nickel	800 to 1,000
	Zirconium	100
PEM	Platinum	0.3
	Iridium	0.7
Solid oxide electrolysis cells (SOEC)	Nickel	150–200
	Zirconium	40
	Lanthanum	20
	Yttirum	< 5

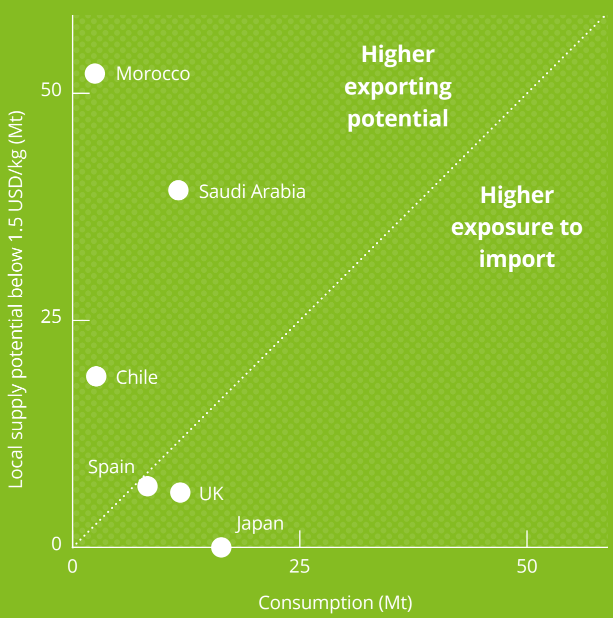
Source: International Energy Agency (2021). This table provides the raw material consumption to install 1 MW of electrolysis.

Implications for trade opportunities

Interregional trade can help reduce the geographic mismatch between demand and low-cost supply. Some of the largest demand centers (primarily European countries, Japan, and South Korea) may not be in a position to produce low-cost hydrogen in sufficient quantities to fully meet demand. By contrast, regions with high renewable endowment and ample land availability—such as Australia and parts of Africa and Latin America—could likely produce cost-competitive green hydrogen in quantities that exceed domestic needs. Trade opportunities and associated cost savings naturally arise from such discrepancies, and several countries (including Australia, Chile, Germany, and Japan) could position themselves as future hydrogen importers or exporters. Several partnerships or memorandums of understanding have already been signed to harness the Global South's renewable energy potential.[57] A diversified transport infrastructure can be key to help facilitate global trade.

Identifying potential green hydrogen importers and exporters

The diversity of renewable energy endowments and land availability across countries can create significant differences in achievable green hydrogen production costs and quantities. A country's consumption profile depends on population size, industrial structure, and economic development, with international trade shaped by divergences in consumption profiles and production potentials. Supply-constrained countries can attempt to lower their procurement cost by procuring all or part of their needs from international markets; countries with ample low-cost production potential may seek to maximize revenues through exports.



Source: Deloitte analysis

As illustrated in this figure, Chile, Morocco, Saudi Arabia, Spain, the United Kingdom, and Japan occupy different positions on the importer-exporter spectrum.

- Northern **Chile** has some of the world's highest solar irradiation levels, boosting the country's export potential for renewable energy.
- **Morocco** has access to outstanding solar and wind resources, which is compatible with a highly competitive large-scale production industry leveraging its proximity to the European Union.
- **Saudi Arabia** benefits from high solar irradiation and abundant available land. Deloitte's outlook shows the country producing 39 Mt of low-cost green hydrogen in 2050, four times its domestic demand. The country is already involved in several international trade agreements to export green hydrogen, which could be one of the building blocks of its strategy to diversify its economy away from petroleum.[58]
- **Spain's** high level of solar exposure makes it one of the best European candidates for green hydrogen production; the country could be close to self-sufficiency in 2050. Yet, Spain can expect significant volumes of imports due to its geographical position as a gateway to proximate demand clusters—notably Germany—minimizing transport costs by leveraging its pipeline connection to Morocco and the pan-European transport infrastructure, including a $2.6 billion Barcelona-Marseille hydrogen pipeline announced in December 2022.[59]
- The **United Kingdom** can count on significant wind power endowment and can mobilize its full competitive potential, producing some 7.5 Mt of green hydrogen based on Deloitte's outlook. Yet, as updates to the UK Hydrogen Strategy suggest, the forecasted strong increase in demand[60] in the 2030s (reaching up to 12 Mt by 2050 in Deloitte's outlook) is likely to prompt imports.
- **Japan** may be constrained by a combination of limited renewable energy potentials and high population density along its coastlines, with high economic industrialization boosting domestic demand levels. In Deloitte's outlook, Japan is one of the primary importing countries.

It is worth mentioning that additional constraints apply for large countries such as the United States and China. Notably, the remoteness of some available land suited for production (for example, desert areas) from consumption or export hubs could entail a high transport cost—and a technical challenge to deploy internal transport infrastructure over long distances—therefore limiting the potential for competitive supply.

Energy security and economic development are likely interrelated components of a resilient hydrogen economy. To help limit the risk of strong dependencies on limited number of exporters, importers should seek to diversify their mix of suppliers, including by developing bilateral relationships, promoting scientific and industrial cooperation, and investing in the appropriate production and transport assets.[61] The participation of the Global South in the hydrogen economy can help improve energy security for all, while providing the Global South with significant development opportunities.[62] In addition, climate change is a global concern, such that the decarbonization of some countries should not be performed at the expense of the efforts of others. Thus, to meet climate neutrality targets in line with Sustainable Development Goals (SDGs), developing and emerging markets should take their fair share of the global value chain and associated co-benefits: jobs, knowledge accumulation, stable revenues, and more.

The most promising option for medium-range transport comes from dedicated pipelines connecting demand centers to close-by production sites or import terminals.

The importance of transport infrastructure

The transport of hydrogen can be technically challenging and has therefore important implications for the structure of the global market (figure 11). Under normal conditions, hydrogen is a volatile and highly flammable gas; contact with air can trigger an explosive reaction.[63] Consequently, pure hydrogen may be costly to transport in industrial volumes compared to other molecules, as are its derivatives. When possible, it should be produced as close as possible to the consumption centers.[64] Apart from pipelines, two solutions currently exist for the safe and affordable transportation of pure hydrogen: *compression and/or liquefaction* in a controlled environment to help increase volumetric density, and *conversion into a more containable carrier* with a reconversion step prior to final use for long distances.

- For medium distances—up to 3,000 km—compression and pipeline transport are competitive options compared to truck, rail, or ship.[65] In the short run, hydrogen could be blended with natural gas in existing pipeline networks, with opportunities of joint consumption (with, granted, limited environmental benefits) or separation prior to final use, a technically challenging and expensive process. Nevertheless, the most promising option for medium-range transport comes from dedicated pipelines connecting demand centers to close-by production sites or import terminals. This will likely require extensive regional and national planning, pipelines being long-lasting assets with large upfront investment needs. In that respect, repurposing former natural gas pipelines can carry real value. Within the limits of existing infrastructure (up to 7,500 km), this would, for instance, reduce transport costs in Europe 55-68%[66] compared to building new pipelines. For short distances, liquid hydrogen shipping could appear as a niche solution.[67]
- For long distances—or where cross-border pipeline projects may be infeasible—hydrogen should be converted to another carrier before being shipped. Conversion to ammonia, for which a dedicated transport infrastructure already exists, or embedding it within liquid organic hydrogen carriers (subject to successful R&D development) are some of the frontrunning options, but methanol and metal hydrides may also be promising potential carriers. All of these options entail costly conversion and reconversion processes, making them viable at scale only in the absence of alternatives or for long-distance trade. While part of the existing ammonia transport supply chain could be reused, new investments in port infrastructure and fleets are inevitable.

Options for transporting pure hydrogen over long distances

Under normal temperature and pressure conditions, hydrogen is a flammable gas with low volumetric density and high volatility. Short- to medium-range transport of the molecule can be done via pipelines at a reasonable cost. However, such infrastructure can be highly capital-intensive and subject to geopolitical tensions and geophysical obstacles (for example, sea trenches) that can make them unsuitable for long-distance transport. Therefore, hydrogen must be either liquefied or converted into a carrier with more favorable chemical properties before reconversion to pure hydrogen. Various cost-benefit studies[68] have identified liquefied hydrogen, ammonia carrier, and liquid organic hydrogen carriers as some of the most promising options.

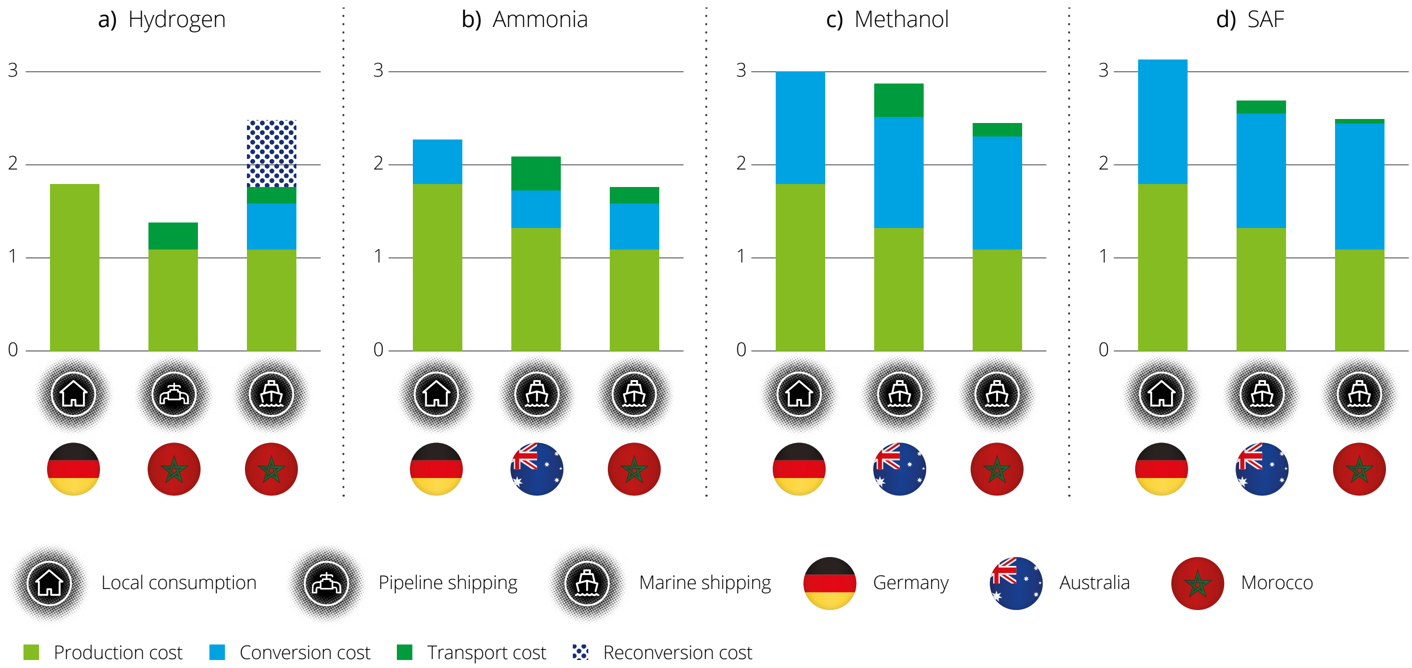
Liquefied hydrogen has a much higher volumetric density than gaseous hydrogen (71.1 KgH_2/m^3 vs 0.08375 KgH_2/m^3), requiring less space to transport the same quantity. However, the hydrogen liquefaction process required to reach and maintain a very low temperature (-253°C, just 20°C above absolute zero) incurs significant energy consumption and financial cost. The regasification of hydrogen is inexpensive and requires no purification or chemical reaction. Overall, the liquefaction process causes energy losses of 30% to 36%. Compared to the cost-competitiveness of pipeline transport and ammonia shipping, liquified hydrogen appears to date as a niche option.

Ammonia is a chemical product (NH_3) that is already widely used in the fertilizer industry, and more broadly in the chemical industry. Clean gaseous hydrogen can be combined with gaseous nitrogen to produce ammonia (Haber-Bosch process), a chemical reaction that comes with energy losses in the range of 12% to 26%.[69] The obtained ammonia is a carbon-free carrier, which has a greater volumetric hydrogen content (107.7 kgH_2/m^3). Compared to hydrogen, the liquefaction can be achieved at a significantly higher temperature (-33°C), greatly facilitating containment and lowering the resulting transport losses. Reconversion to pure hydrogen is possible through cracking, which incurs another 13% to 34% energy loss, and might require additional purification afterward. To date, ammonia is one of the most mature and one of the lowest cost options for long-distance trade of hydrogen: 20 $MtNH_3$ (4 MtH_{2e}) of ammonia are already traded internationally each year within 120 dedicated terminals. The existing global market and associated technologies, regulation, and transport infrastructure can be leveraged to build a clean hydrogen/ammonia market. However, significant new investments throughout the value chain are necessary to keep pace with demand growth. In addition, clearing the way for large-scale development may require addressing security concerns—in particular, health and environmental hazards of mishandled ammonia.

Liquid organic hydrogen carriers (LOHC) are organic compounds based on fossil fuels capable of absorbing and then potentially releasing di-hydrogen molecules. However, the high temperature and pressure conditions required for the absorption chemical reactions can be a technical challenge (150-200°C and 30-50 bars), and the process may require expensive catalysts. Once hydrogen has been absorbed, LOHCs present the highly valuable advantage to be storable and transportable under normal temperature and pressure conditions. Thus, potentially allowing the use of existing oil infrastructure. Hydrogen can be recovered from LOHCs through dehydrogenation, causing most of the energy loss (25% to 35%) of the process and requiring further purification. After dehydrogenation, the organic compounds should be returned for another shipping cycle. In addition, transporting these molecules can present security concerns, since they can be toxic, corrosive, and highly flammable if mishandled. Overall, LOHC transport tends to be moderately capital-intensive but requires large operational costs due to energy consumption which can hamper its competitiveness. Finally, this technology is still experimental and not yet available for large-scale deployment.

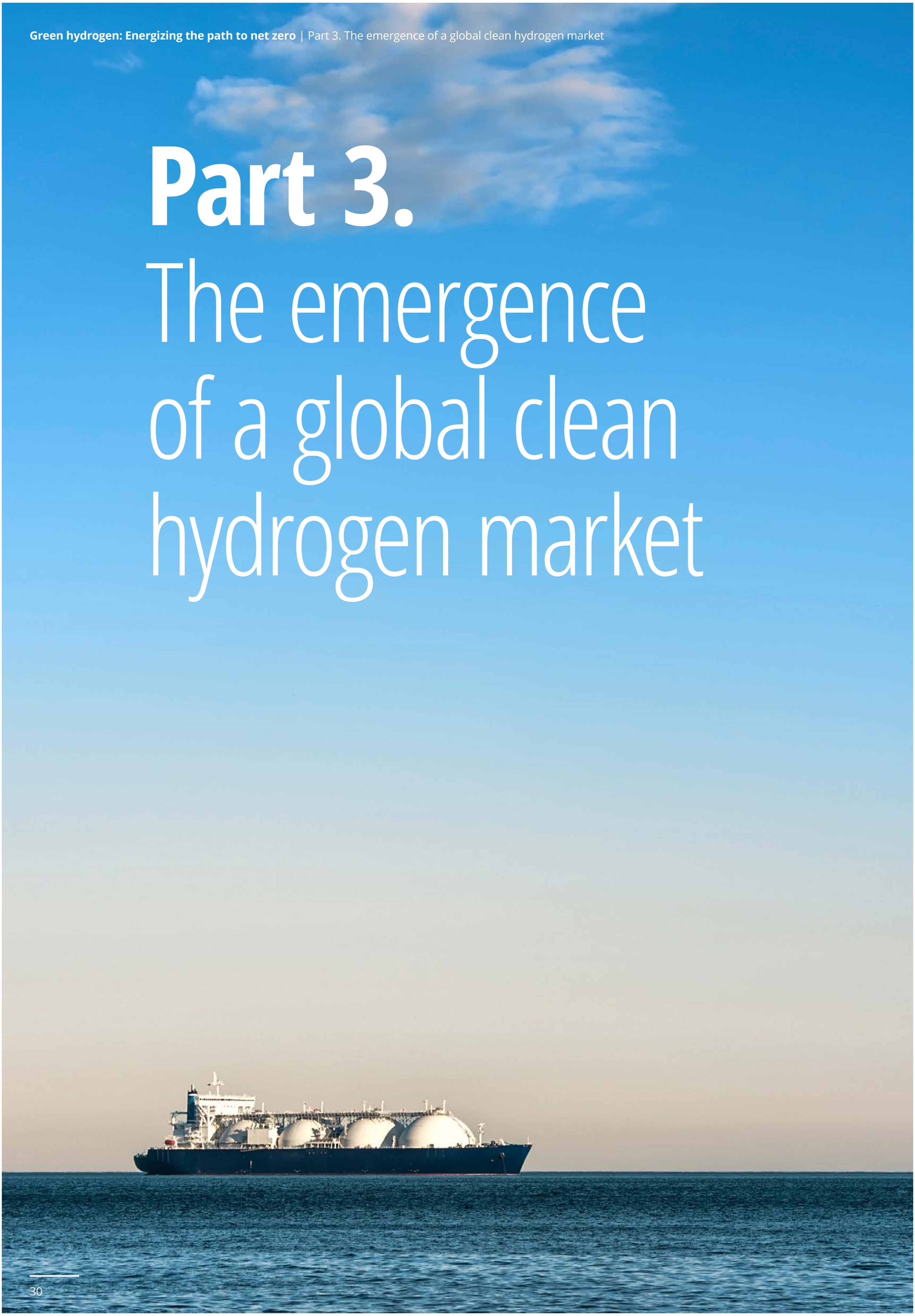
Hydrogen derivatives can be easier to contain and transport than the pure molecule. Further conversion to another carrier is likely unnecessary for hydrogen derivatives (ammonia, methanol, or SAF), such that imports, even from very long distances, can be more competitive than domestic supply, from local or imported pure hydrogen. As a result, some of the most competitive suppliers are more likely to source hydrogen derivatives as final products. Transport costs by commodity can depend on technical requirements (for instance, ammonia should be transported in refrigerated tankers), mass, volumetric density, and distance. For a given distance, the least expensive commodity to transport is SAF, followed by methanol and ammonia. The lower the transport costs, the more producers should be able to leverage their comparative cost advantage to help capture higher market shares. Market concentration could thus be higher for SAF and methanol rather than ammonia and pure hydrogen.

Figure 11. Indicative comparison of sourcing options for Germany in 2050



Source: Deloitte analysis

Note: In Germany, imports are highly competitive though different routes may prevail for the different commodities. For pure hydrogen, imports by pipelines are more competitive than domestic supply on average. For all of the hydrogen derivatives (ammonia, methanol and SAF), seaborne imports are competitive options independently on distance.



Part 3.
The emergence of a global clean hydrogen market

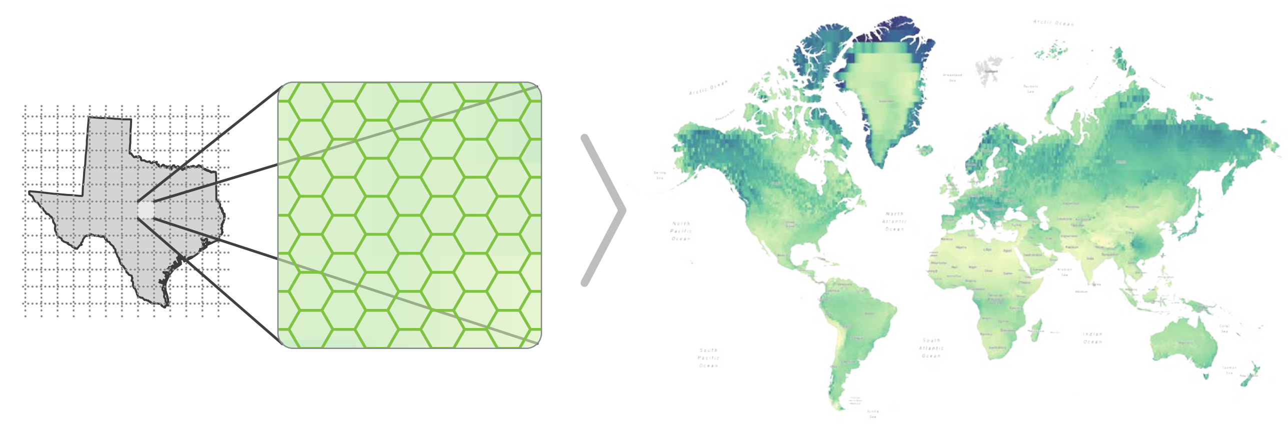
This outlook harnesses Deloitte's Hydrogen Pathway Explorer (HyPE), a state-of-the-art model of global clean hydrogen trade. HyPE is a global clean hydrogen production and trade model laying out cost-efficient supply pathways accounting for a comprehensive set of production sites (more than 38,000 cells), production technologies and their detailed costs, and transport options and their associated costs. In line with the International Energy Agency's Net-Zero Emission pathway,[70] it differentiates pure hydrogen from its main derivatives: ammonia, methanol, and SAF. The obtained quantitative results offer granular and data-driven insights on the structuring of the global clean hydrogen market, complemented by a diverse set of key economic indicators such as supply clusters' revenues and financing needs.

The HyPE model

HyPE is a detailed simulation model that minimizes the total hydrogen supply and delivery chain cost (production and transport to the consumption point) to satisfy global clean hydrogen demand in the period to 2050. Demand is represented on a national level while supply draws on a wide range of production sites, technologies, transport routes, along with technical and economic data (see details in Appendix).

- On the production side, HyPE includes a highly detailed representation of local renewable generation capacities accounting for solar irradiation and wind speed for more than 38,000 geographical units (cells). This green hydrogen production capacity is obtained at a granular scale and competes with blue hydrogen potential, based on natural gas availability for 30 producing countries.
- International trade routes are at the core of the optimization, considering 15 international pipelines, 95 port terminals, and more than 1,500 maritime shipping routes. For each of the considered commodities (pure hydrogen, ammonia, methanol, and SAF) in a specific region, the most competitive supply solution is obtained, trading off domestic production against the available import alternatives, including transport, conversion, and, when necessary, reconversion costs.

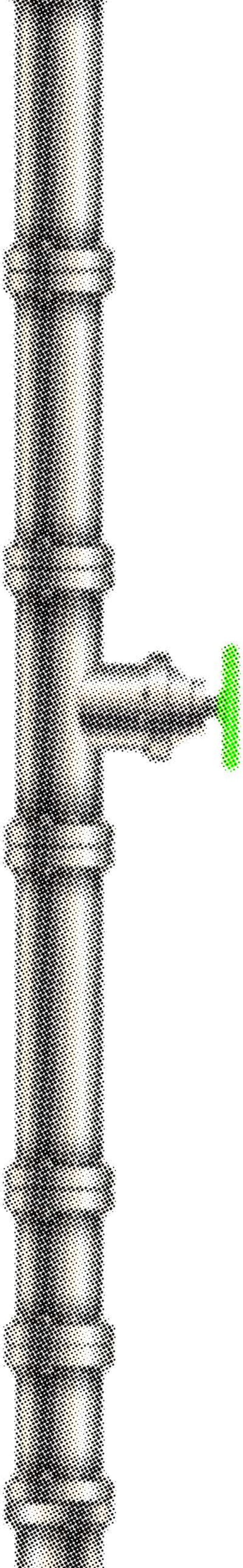
Based on cost-efficient selection of clean hydrogen supply pathways, HyPE provides insights into various market dynamics and business challenges—for instance, optimal infrastructure sizing, investment needs, and levelized cost of hydrogen as well as technology choice for hydrogen production and transport.



A market set for fast growth

In achieving climate neutrality worldwide by the middle of this century, Deloitte's outlook shows the clean **hydrogen market growing in several stages** over the coming decades:

- **In the period to 2030:** The market ramp-up is likely underpinned by replacing current grey hydrogen production with clean hydrogen. Projects initially depend on public support to break even, as illustrated by programs such as the US Inflation Reduction Act and Infrastructure Investment and Jobs Act, the Australian Clean Energy Finance Corporation and regional strategies, the EU Fit-for-55 package and Hydrogen IPCEI program, and Japanese demand-side R&D support schemes such as Green Innovation Fund. In Deloitte's outlook, international trade plays a vital role, serving some 30 MtH_{2eq} in 2030, almost one-fifth of total demand. Trade flows emerge within regional clusters, between supply and demand hubs in proximity, mostly through ammonia shipping. Long-term contracts are crucial to help mitigate quantity risks and provide price stability.
- **During the 2030s:** The market scales up, following the increase in demand as new end uses of hydrogen make inroads. The development of a new transport infrastructure based on dedicated pipelines, port terminals, and storage facilities unlocks the potential of long-distance trade: nearly 75 MtH_{2eq} in 2040. Green hydrogen technologies likely become increasingly important to the acceleration in market growth. Leveraging economies of scale, they continuously catch up on cost terms. More broadly, in this period clean hydrogen projects become less dependent on public support. Increasing market size can also help improve liquidity, with long-term contracts gradually complemented by spot markets. Those contracts play a crucial role in securing strategic volumes as oil and gas markets may gradually decline.
- **By 2050:** The international hydrogen market has reached maturity. As costs continue to fall, supply capacities massively scale up in green hydrogen to help keep pace with demand growth over the 2040s. Major trade hubs are increasingly interconnected as transport routes expand, exchanging almost 110 MtH_{2eq} in 2050. One of the most traded commodities is seaborne ammonia, more than half of which is used as a temporary carrier for pure hydrogen supply. However, in relative terms, 90% of pure hydrogen could still be produced domestically, although there are large regional differences. SAF and methanol are some of the most globalized markets, with trade covering respectively about 44% and 30% of demand by 2050. New end-uses gain momentum, and the market size significantly grows to meet this demand, which can improve liquidity and allows spot markets to dominate price formation.

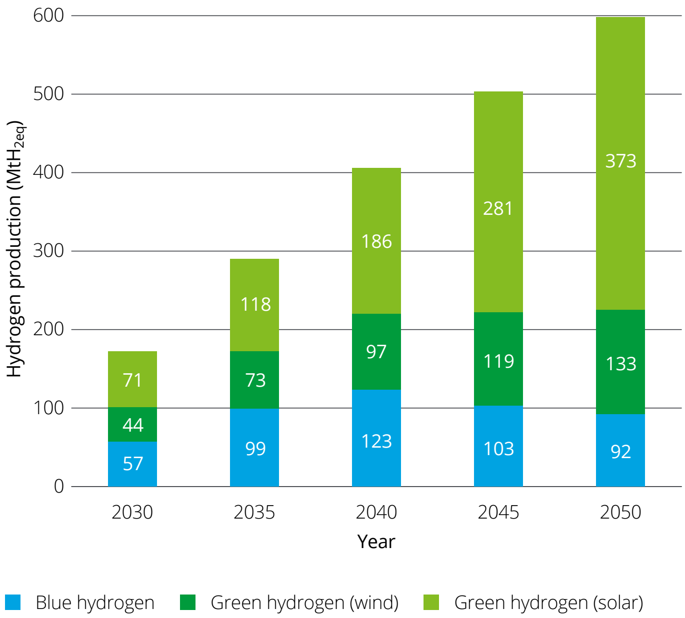


Green hydrogen dominates the market from the beginning

In this model, green hydrogen dominates the supply mix from the start to put the world on track toward climate neutrality by mid-century. Deloitte's outlook sees global production of green hydrogen soaring from 115 MtH_{2eq} in 2030 to 506 MtH_{2eq} in 2050, experiencing an average annual growth rate of 7.7%. With continued cost reduction for solar panels, solar-generated hydrogen supply should become more competitive and is, by 2050, the biggest source of clean hydrogen production. Its share in total clean hydrogen production grows from approximately 40% in 2030 to over 60% in 2050, compared to 25% and 22% for wind-based hydrogen.

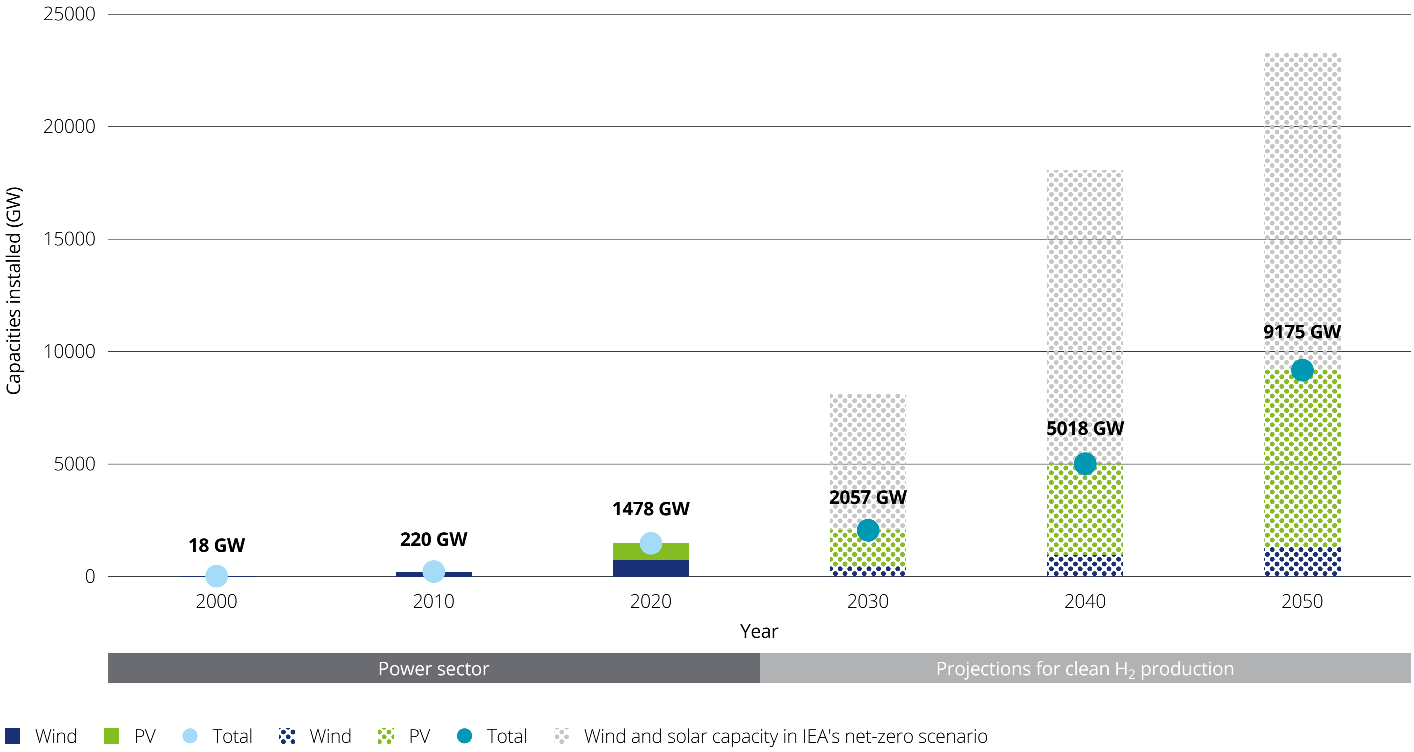
The deployment of new capacities for clean hydrogen production can be a major industrial challenge. Clean hydrogen production requires 2,050 GW of dedicated renewable capacity to be deployed in 2030, and 9,200 GW in 2050. Solar power dominates, with 1,600 GW and 7,900 GW deployed in 2030 and 2050 mainly in China, North America, the Middle East, Australia, and North Africa. Wind power prevails in North America, Europe, and Asia, with 450 GW and 1,300 GW deployed in 2030 and 2050. The challenge may be obvious when looking at the growth in renewable installed capacity observed worldwide between 2000 and 2020, from less than 20 GW to 1,480 GW (figure 13). Achieving climate neutrality

Figure 12. Clean hydrogen supply by technology, 2030 to 2050



Source: Deloitte analysis based on the HyPE model.

Figure 13. Global renewables capacities installed, 2000 to 2020 (history for the power sector), 2030 to 2050 (clean hydrogen production)



Source: Deloitte analysis and net-zero emissions scenario from the International Energy Agency's 2022 *World Energy Outlook* report.

could also entail deployment of renewables outside of the hydrogen value chain: In 2050, installed capacities dedicated to clean hydrogen in Deloitte's outlook represent only about 40% of the power sector's needs in the International Energy Agency's net-zero emissions pathway.[71]

These assets power a global installed electrolysis capacity of 1,700 GW in 2030 and 7,500 GW in 2050. This can also be an enormous challenge when considering the 1.4 GW installed capacity in 2022[72] and the 8 GW/year manufacturing capacity in 2021 (to date, electrolyzers are used mostly in the chlor-alkali industry). Investments in giga-factories may be needed to quickly safeguard the rapid growth in green hydrogen production.

Green hydrogen, however, can also create synergies with the decarbonization of the global energy mix. Leveraging on storage and power generation technologies (including fuel cells and hydrogen-fired gas turbines), green hydrogen can help integrate renewables into the power system by improving flexibility and mitigating congestion.[73] In addition, simplifying permitting processes and lowering the manufacturing costs for solar panels and wind turbines can aid the joint deployment of renewables for electrification.

Blue hydrogen can be a useful transition technology to help build up demand during the ramp-up phase of the hydrogen economy. This could be the case for regions with natural gas reserves such as the Middle East, North Africa, North America, and Australia. This role in the ramp-up is contingent on natural gas availability and the compliance of industries with some of the most stringent environmental standards, via high carbon capture rates and massive methane emission reduction.

Blue hydrogen production peaks in 2040 at almost 125 MtH_{2eq}, nearly one-third of global hydrogen production. As a new investment cycle begins in the 2040s and green hydrogen becomes cheaper, the business case for blue hydrogen may weaken. Meanwhile, tightening environmental standards (regarding unabated CO_2 emissions and upstream methane leakages) can diminish its environmental case. Its market share falls progressively back to 15% in 2050, corresponding to a production just above 90 MtH_{2eq}. To avoid being stranded, investments in blue hydrogen should consider the whole transition dynamics, including the lifetime of equipment, environmental standards, and the need for a widespread use of green hydrogen development in the long run.

Global trade is mostly about derivatives

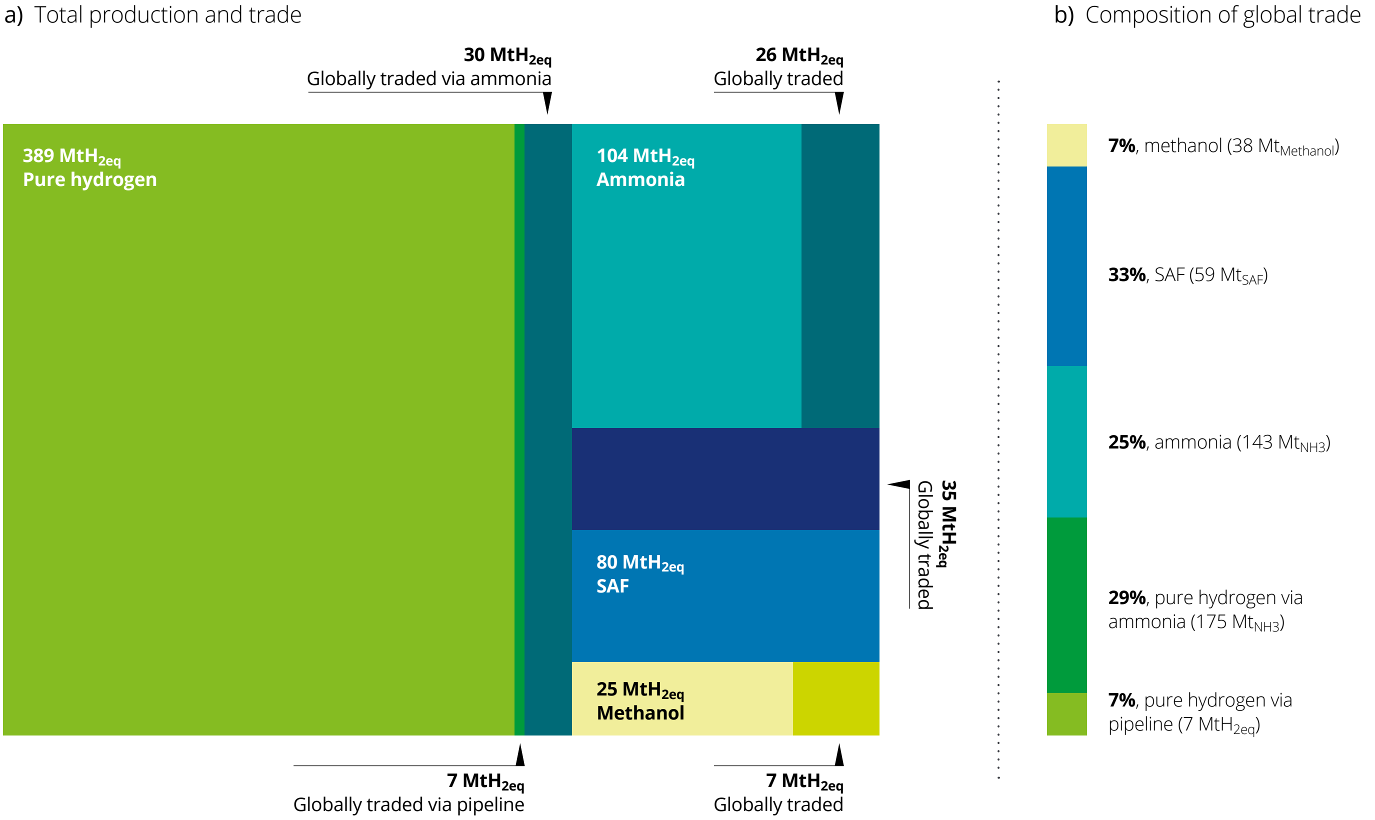
Global trade[74] between major regions represents almost one-fifth of the clean hydrogen market in Deloitte's outlook period, reaching about 110 MtH_{2eq} by 2050. This breakdown can be comparable to the current natural gas market, in which inter-regional exports represented just under one-quarter of the world's consumption between 2010 and 2020.[75] Global trade revolves around hydrogen derivatives, which can be easier to transport over long distances (figure 14).

Ammonia dominates global trade throughout the outlook period. The decarbonization of existing hydrogen uses underpins trade formation: In Deloitte's outlook, 124 Mt of ammonia are exchanged between regions in 2030, accounting for 70% of traded volumes in hydrogen-equivalent terms. As demand for pure hydrogen scales up, ammonia can also become a more prevalent long-distance shipping option. With almost 320 Mt, this commodity could account for just over half of 2050 global trade in hydrogen-equivalent terms. At this date, exports of ammonia are dominated by North Africa and the Middle East, producing 168 Mt and 96 Mt, respectively, and accounting for more than one-third of total ammonia supply.

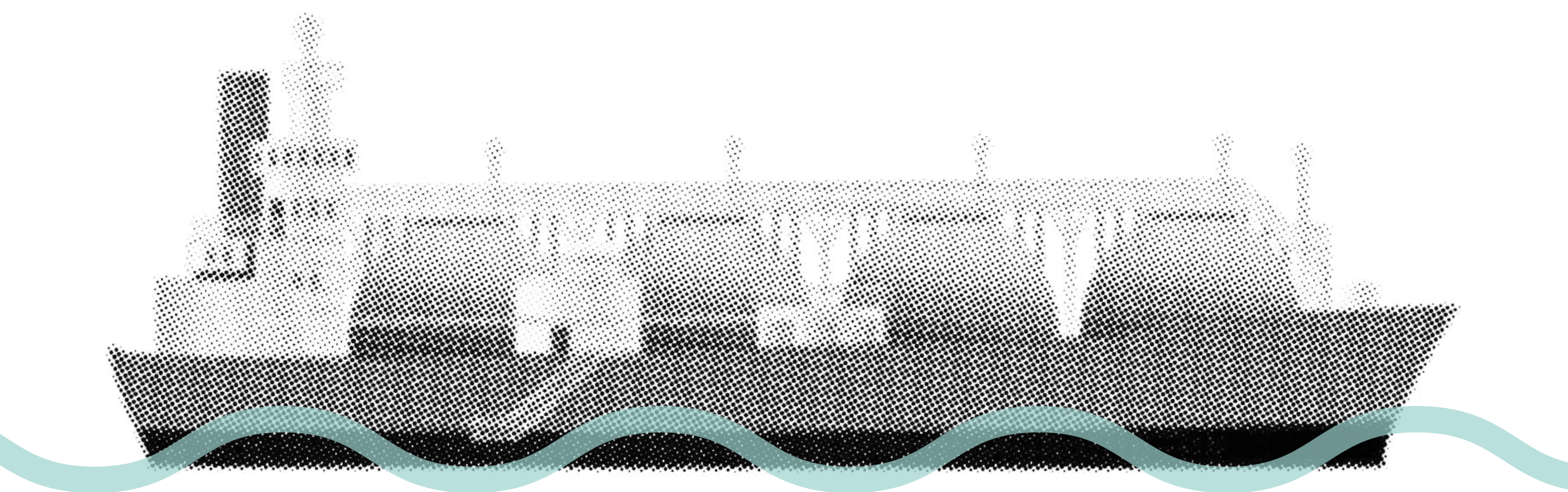
Methanol and SAF are naturally global markets. Between 2030 and 2050, about one-third of methanol and almost half of SAF are traded between major regions (North Africa, Middle East, North America, Australia, Europe, etc.), with 38 Mt of methanol and nearly 60 Mt of SAF being traded in 2050. Like ammonia, methanol and SAF are much easier to transport over long distance than pure hydrogen, insofar as they do not require reconversion and can leverage large-scale international trade infrastructures.

When possible, pure hydrogen should be produced domestically (over 90% of global consumption throughout the outlook period) or imported via pipelines from neighboring regions—only up to 2%, due to limited capacities. Still, seaborne trade from highly competitive regions via conversion to ammonia represents significant volumes and grows from nearly 5.5 Mt in hydrogen-equivalent terms in 2030 (6% of supply) to 31 Mt in 2050 (8%). It contributes to the prevalence of ammonia in global trade at this date (54% of global trade in 2050), which represents one of the most convenient, mature, and competitive shipping options.

Figure 14. Breakdown of the clean hydrogen market by commodities in 2050



Source: Deloitte analysis based on the HyPE model.



Global trade connects key exporting and importing hubs

Hydrogen and its derivatives can be traded between interconnected hubs. Overall, importing regions focus on the closest competitive suppliers to minimize costs, but also seek to diversify their mix of suppliers to enhance energy security, leveraging on retrofitted and new gas pipelines (pure hydrogen) complemented by coastal terminals (ammonia, methanol, and SAF). The dynamics of demand growth, supply ramp-up, and transport infrastructure development imply that these hubs may develop and connect at different rates.

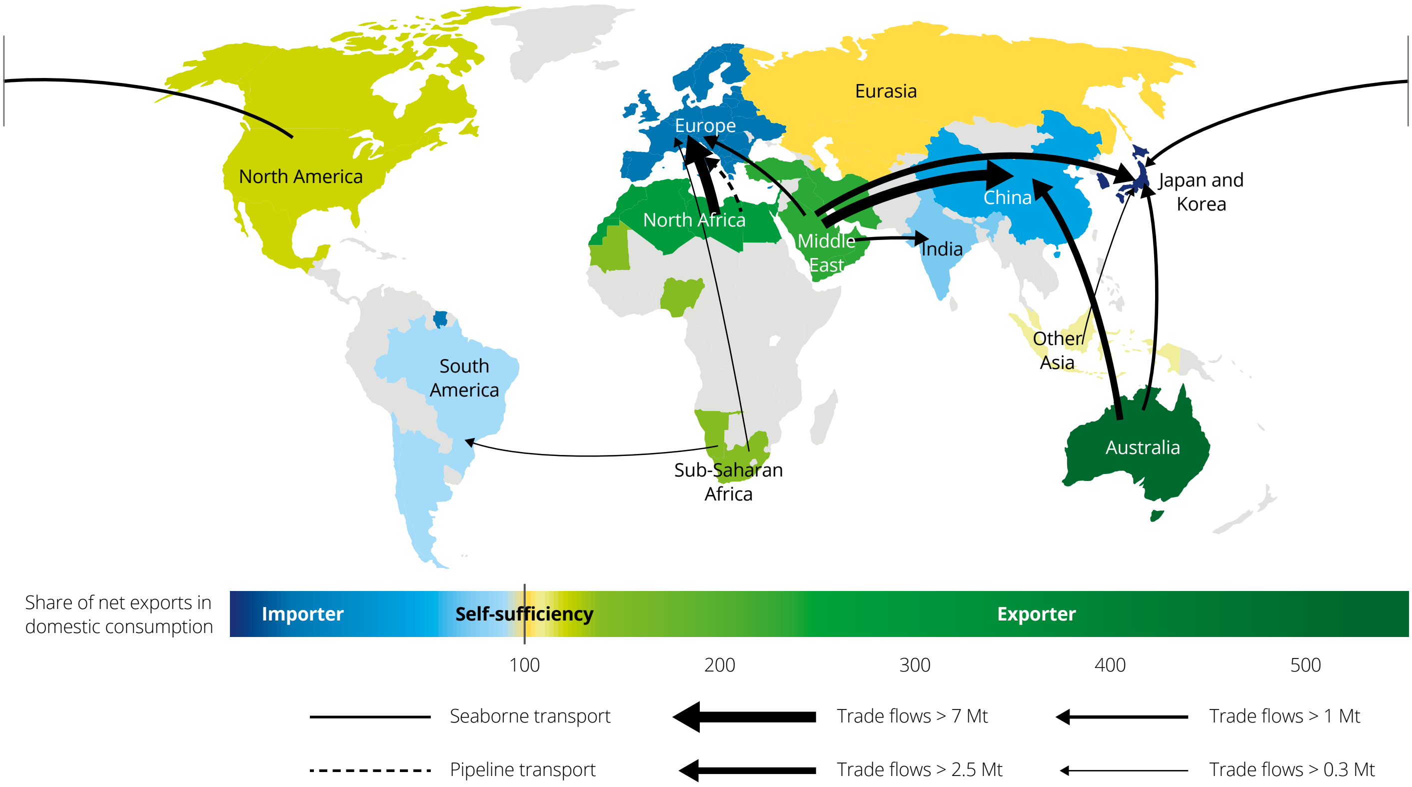
By 2030, clean hydrogen trade between major regions accounts for over 30 MtH_{2eq} (19% of global consumption), mostly driven by the decarbonization of existing ammonia demand (figure 15). As the capacity of the transport infrastructure remains limited at first due to lead times, early trade mostly takes place between neighboring regions.

- In Deloitte's outlook, the Middle East, North Africa, and Australia quickly harness their excess low-cost supply to become some of the key players in the global hydrogen market. The Middle East, historically the largest oil and second-largest gas exporting region, leads global trade in its early years and exports more than 13 MtH_{2eq} by 2030, half of its domestic production. It is followed by North Africa and Australia (7.5 MtH_{2eq} of export each), benefiting from significant cost-competitive green hydrogen potential. These three big exporters concentrate nearly 90% of global hydrogen trade by the end of this decade. On top of their significant clean hydrogen supply potential, these regions are geographically well-placed to serve the growing demand of major close-by demand hubs: China, Europe, Japan, and Korea. North Africa is ideally placed to help serve the growing European demand, leveraging on existing bilateral energy relations, exceptional solar irradiation conditions, existing export infrastructures (including port terminals), and new pipeline connection projects for the 2030s, with 12 MtH_2 of pipeline capacity availability from 2035 on. Regions such as North America should address domestic markets first before turning more extensively toward exports.

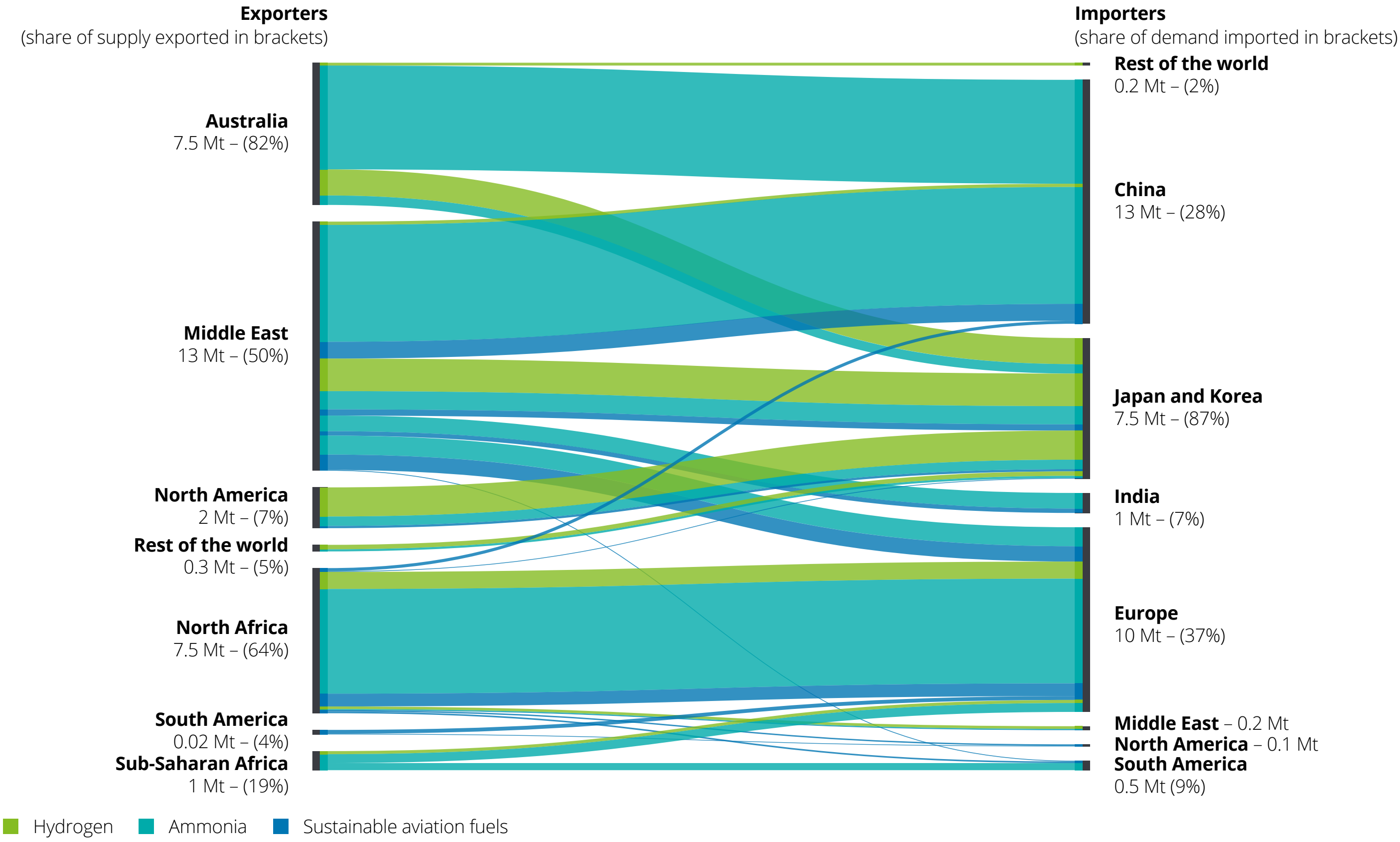
In Deloitte's outlook, the Middle East, North Africa, and Australia quickly harness their excess low-cost supply to become some of the key players in the global hydrogen market.

Figure 15. Global hydrogen trade among key regions, 2030

a) World map of trade



b) Breakdown of trade by commodities



Source: Deloitte analysis based on the HyPE model.

- In Deloitte's outlook, China, Europe, Japan, and Korea are some of the largest importers during the market ramp-up. While China does not face the same land availability limitations as Japan and Korea or even Europe, its strong ramp-up of clean hydrogen demand by 2030 outstrips its domestic production capacity, making China the biggest importers in 2030 (13 MtH_{2eq}). Europe imports nearly 10 MtH_{2eq} (37% of its demand), mostly in the form of ammonia and from North Africa (more than 70% of European imports). Due to severe land constraints, Japan and Korea hold the highest import-to-demand ratio, importing nearly 90% of their internal demand (more than 7 MtH_{2eq}). This structural constraint implies that both countries remain heavily reliant on global trade throughout the outlook period. Together, these four regions import nearly 30 MtH_{2eq} of clean hydrogen and derivatives, accounting for nearly 95% of global imports. Due to a slower demand uptake profile, India remains a marginal importer in the coming decade.

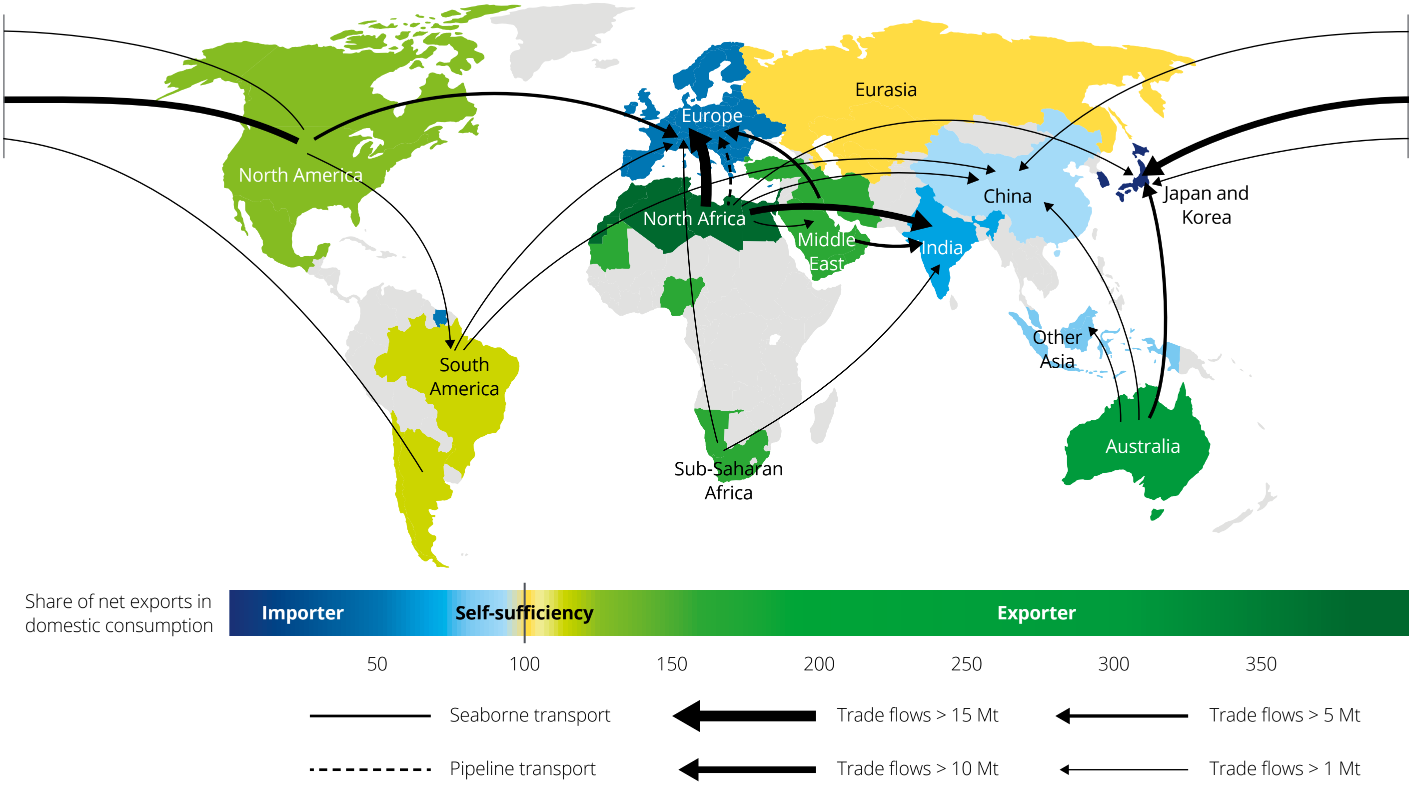
By 2050, the volume of trade could increase by more than threefold to reach 110 MtH_{2eq}, and relations between regional hubs solidify to help form a global market (figure 16). The structuring of a more comprehensive transport and conversion infrastructure allows exporting hubs to exploit the full potential of supply. Hydrogen trade also diversifies, including methanol and SAF as well as pipeline and seaborne hydrogen trade via ammonia.

- In the second half of the outlook period modeled, North Africa and Australia have the greatest export potential compared to their domestic consumption and ship about 70% their domestic production (44 MtH_{2eq} and 16 MtH_{2eq} respectively). North America and the Middle East also appear as export leaders (24 MtH_{2eq} and 13 MtH_{2eq}) despite heavy internal demand that takes around 80% of domestic production. North America emerges as the second-largest exporter due to its high renewable potential and its ability to ship blue hydrogen following the adoption of best available technologies for methane leakage abatement. Altogether, these four regions account for some 45% of global hydrogen production and about 90% of its interregional trade. They also concentrate almost the entire ammonia trade volume (nearly 60% for only North Africa) and nearly 90% of SAF trade (over 30 MtH_{2eq}). South America and sub-Saharan African countries also actively take part in global trade, with almost 10% of traded volumes, nearly entirely in the form of SAF and methanol.

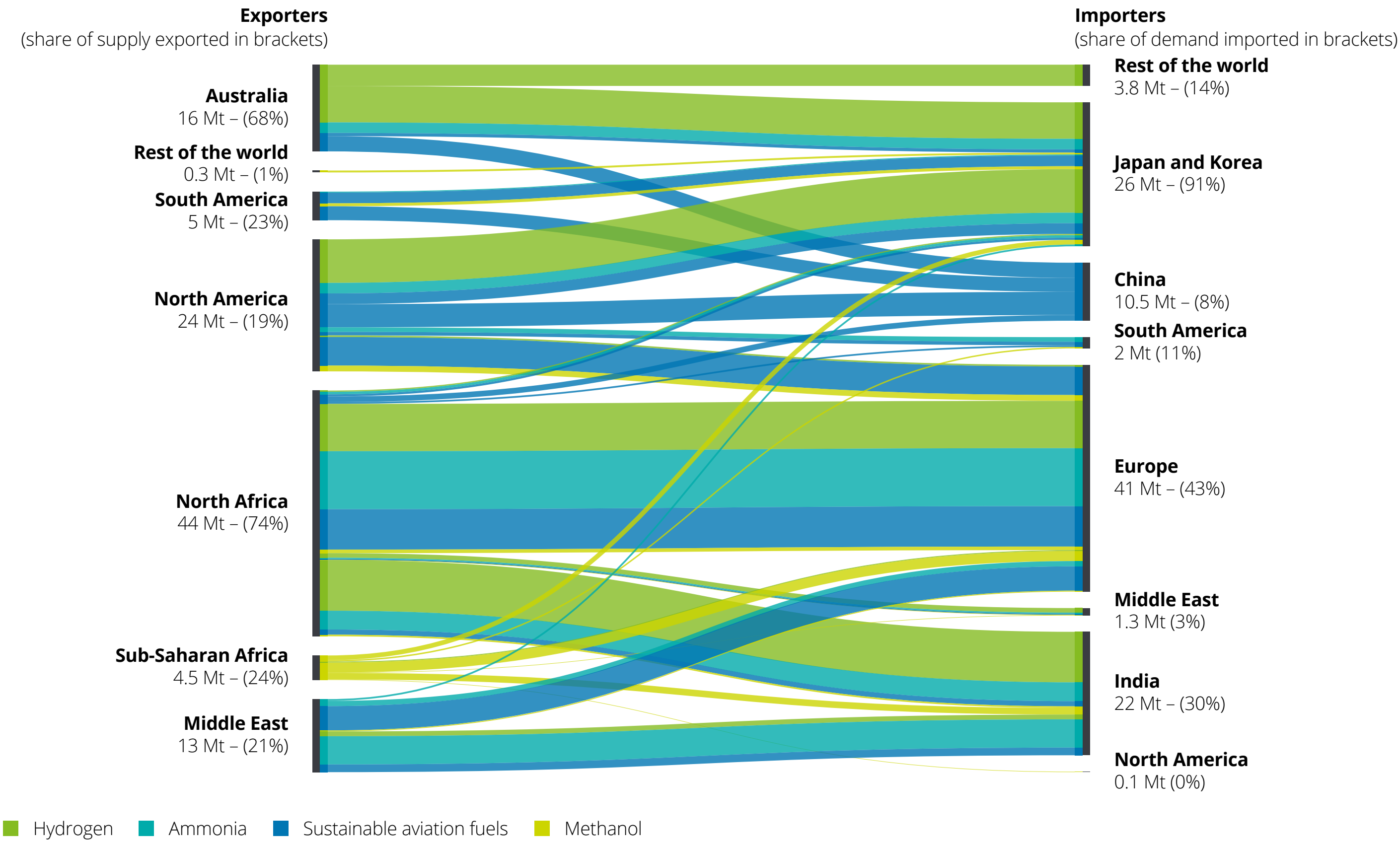
- The Paris-aligned decarbonization scenario that is modelled in this report results in Europe, Japan, Korea, and India, accounting for more than 80% of global trade. While Japan and Korea remain highly dependent on imports, the situation is more balanced in Europe and India, which import 43% (41 MtH_{2eq}) and 30% (22 MtH_{2eq}) of their consumption of hydrogen and derivatives respectively. North Africa is still Europe's main supplier—providing two-thirds of its imports in 2050—as these two regions partially repurpose their existing natural gas pipelines for hydrogen transport, with more than 20 MtH_2 of available annual capacity from 2040 onwards. The interplay between demand and supply for hydrogen is stark in the case of India and is based on the assumption that India will undertake accelerated decarbonization of its industrial and transportation sectors using hydrogen. The modelled scenario is thus far more ambitious than India's declared target of achieving 5 MtH_{2eq} of green hydrogen production capacity by 2030. In the scenario modelled in this report, India is unable to satisfy its clean hydrogen needs by domestic production alone. To be self-sufficient, India will need to superscale green hydrogen production significantly in addition to meeting its stated ambitions of renewable deployment for the power sector. Conversely, initially a net importer, China almost reaches self-sufficiency by 2050 as its domestic green hydrogen production finally catches up with domestic demand. Nevertheless, even after becoming the world's largest clean hydrogen producer (129 MtH_{2eq}), China imports about 10 MtH_{2eq} in 2050. This accounts for around 7% of the country's demand versus 30% in 2030. More broadly, most of the importing regions still produce substantial amounts of hydrogen—in 2050, for example, Europe and India produce about 55 MtH_{2eq} each.

Figure 16. Global hydrogen trade among the key regions, 2050

a) World map of trade



b) Breakdown of trade by commodities



Source: Deloitte analysis based on the HyPE model.

Part 4.
One new market, multiple benefits

Global clean hydrogen trade can trigger significant gains in terms of economic development, competition and efficiency, and overall energy security. Based on Deloitte's outlook, the global hydrogen market reaches US$1.4 trillion in 2050, including some US$280 billion of interregional trade. The integration within a capital-intensive global supply chain fosters local activity, knowledge acquisition, and technological progress. Almost 70% of it benefits developing and emerging markets, with significant co-benefits for sustainable growth. Free and diversified trade spurs economic development while reducing overall system cost up to 25%. Additionally, the hydrogen industry's scale-up facilitates the deployment of renewables, contributing to meeting electrification and decarbonization targets. Finally, Deloitte's pathway showcases how large-scale green hydrogen adoption, by diversifying the mix of suppliers, enhances energy systems' resilience to geopolitical shocks.

Economic development

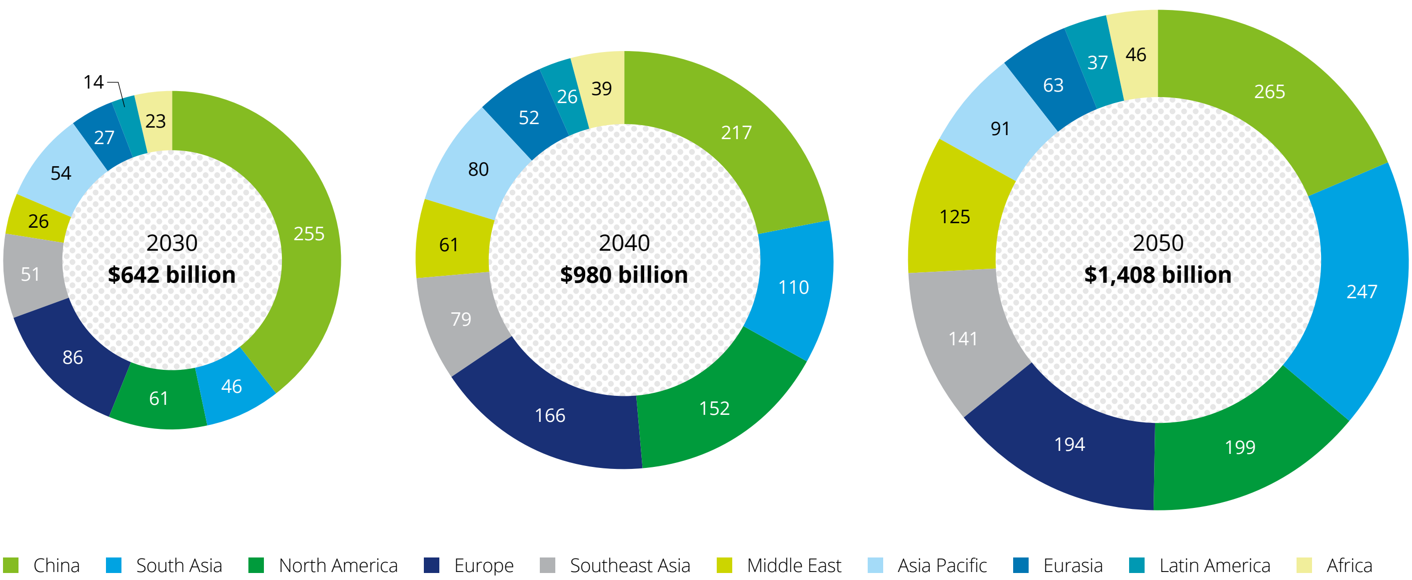
With clean hydrogen driving growth, the overall market can grow substantially, from US$160 billion[76] in 2022—entirely carbon-intensive hydrogen—to more than US$640 billion in 2030 and US$1.4 trillion in 2050.[77] The massive scale-up of green hydrogen lowers costs, meaning that between 2030 and 2040, market size increases less in value (less than 1% of constant annual growth) than in volume (9% of constant annual growth). As productivity gains slow between 2040 and 2050, market growth likely becomes balanced.

Consistent with Deloitte's regional demand outlook, the market potential is largely located in Asia: The continent captures 55% of the value in 2030, driven by skyrocketing demand in China (one of the world's largest producers throughout the outlook period), India, and Indonesia (figure 17). As demand expands in Europe, North America,[78] and the Middle East, the market diversifies by 2050, with Asia's share shrinking to 46%.

The development of the associated global value chain fosters local activities, creates value, and supports green jobs while facilitating retraining during the energy transition. The integration within a capital-intensive supply chain can be a catalyst for economic growth, with the scale-up of manufacturing (of electrolyzers, solar panels, wind turbines, and more), production, and transport capacities boosting local activity. Deloitte's analysis suggests that the clean hydrogen economy could support up to one million new jobs per year by 2030, and double that pace over the following two decades.[79]

The hydrogen economy can be a major part of the broader recompositing of the energy sector, with clean technologies creating up to 14 million jobs by 2030 and another 16 million transferred from the fossil fuel industry.[80] Since clean energy jobs tend to be more labor-intensive than fossil fuel jobs,[81] energy employment grows along the energy transition.[82] Besides, the clean hydrogen economy may offer a privileged conversion pathway for the fossil fuel industry's many transferable skills—for example, hydrogen transport and storage, renewable energy deployment, and large project engineering. Also fostering productivity growth: the fact that much employment in clean energy is high-skilled, with 60% of created jobs requiring a post-secondary degree, more than double the economywide average.

Figure 17. Clean hydrogen market size (US$ billion per year), 2030 to 2050



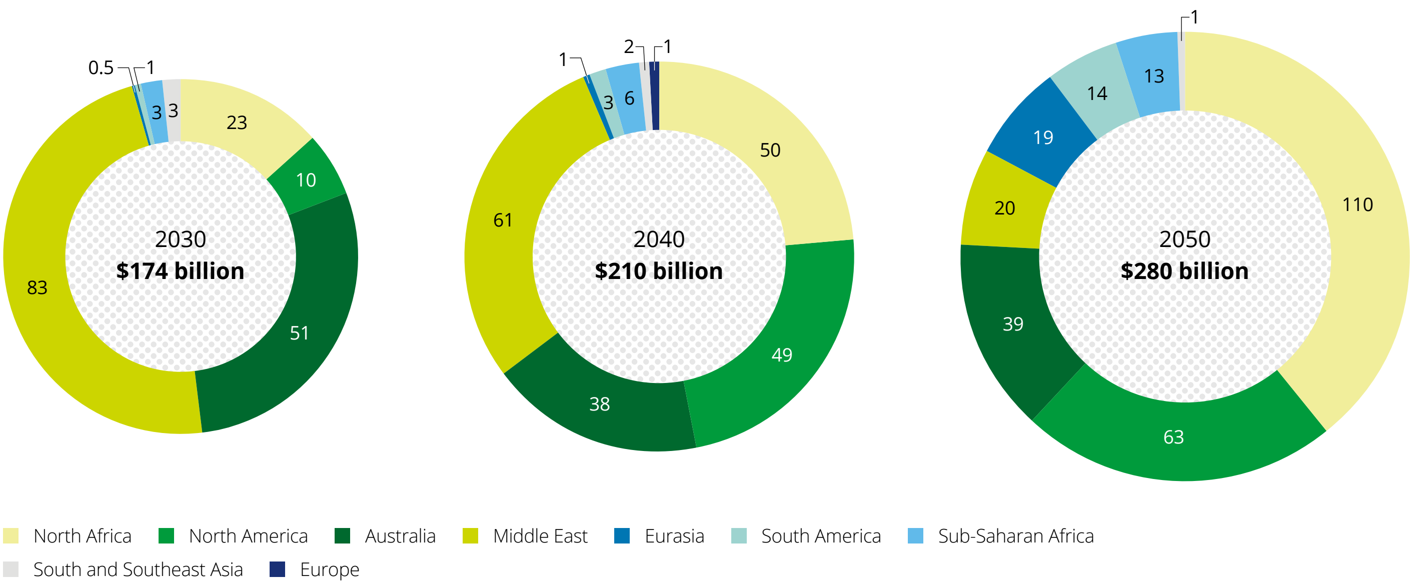
Source: Deloitte analysis based on the HyPE model.

For exporters, hydrogen trade can generate significant revenues—about US$280 billion in 2050 in Deloitte's pathway, more than half going to developing countries—with ripple effects on economic growth. Export revenues (figure 18) mirror North Africa's dominant position in export volumes (US$110 billion in 2050), followed by North America (US$63 billion), Australia (US$39 billion), and the Middle East (US$34 billion). These four regions could account for more than 80% of the export market in 2050. North Africa alone captures almost 40% of trade revenues at this date, more than 10 times its share in total market size. While the Middle East and Australia concentrate more than 75% of annual export revenues in 2030, leveraging existing infrastructure compatible with blue hydrogen, their market share falls to less than 15% each in 2050, roughly on par with North America, as green hydrogen gradually takes over. All of these regions appear to directly benefit from addressing a wider market access than their domestic economy.

Inclusive trade can spur economic development in the Global South by supporting local activity, improving trade balance, and facilitating the global energy transition. In Deloitte's pathway, developing countries could account for almost 70% of export revenues in 2050, supporting up to 1.5 million jobs per year between 2030 and 2050. Global trade significantly improves trade balance—for instance, in Chile (where it represents more than 7% of current GDP[83]), Algeria and Morocco (more than 10%) or Egypt (more than 21%)[84]—while providing access to strong currencies. The green hydrogen economy can also bolster the energy transition in the Global South, which is endowed with renewable energy resources but faces the challenge of providing access to modern energy to growing populations.[85]

The falling costs of carbon-neutral technologies can offer developing economies a unique opportunity to leapfrog fossil fuels in their development path.[86] In addition, green hydrogen could improve clean and affordable electricity access by facilitating the deployment of renewables and improving grid balancing. This opportunity is particularly pressing in Africa,[87] where, as of 2023, green hydrogen or ammonia projects have already been announced in Egypt, Mauritania, Morocco, Namibia, and South Africa. However, the energy transition in developing countries may still be hampered by a lack of infrastructure and limited access to affordable financing. International cooperation is likely necessary to channel resources, share technologies and knowledge (capacity-building), and ease access to financial markets.[88]

Figure 18. Annual export revenues (US$ billion), 2030 to 2050



Source: Deloitte analysis based on the HyPE model.

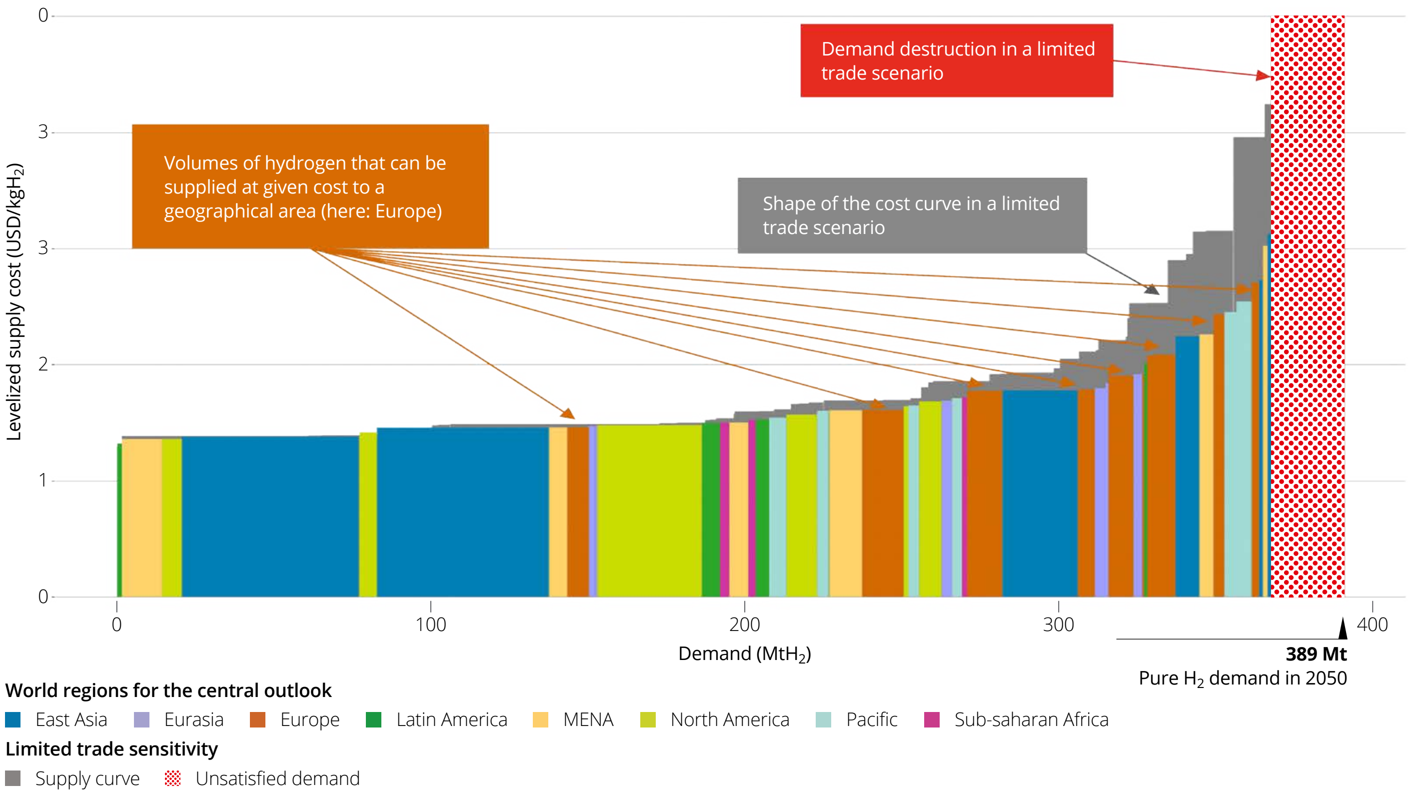
Efficiency gains from free trade

Deloitte's pathway showcases a highly competitive global hydrogen market. Unlike oil or natural gas, the supply curve for pure hydrogen in 2050—including every production route and associated transport costs—could appear rather flat (figure 19). Results show that in 2050, two-thirds of the demand for pure hydrogen (260 MtH_2) could be addressed at a supply cost (that is, including production, conversion, transport, and reconversion costs) below US$1.6per kgH_{2eq}.

Interregional exchanges appear essential for some land-constrained regions. The supply curve obtained for pure hydrogen shows the cost competitiveness and abundant volumes of the Middle East, North Africa, North America, and East Asia.[89] Conversely, some densely populated and industrialized countries, such as India, rely on imports to help fulfill their clean hydrogen demand at a competitive price. Without imports, demand could only be met either at a higher domestic production cost (steeper part of the supply curve), or by using fossil-based technologies. Free trade can help lower the energy transition's cost. History has shown the value of free trade and competition to deliver significant welfare gains.[90] By maximizing resource use at the global scale, free trade can lower the total cost of the hydrogen supply chain compared to a protectionist pathway with interregional volumes limited to a quarter of their optimal level.

- The annual gains from global trade could range between US$180 and US$350 billion[91] in 2050, up to 25% of total market value. This is calculated by contrasting Deloitte's pathway with an alternative scenario, in which leading countries adopt a protectionist mindset and underinvest in transport infrastructure, resulting in four times lower global trade volumes.[92] In the case of pure hydrogen (figure 19), these efficiency gains can be visualized by the area between the supply curves obtained for both scenarios.
- Curbing global trade by introducing tariffs or underinvesting in transport can add significant costs for supply-constrained countries, potentially delaying the global energy transition. In addition, trade barriers could incentivize hydrogen-intensive industries such as steel or ammonia-based fertilizers to relocate to some of the most competitive regions.

Figure 19. Global landed cost curve for pure hydrogen demand per consuming regions, 2050



Source: Deloitte analysis based on the HyPE model; The supply curve under limited trade corresponds to an alternative scenario where global trade is reduced four-fold in volumes (protectionist mindset and underinvest in transport infrastructure). The residual demand (i.e., the demand that could not be satisfied domestically due to limited trade) is priced at the highest supply cost obtained (about US$5 USD/$kgH_2$). The area between the optimal and trade-constrained supply curves (including unmatched demand) materializes the latter additional system cost. The Pacific region includes Australia Indonesia and Malaysia.

Enhanced energy security

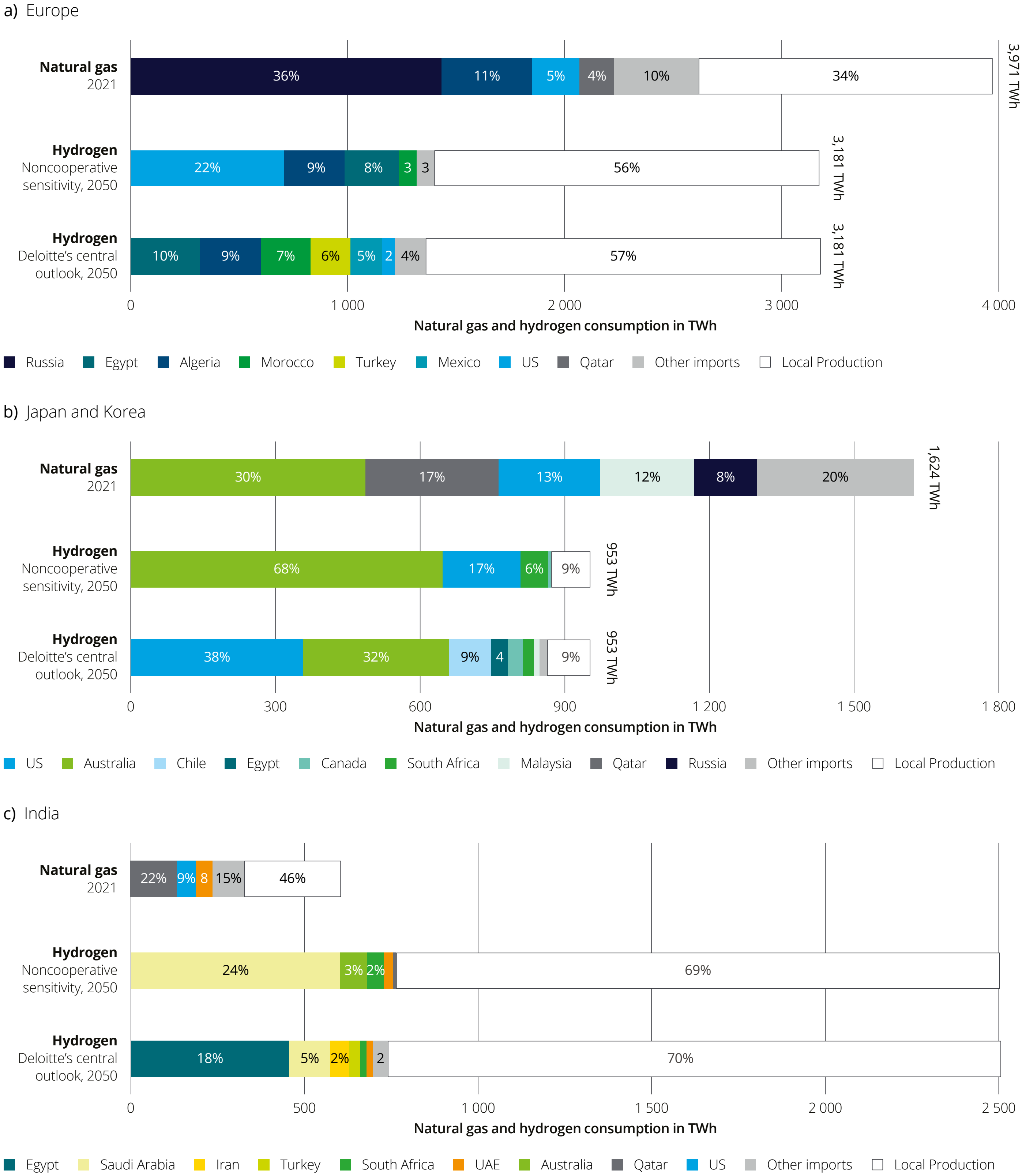
In Deloitte's pathway, green hydrogen's import optionality and large-scale adoption help improve overall energy security and resilience to geopolitical shocks.

- Competitive and diversified, the clean hydrogen economy differs notably from today's oil and gas markets. The fossil fuels industry is an extractive activity characterized by market concentration, high margins, and cartel formation; the recent international turmoil in energy markets highlights some of the economic vulnerabilities that may arise from dependence on unreliable suppliers.[93] Due to growing and overabundant availability of renewable energy, green hydrogen is likely to be a less concentrated market. The market's low entry barriers can help enhance competition and limit excessive profits.
- Unlike blue hydrogen, green hydrogen prices have no direct correlation with natural gas prices, providing protection against the volatility recently observed in Europe and Asia. Therefore, countries could gain the flexibility to control imports, including by selecting trade partners based on political alliances to prevent the use of hydrogen exports to exert political pressure.
- In Deloitte's outlook, the supply mix of main hydrogen importers are more diversified in 2050 than what can be seen in the European and Asian natural gas market today (figure 20). By 2050, the top three clean hydrogen exporters to Europe and India account for about one-quarter of the total consumption in these regions, compared to more than 50% and 40%, respectively, for natural gas in 2021. Besides, both regions could significantly increase their domestic supply, from 34% for natural gas in 2021 to almost 60% for clean hydrogen in 2050 in Europe, and from 46% to 70% in India. While Japan and Korea rely on the United States and Canada to import 70% of their combined demand, both countries simultaneously reduce their external energy needs by more than 40% (670 TWh), and could easily switch hydrogen suppliers to diversify the mix.

Again, international coordination is critical—without it, some of today's major oil and gas producers could play a more active role in structuring the market by promoting blue hydrogen, potentially impairing competition, global energy security, and the energy transition. The fossil fuel industry can leverage established production facilities, a skilled labor force, existing energy trade relations, and natural gas reserves. Governments delaying investment in new transport infrastructure and holding back international efforts to channel resources to the Global South could further reinforce the current central position of oil and gas.

- Noncooperation could entail risk of market concentration. In such an alternative scenario,[94] some of today's major oil and gas producers initially dominate the global hydrogen trade. The Middle East would account for half of volumes in 2030, followed by North America and Australia (20% each). Export opportunities for the Global South could be delayed by more than a decade, undermining their development and energy transition pathways. Global trade gradually diversifies through 2050, North Africa also becoming one of the major exporting regions. Yet, market concentration significantly increases compared to Deloitte's main outlook. Japan and Korea may rely on Australia and the United States (75% and 20% of imports volumes, respectively). The situation could be similar for India and Europe, with 80% and 50% of imports from Saudi Arabia and the United States. Such excessive market concentration could reproduce some pitfalls of the oil and gas market with higher margins, greater price volatility, and depreciated overall energy security at the expense of importing countries, as with the energy crises sparked by the Russia-Ukraine conflict.[95]
- Excessive reliance on blue hydrogen could increase the risk of technological lock-ins and delay the energy transition. The share of blue hydrogen may be significantly higher in Deloitte's sensitivity scenario with limited cooperation: Quantities are almost one-quarter higher in 2030 (70 MtH_{2eq}) and two-thirds higher in 2050 (150 MtH_{2eq}). The resulting higher residual and indirect emissions (50 $MtCO_{2eq}$ of annual emissions in 2050, about the same as the Hungarian CO_2 emissions in 2021[96]) weaken clean hydrogen's contribution in tackling global warming. Besides, unlike green hydrogen, investment in blue hydrogen infrastructure—reformers, CCS, natural gas supply—likely has no stimulating effects on renewable energy deployment and could actually extend reliance on unabated natural gas, which is incompatible with long-run climate neutrality. Such technological lock-in could be detrimental to green hydrogen and may increase the risk of stranded assets. Yet, blue hydrogen eventually fades away in any case, as the technology's environmental case and business case both diminish.

Figure 20. Supplier mix in key importing regions for natural gas (2021) and hydrogen (2050)



Source: Deloitte analysis based on the HyPE model and BP, *Statistical Review of World Energy*.

Note: Hydrogen in energy terms is represented in its low heating value (LHV).
The hydrogen noncooperative scenario deviates from this central outlook by a delay in new transport infrastructure, the earlier worldwide adoption of Best Available Technologies (BAT) for blue hydrogen (2030 vs. 2040 in this central pathway), the absence of financial support to developing and emerging markets (current levels of WACC assumed), and the lack of diversification strategy from the main importing regions.

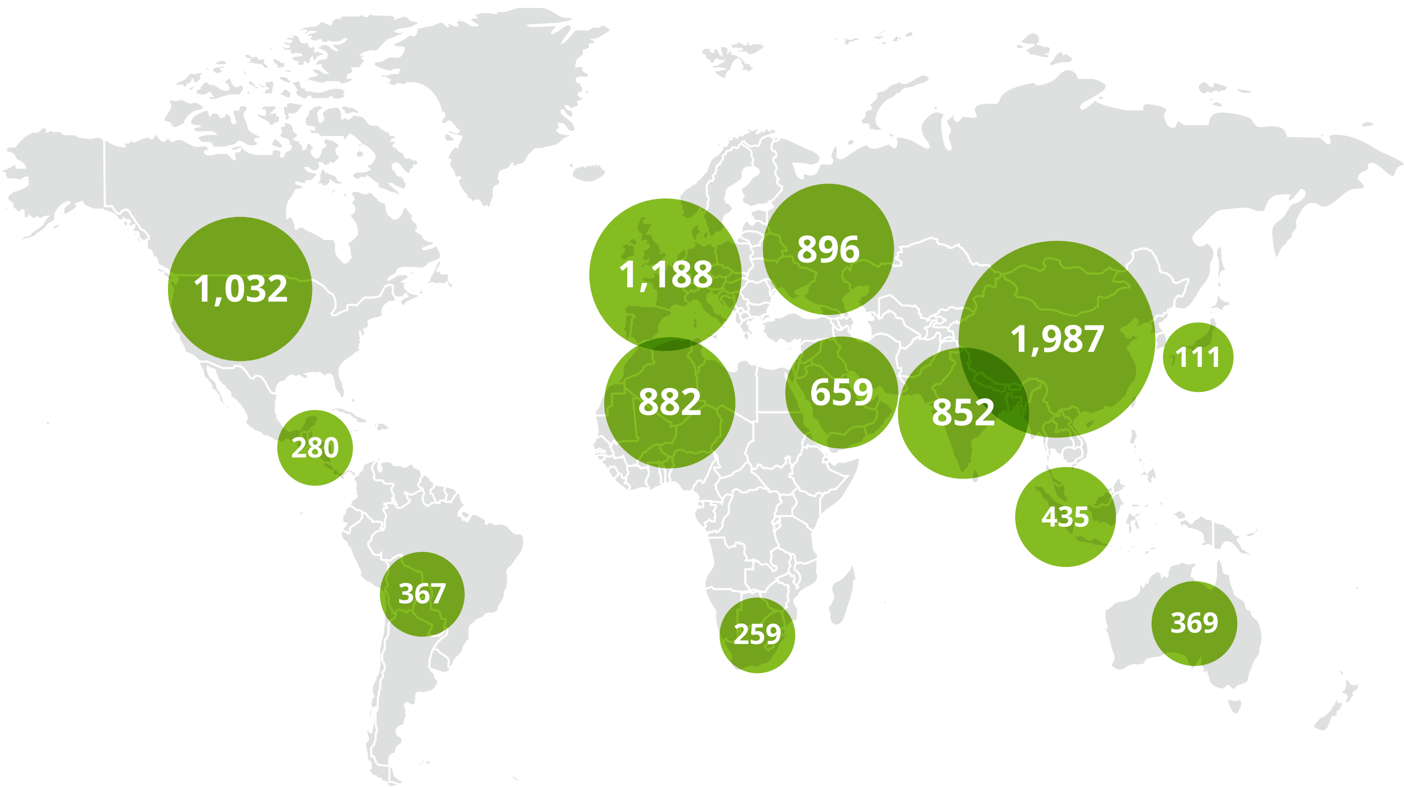
Part 5.
Over US$9 trillion of investment needed

Investments should happen globally

Deloitte estimates an overall global investment need of US$9.4 trillion in the global hydrogen supply chain by 2050 in cumulative terms, with US$3.1 trillion going toward developing economies (figure 21). These figures may seem high, but considerably less so when spread out: Raising US$9.4 trillion in financing over a 25-year period corresponds to 23 times global investment in oil and gas production of the year 2022.[97] This endeavor is likely manageable if the decline in spending on oil and gas can be channeled to clean hydrogen—something that international oil and gas companies have started doing. As some of the main consumption regions, China, Europe, and North America require expenditure of US$2 trillion, US$1.2 trillion, and US$1 trillion, respectively. Significant funding should also be raised in developing countries for export purposes (including almost US$900 billion in North Africa, nearly US$400 billion in South America, and nearly US$300 billion in each of Sub-Saharan Africa and Central America), posing significant challenges. The hydrogen economy's emergence can be a unique opportunity to attract foreign investment in the Global South, a trend that may be already underway—the €250 million German PtX Development Fund is an example of it.

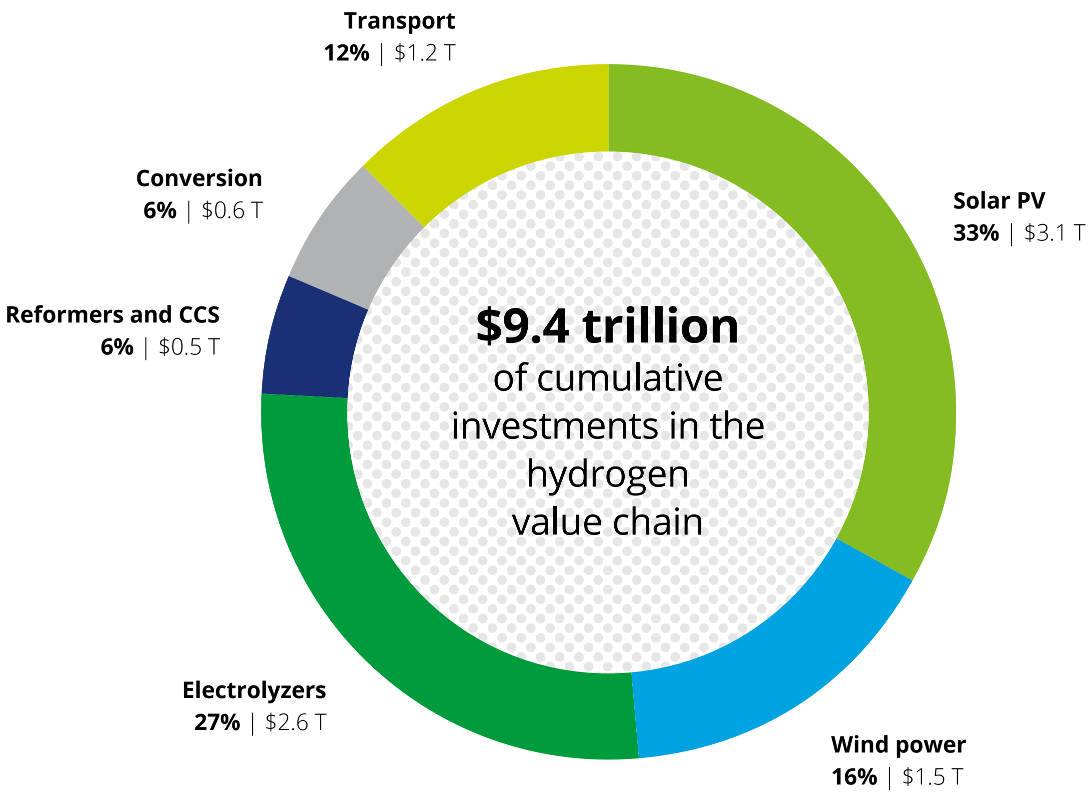
According to Deloitte's outlook, green hydrogen production accounts for the bulk of investments with over 75% of total requirements (US$7.2 trillion), posing industrial and deployment challenges (figure 22). Capital spending for this technology is likely needed both in power generation (with US$3.1 trillion and US$1.5 trillion dedicated to, respectively, the manufacturing and installation of 7,900 GW of PV and 1,300 GW of wind capacity) and electrolyzers (US$2.6 trillion for 7,500 GW). Ramping up the green hydrogen value chain requires the timely scale-up of equipment manufacturing and a seamless deployment of renewable energy assets. Blue hydrogen capital expenditures (US$600 billion) are concentrated in the first half of Deloitte's outlook period, as this technology helps to support market ramp-up before peaking around 2040.

Figure 21. Cumulative investments in the clean hydrogen supply chain (US$ billion), 2050

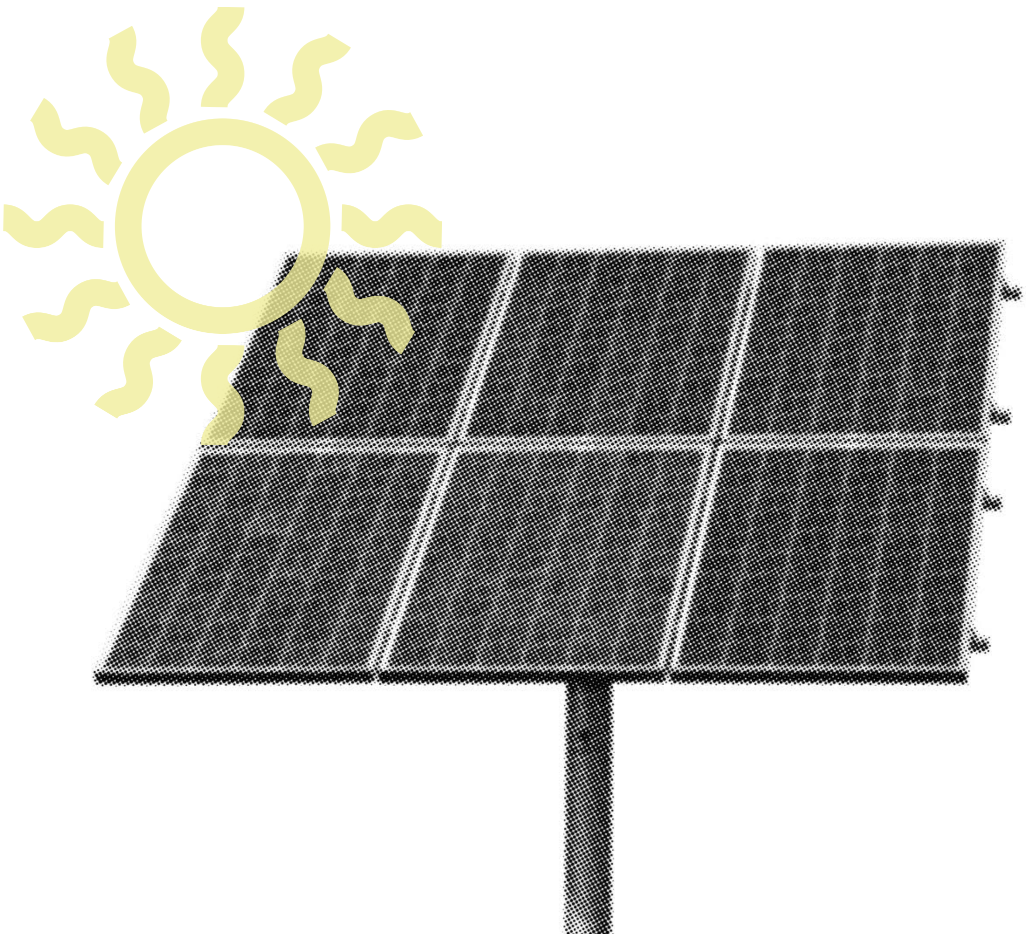


Source: Deloitte analysis based on the HyPE model.

Figure 22. Cumulative investments in the hydrogen value chain (US$ trillion), 2050



Source: Deloitte analysis based on the HyPE model.



Transport and conversion assets should not be neglected

Interregional trade underpinning the green hydrogen economy likely cannot happen without the development of a large-scale transport infrastructure dedicated to hydrogen commodities. Against the backdrop of strong growth in clean hydrogen trade in Deloitte's outlook, major developments of transport networks should be brought online, including inland transportation, conversion units, storage facilities, export and import terminals, and more. Although first import projects can leverage on existing infrastructure, new installations are likely needed, since those currently in use may not necessarily be located where the bulk of the green ammonia development is happening. To help build the international clean hydrogen market, investments should be channeled towards a new transport network consistent with worldwide cost-efficient production, benefiting both importers and exporters.

About one-fifth of total investment needs (US$1.7 trillion) should be dedicated to conversion and transport assets to avoid costly bottlenecks.

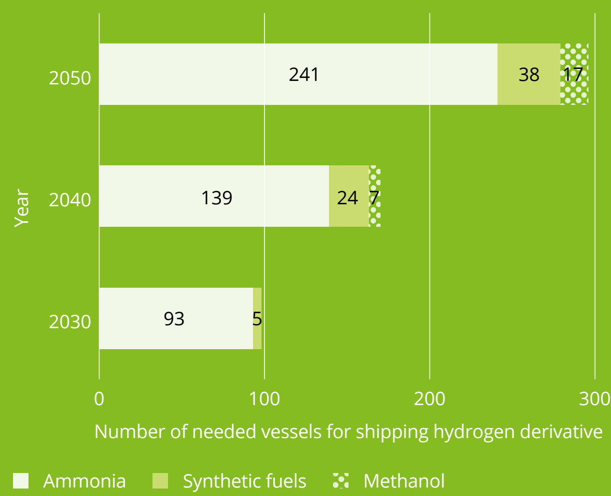
- Pipeline transport, though highly capital-intensive, is one of the most attractive options for pure hydrogen and could require more than US$1 trillion in cumulative investment terms. Intra- and inter-regional networks can be essential to help connect demand centers with production sites and port terminals. Up to 750,000 km of dedicated pipelines may be needed by 2050 to help connect the main industrial clusters. The retrofit of existing natural gas pipeline networks can reduce investment requirements, requiring five times less capital spending.[98]
- The construction of maritime infrastructure (up to US$100 billion) can support the resilience of the global hydrogen value chain. Long-distance shipping can deliver significant cost savings while fostering market resilience. Unlike bilateral pipeline connections, maritime import terminals can receive export from anywhere, providing important flexibility to switch suppliers, if need be. The substitution of Russian natural gas imports via pipelines to Europe with liquefied gas from several locations is a case in point. In Deloitte's pathway, about 100 tankers, mainly dedicated to ammonia shipping, could be needed by 2030, with that fleet further tripling in the period to 2050. The main trade routes in 2050 connect North Africa to India (70 vessels), North America to Japan and South Korea (around 50), and Australia to Japan and South Korea (around 30).
- Conversion and reconversion units constitute another crucial part of the clean hydrogen supply chain (US$500 billion). To help foster economies of scale, these assets should be preferably located within exporting or importing hubs—that is, converging points for hydrogen flows—for both domestic demand and exports.

Tanker fleet requirement

Hydrogen derivatives can be shipped by tankers: specialized vessels designed to carry liquids in bulk. The size of the global fleet could depend on several factors such as distance traveled, sailing speed, and vessels' average size and turnaround time. In Deloitte's outlook, the fleet increases over time, commensurate with growth in trade.

About 100 tankers may be needed in 2030 and 300 in 2050. Ammonia vessels dominate the fleet, given the dominance of this derivative in international trade. However, fleet share falls from 95% in 2030 to just over 80% in 2050 with rapid growth of methanol and SAF trade from the late 2030s onward. Deloitte assumes a fleet of only very large gas carriers, each with capacity of 80,000 m^3, the largest common size for liquid petroleum gas or ammonia shipping, corresponding to 53,000 deadweight tonnage (dwt) of ammonia, 62,000 dwt of methanol, or 63,000 dwt of SAF.

The demand for tankers could be satisfied by partial repurposing of existing fleets of oil and chemicals tankers (4,887 large and very large tankers as of 2020) and LNG tankers (961 large and very large tankers).[99]



Source: Deloitte analysis

Investments should take place now

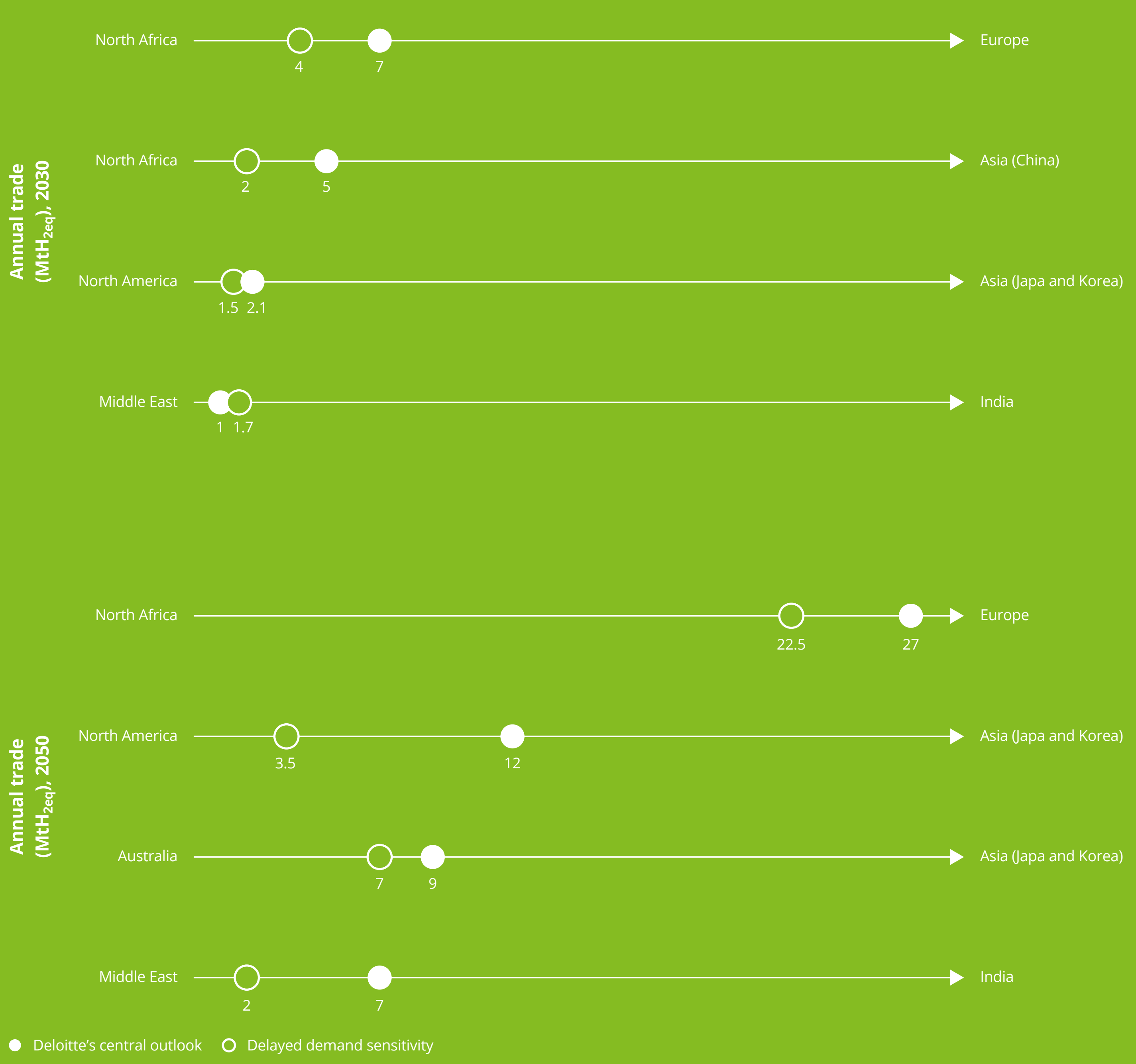
Fixed assets should be planned with a long-term view. Investment in production assets should consider at least a 20-year lifetime for the reformers and electrolyzers,[100] with a 25-year lifetime for renewable assets such as wind and solar power.[101] Investments in the transport infrastructure can break even in a 20-year period.[102] Long-term planning is therefore crucial to help avoid lock-in effects, especially regarding blue hydrogen. The planning should prioritize production infrastructure and trade routes that withstand technological, geopolitical, and deployment uncertainties. For blue hydrogen in particular, an economic lifetime of two decades implies a window of opportunity focused on the transition's early decades. All energy sector stakeholders, including countries, companies, and other players, should work to eliminate methane leakage and residual emissions from CCS should be avoided by the second half of this century.

The replacement of current grey hydrogen production (nearly 95 MtH_{2eq} in 2021[103]) with clean hydrogen represents a substantial no-regret investment. Even if a 10-year delay were to hinder clean hydrogen demand, no-regret early investment could be made in some of the frontrunner regions such as North America, the Middle East, North Africa, and Australia, which could still produce 16 MtH_{2eq}, 9MtH_{2eq}, 7.5 MtH_{2eq}, and 3 MtH_{2eq}, respectively, in 2030 (figure 23), including 2.1 MtH_{2eq}, 2.2 MtH_{2eq}, 4.4 MtH_{2eq}, and 2.4 MtH_{2eq} for exports. In such a scenario, global trade could still account for almost 15 MtH_{2eq} in 2030. Based on regional needs, four robust trade routes can be identified: North Africa to Europe, Australia to Asia (China), North America to Asia (Japan and Korea), and the Middle East to India. Therefore, a first wave of both public and private investments can and should take place now, on these robust production and trade routes.

Some of the main export hubs and trade routes should be robust through 2050, helping with the bankability of associated projects. With a 10-year delay in demand uptake, global hydrogen trade could remain through 2050: above 75 MtH_{2eq}, accounting for more than 70% of the volumes obtained in the central pathway. Some of the key exporting regions are likely unchanged: North Africa (31 MtH_{2eq}), Australia (10 MtH_{2eq}), North America (5.5 MtH_{2eq}), and the Middle East (4 MtH_{2eq}) concentrate more than 65% of interregional trade. The trade routes identified for 2030 remain resilient in 2050 as well: North Africa to Europe, Australia to Asia (Japan and Korea), North America to Asia (Japan and Korea), and the Middle East to India.

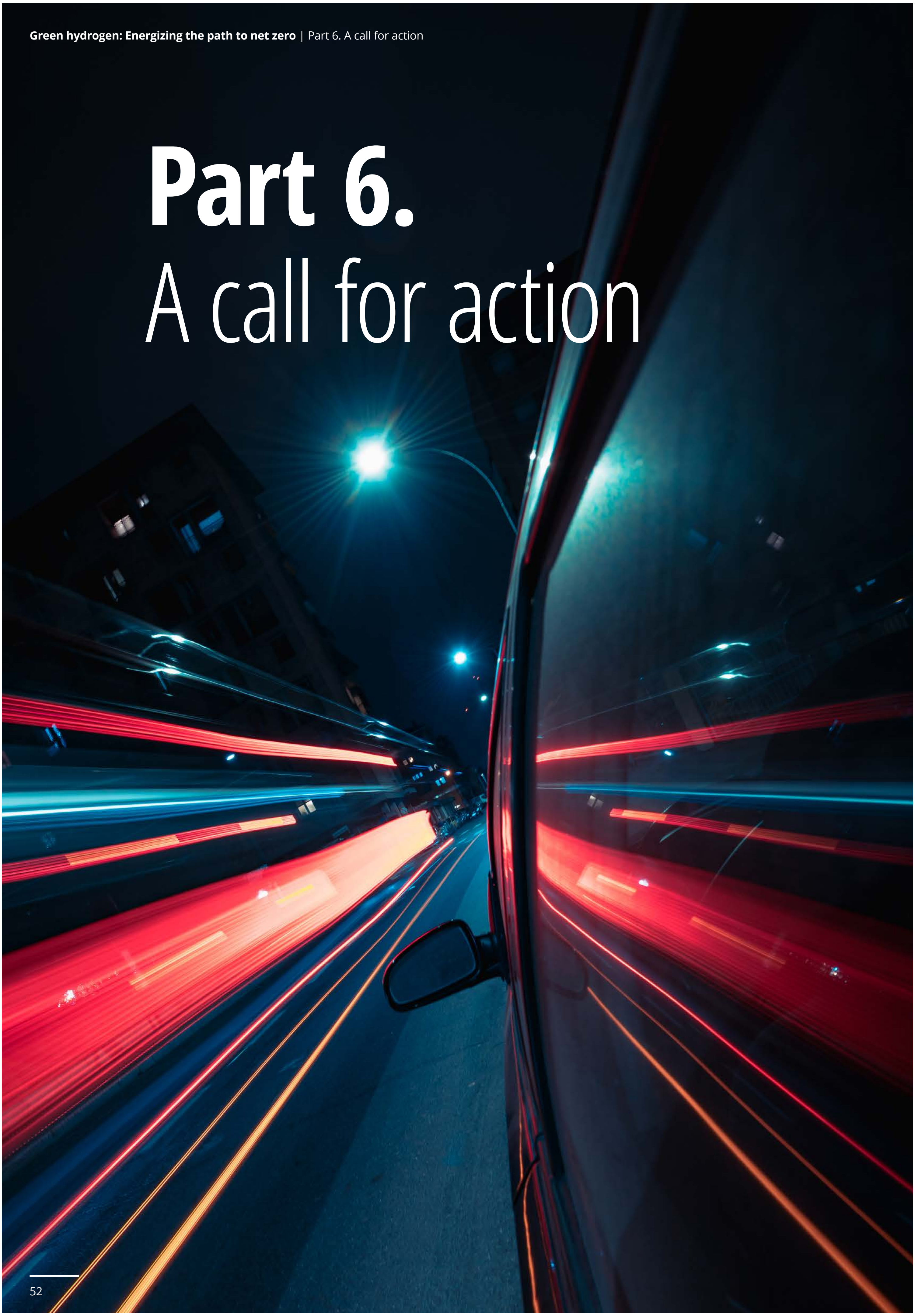
Long-term planning is crucial to help avoid lock-in effects, especially regarding blue hydrogen. The planning should prioritize production infrastructure and trade routes.

Figure 23. Some of the most resilient trade routes, 2030 and 2050



Source: Deloitte analysis based on the HyPE model.

Part 6.
A call for action



Help lay the foundations for a climate-oriented market

To reiterate, achieving climate neutrality to limit global warming is the key driver for the ramp-up of the hydrogen economy at local, regional, and global levels. It entails the global commitment to robust and accountable climate targets based on the Paris Agreement. At a more micro level, sectoral climate-related targets (in, for example, the steel industry or the transport sector) can play a crucial role in the rollout of hydrogen applications. Beyond the setting of clear targets, the development of transparent, accountable, and predictable decarbonization pathways is one of the key enablers of the hydrogen economy.

Even if most of the fundamental technologies—such as electrolysis, some industrial applications, and fuel cells—are already available, scaling up a hydrogen market likely needs considerable innovation efforts. On the one hand, cost reductions and industrialization should be secured for existing technologies. On the other, the development and upscaling of systems required to complete the clean hydrogen value chain are still to be achieved, especially regarding long-distance transport and conversion and reconversion assets.

National and regional hydrogen strategies can make a significant contribution to all stakeholders of the hydrogen economy by providing visibility and credibility on development prospects in production, transport, and end uses. However, in such a nascent market, uncertainties about market outlook can hold back private investment needed to secure economies of scale. Policy support to give visibility on opportunities throughout the value chain could help unlock the market ramp-up. The combination of a clear vision, ambitious targets, and a comprehensive support toolkit can stimulate the pipeline of projects. The current European and US programs and strategies noted previously are cases in point.

International cooperation can help facilitate free trade and mitigate political friction that economic transformation generates. The development of hydrogen applications indeed creates incentives to shift some activities and manufacturing—for example, steel and ammonia-based fertilizer—to regions with lowest production costs. Political efforts to prevent such adjustments could delay the energy transition, strengthen hydrogen-intensive industries' incentives to relocate, and globally raise overall costs. In contrast, taking into account regional specificities in national strategies and fostering international dialogue can help to identify and solve the potential conflicts.

Robust and accountable certification of clean hydrogen is another prerequisite for the market ramp-up. This requires both clear and transparent methods and a comprehensive technical infrastructure to help enable robust tracking and avoid double counting. The entire certification process likely needs internationally harmonized approaches. As a pragmatic approach and temporary solution, systems of mutual recognition of certifications would be of high importance and urgency given the varying levels of progress and different related jurisdictions. However, certification should not only focus on GHG emissions but include other sustainability criteria such as governance and social standards. In view of the active role of the Global South in the future global hydrogen economy, a stronger involvement of actors from these countries in the development of these norms is likely needed to help ensure an economic and environmental level playing field.

Global alliances to facilitate the transfer of know-how and best practice, and to establish local value chains are likely needed as well to help bolster the ramp-up and rapid establishment of international hydrogen markets. Hydrogen production and application systems being predominantly high-skill technologies, international collaboration should encompass all stakeholders, including academia, industry, and regulators.

National and regional hydrogen strategies can make a significant contribution to all stakeholders of the hydrogen economy by providing visibility and credibility on development prospects.

Create a business case

To unlock the ramp-up of the green hydrogen economy, it is necessary to bridge the existing cost gap between grey and clean hydrogen and between conventional and hydrogen-based applications. One of the first tools here is carbon pricing, which serves to increase the cost of GHG-emitting options and help reduce this gap. Carbon price should include all of the externalities caused by the related GHG emissions, or be complemented by other policy instruments. Beyond support for R&D or demonstrator pilot projects, governments can implement a wide range of policy instruments such as removing barriers to market entry, direct subsidies, fiscal incentives, public guarantees, carbon pricing or carbon contracts for difference, or creating green pilot markets for hydrogen-based products such as green steel or green chemicals. One of the key challenges in this context is to maintain consistency between the policy support mechanisms for the production and the use of clean hydrogen to avoid efficiency losses, potentially high windfall profits, and consequently insufficient market ramp-up dynamic.

In many applications, the widespread adoption of new technologies is necessary. Many hydrogen applications are not just about replacing conventional energy sources or feedstocks with clean hydrogen commodities—they could also entail full technology switches or capital-intensive repurposing of assets such as green steel production, ammonia and methanol use in the maritime transport, or adoption of hydrogen fuel-cell electric vehicles. Addressing these technology challenges in all of their components—for example, cost structures, qualification needs, and habit persistence—is one of the key success factors for the development of new business models, both for policymakers and for the industry.

Robust business models for both the production and use of clean hydrogen and its derivatives can develop only if the necessary infrastructure is available with sufficient lead time. Early planning and rapid creation of transport and storage infrastructure (including conversion and reconversion assets) should therefore be a central component of any ambitious hydrogen policy. This can include smart models, to compensate for the risks associated with the temporary underutilization of these infrastructure during market ramp-up. Governments and regulators also have a key role to play to help guiding investors towards more reliable investment routes.

Long-term contracts are expected to play a prominent role, especially during market ramp-up, for infrastructure investors and operators as well as for producers and users. Reducing revenue risks may require long-term contracts and associated hedging strategies, including public-backed guarantees. Such contracts can be necessary to help ensure investments' bankability in the early phases of the hydrogen market development and could mitigate price volatility, not only for domestic markets but for international trade. Pooling of hydrogen procurement or regional cooperation approaches can also play an important role.

The development of contractual and market infrastructures—for example, trading platforms and spot markets, hedging products and future markets—should be prerequisites for viable, lasting business models. While the clean hydrogen market should leverage existing conventional commodity markets, new developments may also be required to help account for the specificities of the hydrogen economy such as certification. Public support and industry involvement during market ramp-up should address these dimensions to help facilitate these markets' timely development.

Robust business models for both the production and use of clean hydrogen and its derivatives can develop only if the necessary infrastructure is available with sufficient lead time.

Ensure long-term resilience

National strategies should focus on supply diversification targets, especially in the ramp-up phase. The resilience of energy and raw materials supply could be crucial to help avoid bottlenecks during the hydrogen economy's scale-up. On the consumer side, resilient clean hydrogen supply structures should be secured as well; market concentration should be avoided to help strengthen energy security, improve competition, and foster resilience. Both public support and corporate strategies should explicitly foster alliances with future production countries and encompass diversified infrastructure—such as gigafactories for electrolyzers and renewables—across the value chain during the market structuring.

The highly competitive transport of hydrogen via pipelines could require political support, especially for the cross-border infrastructure. In a fiercely competitive environment and with heightened geopolitical tensions in many parts of the world, pipeline policies should be carefully designed and strike the right balance between foreign policy, energy policy, and human rights. Governments should put safeguards in place to help cope with the potential underutilization of pipelines, especially in the ramp-up phase.

Marine transportation is a crucial flexibility option for the future clean hydrogen market. The timely commissioning of export and import terminals, as well as tanker fleets' availability, can be an important facet of a resilience-oriented hydrogen ramp-up. Public support to hedge against default risks—for example, public guarantees—on both the production and demand sides can help to channel investment flows.

Repurposing existing assets can provide a significant share of the transport infrastructure, with the resulting transformation plans mitigating the risks associated with stranded assets in the fossil fuel industry and facilitating the energy transition. More broadly, Deloitte's outlook envisions that the hydrogen economy could be one of the major components of the transition of the energy sector, including job retraining.

Ensuring a resilient hydrogen supply also entails the adoption of minimum standards for strategic hydrogen reserves or other stockpiling concepts. Governments should address technical and regulatory prerequisites from the market's early stages, to help cope with possible tensions between initially scarce supply volumes during the ramp-up stage. As with oil and natural gas stockpiling, governments should reach international agreements as soon as possible.

The hydrogen economy's direct and indirect contributions to local and regional value creation can help foster economic growth and political stability. In particular, hydrogen can help to increase the stability and resilience of existing and new trade routes, especially with future production centers. It should therefore also be systematically incorporated into development targets and policies.

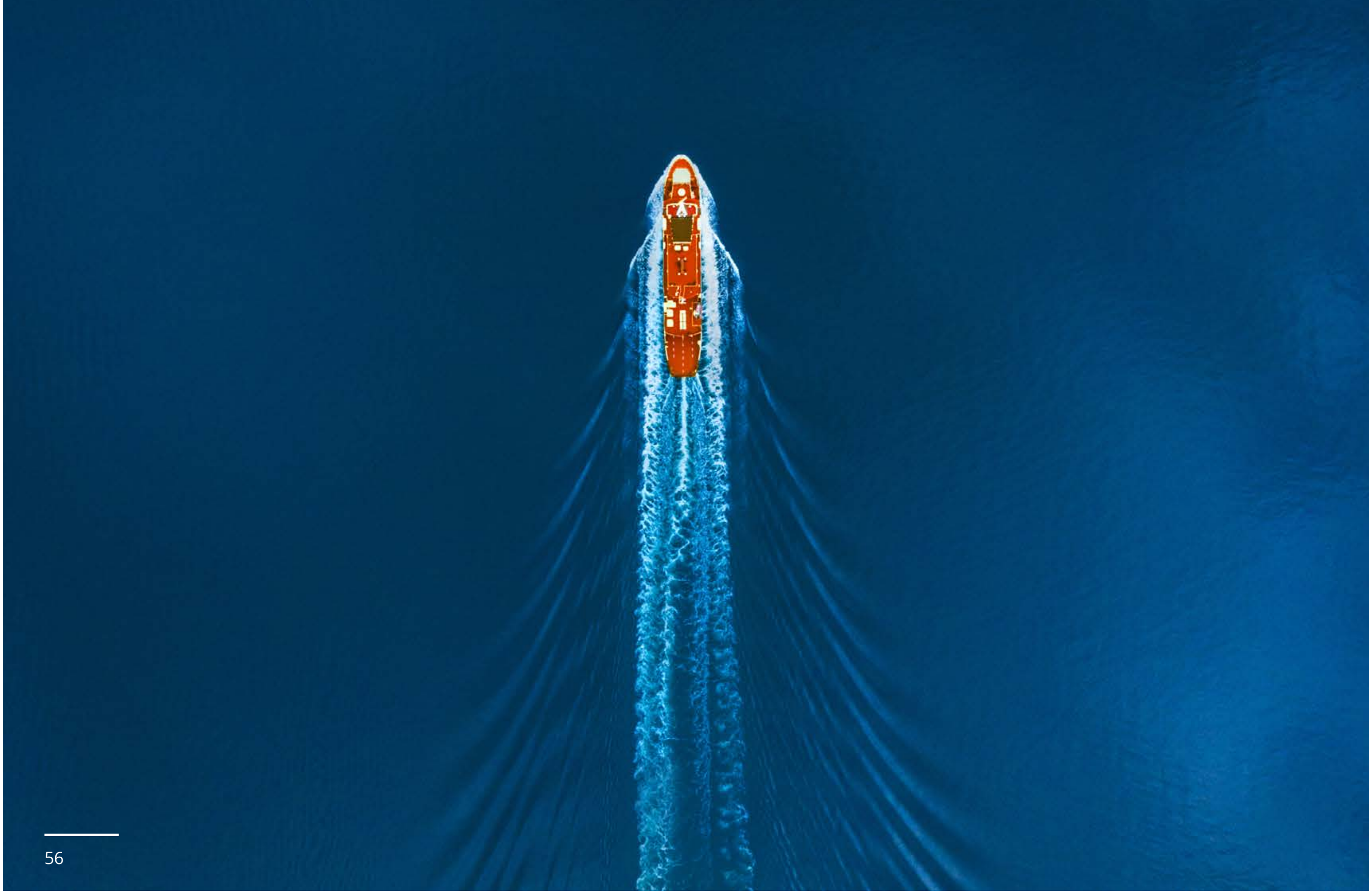
Balancing competition and cooperation

International cooperation will likely be crucial to help foster the timely growth of the clean hydrogen market—and to help ensure a level playing field across global regions and economies. The ramp-up of the hydrogen economy is likely to remain a strategic battlefield of international competition among companies, regions, and countries during the entire outlook period toward 2050.

The current cost difference between clean and grey technologies means that governments may need to offer support to initiate market ramp-up. This could encourage some countries to engage in a race for economies of scales to dominate the future market. In view of clean hydrogen's role in the energy transition, international cooperation should be sought as early as possible. Through appropriate international agreements, standards harmonization, and industrial policy coordination, governments can leverage synergies for climate and energy policies to help deliver a sound, growing market benefiting all.

Governments should address technical and regulatory prerequisites from the market's early stages, to help cope with possible tensions between initially scarce supply volumes during the ramp-up stage.

Appendix: The Hydrogen Pathway Exploration (HyPE) model



Deloitte's HyPE model is a dynamic optimization model focusing on global clean hydrogen supply. It provides cost-optimal production and trade routes for clean hydrogen, considering all potential production sites and possible transport options. HyPE represents in a detailed manner the value chain for clean hydrogen and its derivatives, from production until the point of final consumption (figure 24).

The approach builds on a linear programming model choosing the least expensive way to supply global hydrogen demand, represented in different demand clusters, considering different upstream options (e.g., green hydrogen from renewables, blue hydrogen from natural gas), transport modalities (trailers, pipelines, bunkers), physical media (gaseous or liquefied hydrogen, ammonia), and end-use commodities (pure hydrogen, ammonia, methanol, and synthetic aviation fuels). The resulting cost structure, while driven by production costs, also includes transport costs as well as conversion and reconversion costs depending on the transport option and end-use requirement. The optimization can be performed in a global way, minimizing the overall cost of the hydrogen supply and trade from 2025 up to 2060.

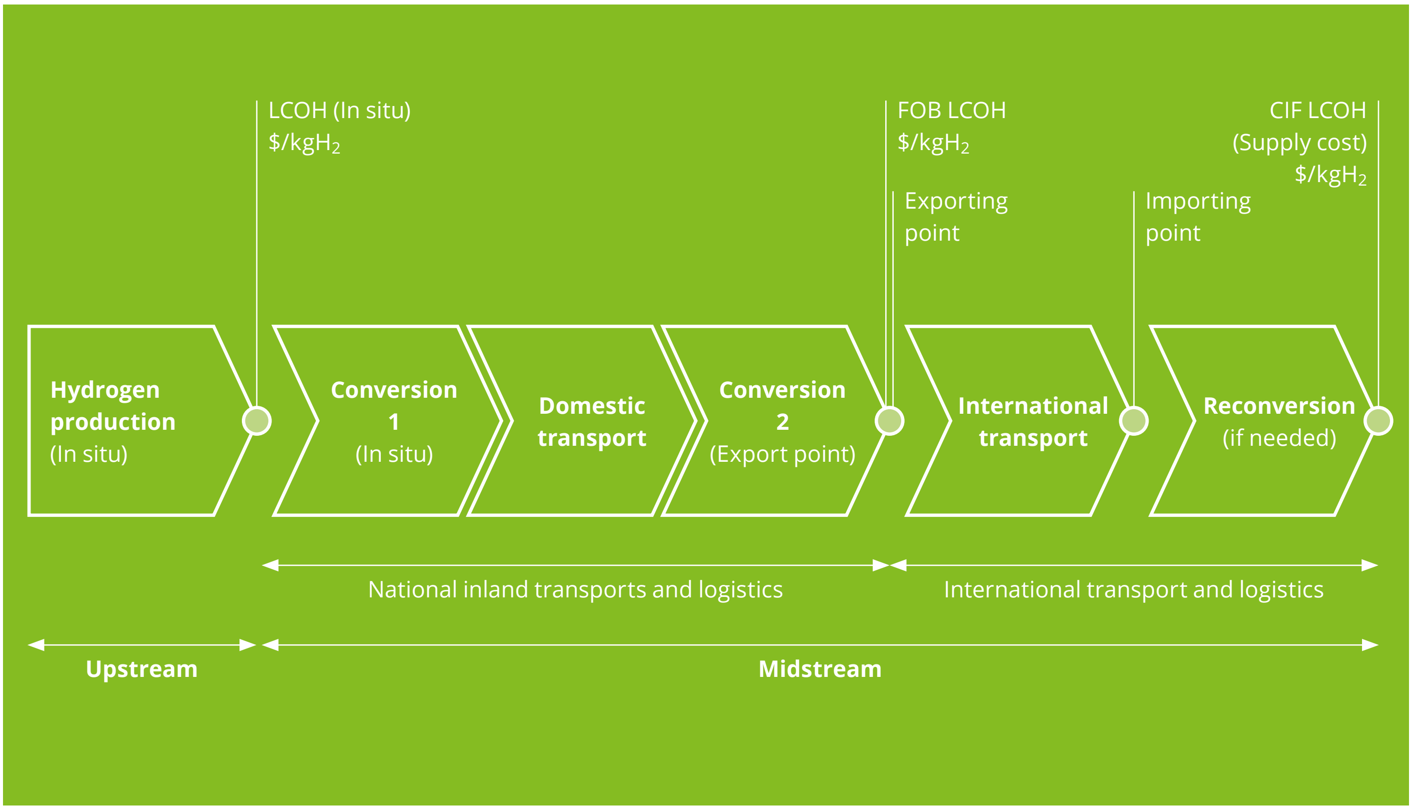
Upstream representation: hydrogen production

Green hydrogen

In HyPE, green hydrogen can be produced either via electrolysis of variable renewable energy sources (wind and solar power) or from processes based on biomass (biomass reformation, bio-pyrolysis), which can in some cases allow negative emissions. From a system-level optimization perspective, green hydrogen from biomass can be produced to offset the residual emissions linked to some processes such as blue hydrogen production. Without this offset opportunity, green hydrogen production from biomass (providing negative emissions) cannot be an economically viable option, as it is significantly more expensive than other clean hydrogen supply options. This study focuses on a clean hydrogen market without constraints on emission offsetting. Therefore, current analysis focuses mainly on green hydrogen production via electrolysis; biomass-based hydrogen production is out of the scope.

The production of green hydrogen from variable renewable energies depends on local factors such as wind speed and solar irradiation as well as the availability of suitable land and water

Figure 24. Hydrogen imports value chain[104]



Source: Deloitte analysis

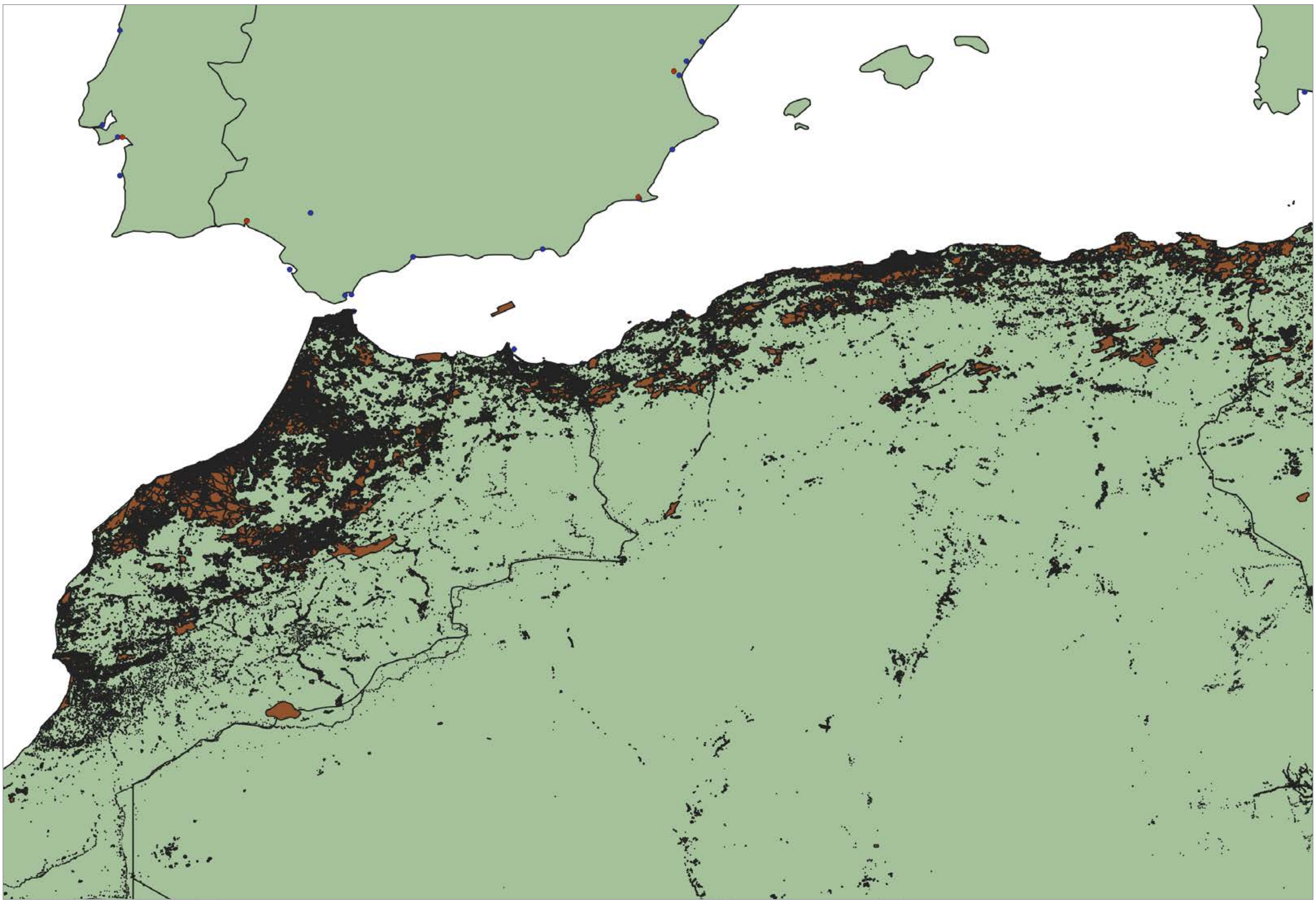
access. The methodology developed for HyPE for the estimation of feasible solar and wind resources to produce green hydrogen is based on multiple studies,[105] as is the fixed and variable costs of renewable energy plants and electrolyzers.[106]

HyPE calculates the available wind and solar potential for green hydrogen production via mapping the world with an adjustable grid from 0.5° to 2.5° cells that are projected on the selected countries around the globe, for a total of up to 38,000 cells. For each cell, both an annual wind speed time series and an annual solar irradiation time series[107] are used to calculate the solar and wind capacity factors at the centroid location of that cell. As such, hourly hydrogen yields can be derived from the weather data for the year 2016. For onshore wind turbines, a hub height of 130 meters and a corresponding power curve were considered to obtain the hourly wind yield at every cell. The model considers fixed ground-mounted PV systems with optimized tilt angles (as a function of the cell latitude) to represent solar power plants.

The maximum available land on each cell for wind and solar installations helps to lay the groundwork for identifying the green hydrogen supply potential. This available land includes total surface of the cell, excluding the land covered with water bodies, forests, natural parks, and cities, as well as land that is currently in use (or planned to be) for economic activity such as industry or agriculture. These renewable potentials were used to determine the potential of green hydrogen supply at each cell (figure 25). Using the ENSPRESO database assumptions,[108] wind turbines and solar panels can potentially be deployed on only 5% and 1.5% of the available land. The capacity that can be installed over a given surface can be calculated using power density of solar and wind power technologies. This report considers 85 MW/km^2 of power density for solar power and 10MW/km^2 for onshore wind power.[109]

Renewable energy sources should not be installed at any rate, and annual growth in the renewable installed capacities is likely constrained via technology- and country-specific deployment rates. These deployment rates are set to mimic industrial and regulatory rigidities that prevent the industry from being developed overnight.

Figure 25. Determination of the maximum available space for the installation of renewable energies using land-use data



Source: Deloitte analysis

Green hydrogen cost calculation

$CAPEX_{tech,y}$ — Initial investments for a given production technology $tech$ on year y
$OPEX_{tech,y}$ — Maintenance and operational costs for a given $tech$ and year y
$WACC_{tech,y,country}$ — Weighted Average Cost of Capital in the $country$ and year y per $tech$
$E_{tech,cell}$ — Annual energy output per $tech$ on a production $cell$ in kilograms of hydrogen
$CF_{h,tech,cell}$ — Capacity Factor: energy produced out of one kW of capacity installed, in kWh,per hour $h,tech$ on a production $cell$
$\eta_{electrolysis}$ — Consumption of electricity of the electrolyzer in kg/kWh
lt_{tech} — Lifetime of the production technology $tech$ considered

$$LCOH_{tech,y,country} = \frac{CAPEX_{tech,y} + \sum_{t=1}^{lt_{tech}} \frac{OPEX_{tech,y}}{\left(1 + WACC_{tech,y,country}\right)^t}}{\sum_{t=1}^{lt_{tech}} \frac{E_{tech,cell}}{\left(1 + WACC_{tech,y,country}\right)^t}}$$

$$E_{tech,cell} = \sum_{h=1}^{8760} CF_{h,tech,cell} \times \frac{1}{\eta_{electrolysis}}$$

Figure 26. Hydrogen production technology cost data including investment and operation and maintenance (O&M) costs

Technology	Efficiency (%)		Lifetime (years)		Overnight cost (US$/kW)		Fixed O&M costs (US$/kW)		Variable O&M costs (US$/kWh)[110]	
	2030	2050	2030	2050	2030	2050	2030	2050	2030	2050
SMR	75.8	75.8	25	25	934	934	44	44	0.8 – 1.47	1.68 – 2.11
SMR + CCS	72.2	72.2	20	20	1397	1314	42	39	0.47 – 1.18	0.67 – 1.22
GHR + CCS	83.3	83.3	20	20	870	870	27	27	0.48 – 1.13	0.46 – 0.85
ATR + CCS	73.5	73.5	15	20	812	812	24	24	0.50 – 1.20	0.48 – 0.92
Pyrolysis	57.1	57.1	20	20	2312	2312	104	104	0.2 – 1.09	0.14 – 0.71
Alkaline electrolysis	69	75	20	20	447	295	7	4	0.61	0.61
PEM electrolysis	64.5	80	7	9	585	440	17	13	0.61	0.61

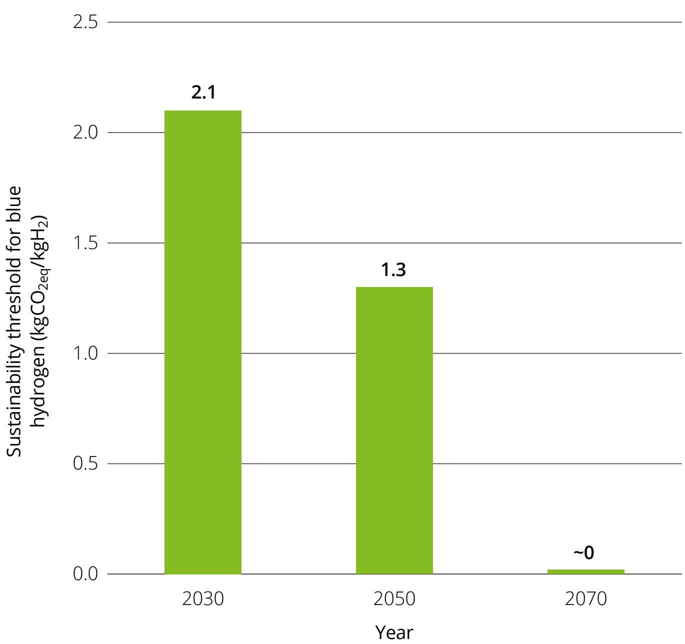
Source: Deloitte calculations, based on IEA,[111] Seck et al.[112] and Schmidt.[113]

Low-carbon hydrogen from natural gas

Deloitte has assessed the domestic consumption trajectories of natural gas-producing countries and their commercial balance for natural gas following the International Energy Agency (IEA)'s net-zero pathway in its 2022 World Energy Outlook.[114] All producing countries with a positive export balance and the main producing countries with negative balance (notably China, the United Kingdom, and the United Arab Emirates) were considered. Given that these countries have well-developed natural gas infrastructure, production facilities are assumed to be installed near the location of the current exit points for natural gas trade (pipeline and/or terminal) to avoid additional inland transport costs. The figures of natural gas production, commercial balance of natural gas, and reserves available for each considered country have been extracted from BP's most recent Statistical Review of World Energy.[115] The evolution of these figures are adjusted to be in line with the IEA's net-zero pathway,[116] assuming no new investments in exploration activities.

Blue hydrogen is considered to follow strict environmental standards to become available for global trade. This reasoning follows the definition of sustainable or low-carbon hydrogen that has appeared recently on policymakers' agendas such as the European Union (EU Taxonomy[117]), United Kingdom (Low Carbon Hydrogen Standard[118]), and United States (Clean Hydrogen Production Standard[119]) for the creation of sustainability standards. To date, one of the most stringent regarding the GHG footprint is the United Kingdom's, requiring blue hydrogen's GHG footprint in 2025 to be smaller than 2.4 $kgCO_{2eq}/kgH_2$, covering direct emissions along with methane emissions associated with natural gas supply. To help identify the blue hydrogen that can be traded over the outlook period, Deloitte extrapolated this most stringent standard of 2.4 $kgCO_{2eq}/kgH_2$ in 2025 to bring it to zero in the second half of this century, as reaching to net-zero means also a full Scope 3 emission reduction in the upstream as well as the downstream (figure 27). As blue hydrogen can never reach complete carbon neutrality—it is impossible to abate all of the upstream natural gas emissions and to capture all of the CO_2 released on the reformation—this implies a total phase-out of blue hydrogen by 2070. Such a constraint implies that blue hydrogen supply should peak no later than 2040, as the new investments in the reformation plants should be avoided from this date on to avoid stranded assets, assuming a plant lifetime of 30 years for reformers with CCS.

Figure 27. Sustainability threshold that natural gas-based low-carbon hydrogen should comply as a global tradability prerequisite



Source: Deloitte analysis based on the existing standards and global emission-reduction targets.

Two sets of natural gas-based low-carbon hydrogen supply technologies with corresponding technical and economic assumptions in figure 26 are assessed:

- *Reformers with CCS*: steam methane reforming (SMR), autothermal reforming (ATR), and gas-heated reforming (GHR), all coupled with carbon capture and storage (CCS). The calculation of the average cost of CO_2 transport and storage[120] follows the assumption that depleted oil and gas fields and rock formations are available within a reasonable distance around the production sites.[121]
- *Methane pyrolysis*, including carbon black by-product revenues, is assumed to be commercially available from 2030 onward.

The cost of natural gas supply for low-carbon hydrogen production follows regional natural gas prices of IEA's net-zero scenario, which were also reassessed and fact-checked by calculation of wellhead natural gas levelized supply cost for each region. The wellhead natural gas prices were verified by benchmarking them against typical average wellhead cost of basins of similar type for each region: onshore, deep, shallow, or ultra-deep. The estimated prices strongly converge with IEA's regional natural gas prices, as this study follows IEA's logic of no new investments in oil and gas exploration and production in a net-zero world. Calculated natural gas prices include no tax; nevertheless, this study accounts for the compensation for unabated CO_2 emissions (for reformers with CCS) as well as upstream methane emissions by assuming IEA's net-zero carbon price values for each considered region.[122]

Capture rate of CCS units are assumed to be 90% in the beginning of the outlook period, increasing linearly to 95% by 2050 which is considered to be the maximal carbon capture rate[123] . For each country, the climate footprint of blue hydrogen supply can be calculated via summing its residual CO_2 emissions (uncaptured CO_2 with CCS) and its upstream methane emissions (emissions associated with oil and gas exploration and production, gas gathering and boosting, and gas processing) from natural gas production until blue hydrogen production. These values are gathered from the country-specific scientific publications,[124] emissions reported to United Nations Framework Convention on Climate Change (UNFCCC), and IEA's Methane Tracker Database.[125] Then, these upstream methane emission values are converted to CO_2-equivalent (CO_{2eq}) terms considering a global warming potential[126] (GWP) of 20 years; GWP_{20} of methane is equal to 82.5 CO_{2eq}.[127] Deloitte assumes the adoption of best available technologies in methane abatement starting from 2040 and maturing by 2050, following different technologies' abatement potential in IEA's Methane Tracker Database.[128]

Commodity representation

This study considers the supply of pure hydrogen and its main derivatives as commodities that can satisfy the demand for clean hydrogen: ammonia (NH_3), methanol (CH_3OH), and synthetic aviation fuels (e-kerosene, following the $C_{12}H_{26}$ formula). The corresponding conversion costs from hydrogen and the specific transport costs for each commodity are calculated and follow a linear optimization logic. The constraints on the production capacities are shared for the different commodities, leading to an optimal choice of the commodity produced on each cell, to minimize the total cost of hydrogen and its derivatives' supply and delivery cost.

Midstream transport representation

Depending on the distance between production and delivery points, several transportation paths are currently envisaged and integrated into the modeling framework in accordance with the overall technology-neutral approach.

National transport of hydrogen

For national inland transports, multiple options are considered: hydrogen trucks (either with compressed hydrogen or ammonia trucks) and when available in the country, domestic hydrogen-repurposed gas pipelines. For the green hydrogen supply, also offsite production of hydrogen via electric grid (mainly for regions with advanced power grid such as Europe) is considered as an indirect hydrogen transport option. This means that green hydrogen is produced in the consumption points, via transporting renewable generation to the electrolyzers located in the consumption sites, via power grid. Hydrogen derivatives (ammonia, methanol, and SAF) are converted only at the consumption location for the domestic use, and at the export site for export purposes.

International transport of hydrogen

The main hydrogen transport options across countries are pipelines and maritime routes via tankers, transporting hydrogen or one of its derivatives. Assuming that continuously phasing out natural gas is necessary to reach climate-neutrality targets by 2050, it is assumed that natural gas pipelines could be partially repurposed for hydrogen transport by 2040, or sooner if a regional road map explicitly mentions it.[129] Some of these pipelines are expected to be unidirectional; others could allow bidirectional hydrogen flows for an optimal trade allocation. For calculating the LCOH component of hydrogen transmission by pipeline, assumptions on the interconnectors, its route, length, and capacity have been collected on Global Energy Monitor's Global Gas Infrastructure Tracker (figure 28).[130] It is assumed that repurposed pipelines can enable the same capacity of the natural gas pipelines before repurposing. Hydrogen injection to the pipelines is located according to the gas network topology and existing compression stations, where only a single injection and withdrawal point per country is considered.

Shipping is one of the most convenient options to transport hydrogen around the globe. The opportunity to develop the appropriate terminals for maritime trade has been enabled for every country geographically eligible; landlocked countries can still access the ports of their neighboring countries. Therefore, the HyPE model includes 95 seaborne terminals and more than 1,500 trade routes between them. Corresponding maritime distances are calculated assuming that the tankers can navigate the Suez Canal but not the Panama Canal.

Pure hydrogen can be transported as liquefied hydrogen, in Liquid Organic Hydrogen Carriers, or as converted ammonia before reconversion at the import terminal; the last option is the least expensive over long distances. Hydrogen derivatives can also be converted before being exported via shipping for reduced transport costs. Figures 29 and 30 present the cost assumptions for the transport of hydrogen and its derivatives.

Figure 28. Considered retrofitted pipelines

Exporting country	Importing country	Repurposing year	Max volume (MtH_2/year)	Length (km)
US	**CAN**	2040	15.1	3,848
US	**MEX**	2040	5.57	302
IRN	**TUR**	2040	3.71	2,577
NOR	**BEL**	2040	14.2	1,150
TUN	**ITA**	2030	6.17	155
DZA	**ITA**	2030	6.17	1,075
DZA	**ESP**	2040	3.10	757
DZA	**ESP**	2040	3.10	210
DZA	**ESP**	2040	4.80	1,082
MAR	**ESP**	2040	4.80	45
TUR	**GRE**	2040	3.07	110
RUS	**CHN**	2040	13.1	1,067
UZB	**CHN**	2040	6.12	1,645
KAZ	**CHN**	2040	7.65	1,115
TKM	**CHN**	2040	37.3	1,833

Source: Deloitte analysis based on Global Gas Infrastructure Tracker data.[131]

Figure 29. Grid, pipeline, and road transport costs for hydrogen and derivatives

Transport option	Production	Conversion[132] (if any)	Transport[133]	Reconversion (if any)		Unit
Electricity transport via the grid for hydrogen production in consumption point	**From all renewable energy sources available in the cell**		**Grid**		Injection point (Consumption cluster or exporting terminal)	US$/kg$H_2$/1000km
			(2030) Cost = 0.45 D *(2050) Cost = 0.39 D* *D: Distance*			
Pipeline	**From all sources available in the cell** — Depends on the technology and resources available		**Hydrogen pipelines**			
			Cost = 0.13 D + 0.01 *D: Distance*			
Road trucks			**Gasified trucks**			
			(2030) Cost = 3.02 D + 0.29 *(2050) Cost = 2.92 D + 0.27* *D: Distance*			
Hydrogen transport via liquid ammonia trucks		**Ammonia synthesis**	**Liquid methanol trucks**			
Liquid ammonia trucks		*(2030) 0.44* *(2050) 0.35*	*(2030) Cost = 0.66 D + 0.05* *(2050) Cost= 0.51 D + 0.03* *D: Distance*	**Ammonia catalytic cracking** *(2030) 0.27* *(2050) 0.22*		
Methanol trucks		**Methanol synthesis**	**Liquid methanol trucks**			
		(2030) 1.60 *(2050) 1.36*	*(2030) Cost = 0.51 D + 0.03* *(2050) Cost= 0.39 D + 0.02* *D: Distance*			
Synthetic aviation fuel trucks		**SAF synthesis**	**Liquid SAF trucks**			
		(2030) 1.50 *(2050) 1.26*	*(2030) Cost = 0.16 D + 0.01* *(2050) Cost= 0.13 D + 0.01* *D: Distance*			

Source: The Hydrogen 4EU project.[134]

Figure 30. Shipping costs for hydrogen and derivatives

Transport option	Commodity at the exporter port		Conversion[135] (If any)	Transport[136]	Reconversion (If any)		Commodity at the importer port	Unit
Hydrogen shipping via liquified hydrogen	Hydrogen	New dedicated exporting terminals including storage		**Liquified hydrogen shipping** *(2030) Cost = 0.09 D + 0.88* *(2050) Cost= 0.08 D + 0.68* *D: Distance*		Importer ports: refurbished dedicated importing terminals	Hydrogen	US\$/kgH_2/1000km
Hydrogen shipping via ammonia	Hydrogen		**Ammonia synthesis** *(2030) 0.44* *(2050) 0.35*	**Liquified ammonia shipping** *(2030) Cost = 0.02 D + 0.09* *(2050) Cost= 0.01 D + 0.07* *D: Distance*	**Ammonia catalytic cracking** *(2030) 0.27* *(2050) 0.22*		Hydrogen	
Ammonia shipping	Hydrogen		**Ammonia synthesis** *(2030) 0.44* *(2050) 0.35*	**Liquified ammonia shipping**			Ammonia	
	Ammonia			*(2030) Cost = 0.02 D + 0.09* *(2050) Cost= 0.01 D + 0.07* *D: Distance*				
Methanol shipping	Hydrogen		**Methanol synthesis** *(2030) 1.60* *(2050) 1.36*	**Liquified Methanol shipping**			Methanol	
	Methanol			(2030) Cost = 0.01 D + 0.08 (2050) Cost= 0.01 D + 0.06 D: Distance				
Synthetic Aviation Fuels shipping	Hydrogen		**SAF synthesis** *(2030) 1.50* *(2050) 1.26*	**Liquid SAF shipping**			Liquified Ammonia shipping	
	SAF			*(2030) Cost = 0.01 D + 0.03* *(2050) Cost= 0.01 D + 0.02* *D: Distance*				

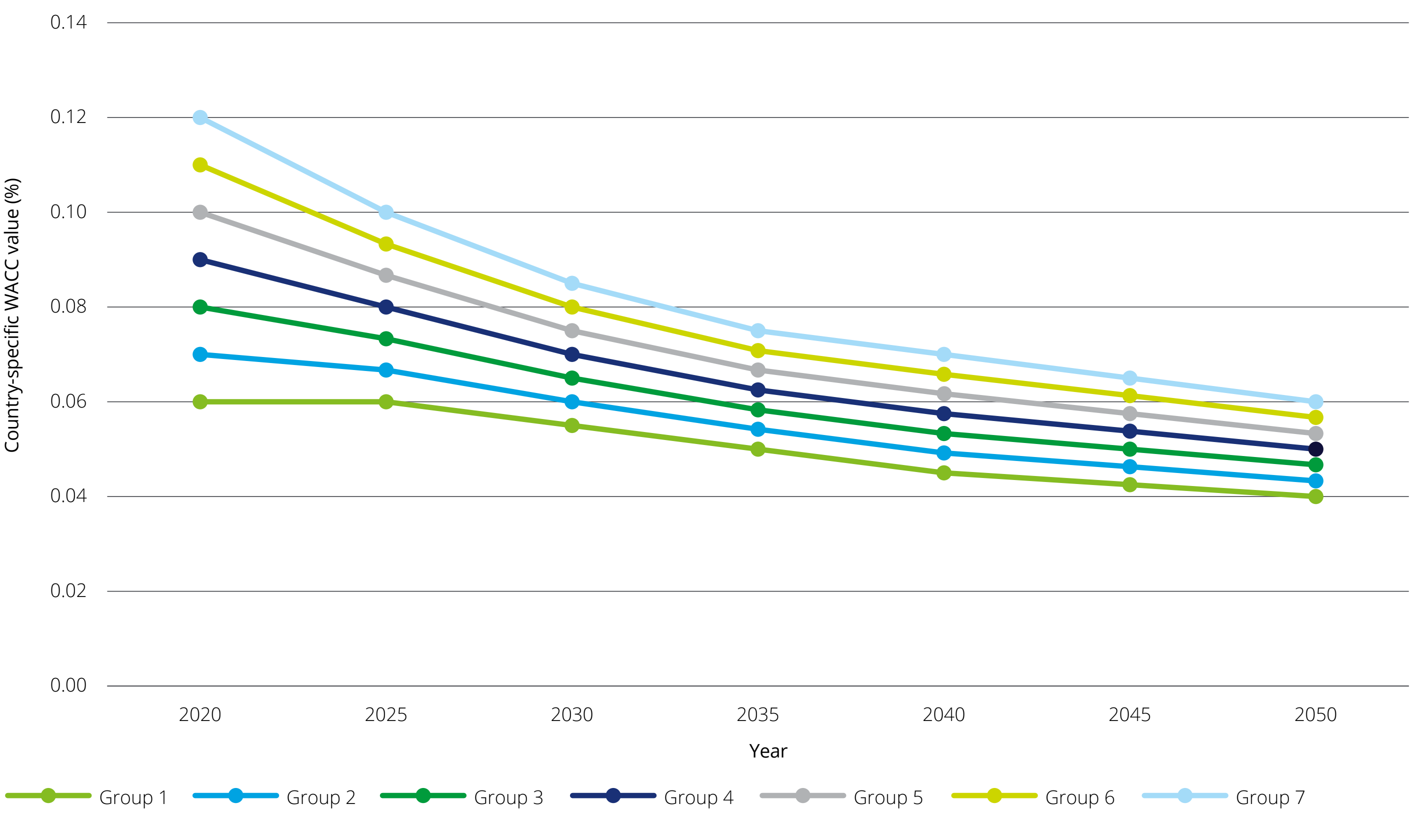
Source: The Hydrogen 4EU project.[137]

Calculation of country-specific cost of capital

As any investment, the cost of capital of clean hydrogen projects should reflect their risk profile, including local regulatory and political risks. This can affect LCOH calculation. In practice, countries are divided into seven different groups, according to the Organization for Economic Co-Operation and Development (OECD) country risk classification for officially supported export credits.[138] The lower and upper bound of current WACC levels are derived from International Renewable Energy Agency calculations,[139] while future values are extrapolated to match the expectations found in the literature. This methodology allows to approximate a country-dependent risk-adjusted weighted average cost of capital for the LCOH calculation.

The study considers a range of WACC going from 6% in 2020, in economically stable regions and countries such as Western Europe, North America, and Australia, to more than 12% in countries such as Iran or Argentina that face long-lasting political or monetary instability (figure 31).[140] WACC trajectories are decreasing, as progressive adoption of hydrogen technologies and uptake in demand will likely lower projects risks and are converging across country groups, which models the effects of creating financial risk transfer mechanisms or resorting to concessional (or international) finance.

Figure 31. Country-specific WACC used in LCOH computations



Source: Deloitte estimates based on OECD country risk classification.

Note: Groups of countries and regions are defined by the following classification. Group 1: Europe, North America, Australia, Chile. Group 2: China, Saudi Arabia, United Arab Emirates. Group 3: India, Qatar, Mexico, Morocco. Group 4: Colombia, South Africa. Group 5: Brazil, Egypt, Turkey. Group 6: Namibia, Nigeria, Ukraine. Group 7: Argentina, Iran, Tunisia.

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126. Global warming potential (GWP) is one of the most widely used climate metrics to assess the relative potency of different GHG emissions (such as CH_4), in comparison to the reference gas: CO_2. GWP can be estimated over a chosen time frame, 20 (GWP_{20}) and 100 (GWP_{100}) years being the most common time frames. Both metrics have evolved to be default metrics in the policy arena. Most scientific literature, assessing the impacts of greenhouse gases on climate change, assess longer time effects, using GWP_{100}. However, the most recent IPCC assessment report highlights that the metric depends on the considered context and the period during which the CO_2 emissions should be stabilized in the atmosphere.
127. According to Sam Abernethy and Robert B. Jackson, "Global temperature goals should determine the time horizons for greenhouse gas emission metrics," Environmental Research Letters Vol. 17, No. 2, February 9, 2022, in case of choosing GWP as the metric, the considered reference GWP period should include the period between the assessment year (2023) and the methane concentration stabilization year (2045), that is closest to GWP20.
128. More precisely, the Hydrogen4EU, "Hydrogen for Europe: Charting pathways to enable net zero," BAT adoption timeline has been postponed to 2040 to account for this study's global scope.
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130. Following the European REPowerEU plan (in response to Russia's invasion of Ukraine), the current study excludes potential commodity trades between Russia and the OECD countries from the trade options.
131. Global Energy Monitor, "Global gas infrastructure tracker."
132. Conversion and reconversion costs account for the investment costs of the conversion reactors and electricity consumption for the processes. Electricity prices are modeled and calculated separately for each country and vary between US$15/MWh and US$150/MWh in 2030 and US$20/MWh and US$175/MWh in 2050, depending on the considered country.
133. Transport costs account for the investments and operation and maintenance costs of the electric transmission lines and associated power electronics for the transport via power grid, for investments in vehicles, compression, and fuel costs for transport via trucks and for the refurbishment and compression costs for transport via refurbished natural gas pipelines. Methanol and synthetic aviation fuels can be transported in the same tankers as ammonia. Therefore, fixed and variable transports costs of these hydrogen derivatives can be derived from the extrapolation of transports costs of ammonia via a stochiometric analysis based on their mass and volumetric energy densities.
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135. Conversion and reconversion costs accounts for the overnight costs of the conversion and reconversion reactors, for their annual operation and maintenance costs and for the electricity consumption for the conversion and reconversion processes. This analysis models and calculates electricity prices separately for each country; they vary between US$15/MWh and US$150/MWh in 2030 and US$20/MWh and US$175/MWh in 2050, depending on the country.
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140. Groups of countries and regions are defined by the following classification. Group 1: Europe, North America, Australia, Chile. Group 2: China, Saudi Arabia, United Arab Emirates. Group 3: India, Qatar, Mexico, Morocco. Group 4: Colombia, South Africa. Group 5: Brazil, Egypt, Turkey. Group 6: Namibia, Nigeria, Ukraine. Group 7: Argentina, Iran, Tunisia.

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