Deloitte.

Hydrogen
Pathways to decarbonization

Key enabling role of hydrogen

The many colors of hydrogen

Despite hydrogen being the most abundant element in the universe (Britannica, 2022), on earth it can rarely be found in pure form (International Renewable Energy Agency (IRENA), 2022a). It is typically bound with oxygen to form water or with carbon to form different hydrocarbons like fossil fuels (National Grid, 2022a). Therefore, hydrogen cannot be extracted (unlike oil or natural gas) but must be produced, expending energy. Let's start by clarifying the most important terminology around hydrogen production technologies as it is standard use in the industry (National Grid, 2022b).

- **Grey hydrogen** is steam methane reforming of natural gas. This is today's dominant production technology. It is highly carbon intensive.
- **Blue hydrogen** is steam methane reforming in combination with carbon capture and storage technology. This reduces the carbon intensity of the hydrogen substantially but does not bring it to zero (due to failure to capture all emissions – both CO_2 and methane from natural gas). It is therefore also called low-carbon hydrogen.
- **Green hydrogen** is producing hydrogen from water via electrolysis using electricity generated by renewable energies (i.e., solar photovoltaic (PV), wind, and hydropower). If the electricity is 100% renewable, green hydrogen is carbon free.
- **Turquoise hydrogen** (from pyrolysis of natural gas) or pink, sometimes also called red hydrogen (from nuclear), are technologically less advanced.

Clean hydrogen refers to green hydrogen as well as blue if it complies with stringent standards on methane emissions and CO_2 capture.

Role of hydrogen in decarbonization

Hydrogen as a potentially clean enabler of the decarbonization of our energy system has received a lot of attention in recent years. While Green hydrogen has been in focus with lots of talks, events, and studies, the actual role in production was still very low. Now, we see a tangible shift in market relevance towards bankable projects and more attractive investment opportunities.

Today, globally, some 95 million tons of hydrogen are produced, virtually all grey hydrogen. This hydrogen is primarily used in refineries to upgrade fuels or in the chemical industry (e.g., to produce ammonia (International Energy Agency (IEA), 2022a). Hydrogen is therefore currently mainly used as feedstock, not as energy. In a net-zero scenario by 2030, green hydrogen will need to account for two-thirds of the market with the remaining covered by blue hydrogen with robust carbon capture and storage (CCS) technology, Deloitte Center for Sustainable Progress' (DCSP) analysis shows (Analysis based on DCSP's in-house global hydrogen trade model HyPE). Replacing existing grey hydrogen production with green hydrogen or blue hydrogen is therefore a natural starting point to help reduce global CO_2 emissions markedly. Using hydrogen as energy – next to its use as feedstock – could be a key element on the pathway to net-zero emissions (Seck, et al., 2022). Clean hydrogen molecules will start to play a critical role in the decarbonization of the hard-to-abate sectors, such as fuel for high temperature processes and heavy-duty transport (due to energy density to weight ratio of batteries), and to store electricity from variable renewables (International Renewable Energy Agency (IRENA), 2022b). However, using hydrogen as energy only makes sense if the hydrogen has a higher value than the energy that was initially spent to produce it. This requires rapid and robust scaling of technologies such as electrolyzers.

The hydrogen market outlook (demand and supply)

The growing clean hydrogen demand from the hard-to-abate sectors

Clean hydrogen provides a crucial pathway to help decarbonize hard-to-abate sectors such as heavy industry and transport. Research findings from the DCSP analysis conclude achieving net-zero by 2050 globally requires the development of a clean hydrogen market capacity of 170 million tons (MtH_{2eq}) by 2030 and growing to nearly 600 MtH_{2eq} by 2050 (Figure 1) [1].

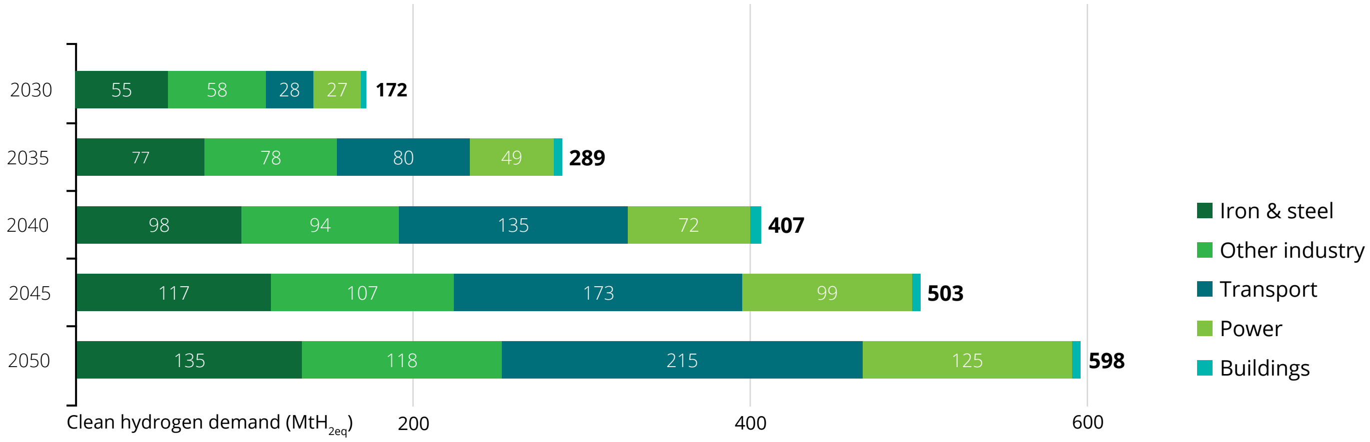


Figure 1: Global hydrogen demand by major economic sector
Source: Deloitte analysis based on (International Energy Agency (IEA), 2022c) (DNV, 2022)

According to DCSP's analysis, the demand may initially be driven by the decarbonization of existing industrial uses of hydrogen, notably for ammonia production. A net-zero transition may then underpin fast growth in demand, cementing the role of hydrogen as a versatile solution to decarbonization. By 2050, industry sectors (e.g., iron and steel, chemicals, and cement) and transport (e.g., aviation, shipping, and heavy road transport) will likely account for 42% and 36% of total clean hydrogen demand respectively (Hydrogen4EU, 2022) (Seck, et al., 2022) (International Energy Agency (IEA), 2022a). Overall, clean hydrogen can help deliver crucial carbon emission reductions, abating up to 85 $GtCO_{2eq}$ in cumulative emissions by 2050[2]. Used directly as pure hydrogen, or as feedstock to produce more suitable derivatives that are adapted to certain industrial applications and infrastructure, such as ammonia, methanol, or sustainable aviation fuels (SAF), DCSP research suggests clean hydrogen will likely be a global market from day one. While demand will start in industrialized economies, the hydrogen economy is also a major sustainable growth opportunity for developing countries.

[1] Deloitte analysis regarding the clean hydrogen outlook

[2] Clean hydrogen can replace coal, oil and natural gas both as feedstock and energy source. The avoided emissions in the corresponding sectors are equal to the carbon footprint of the replaced fossil in a counterfactual consumption trajectory. For instance, in residential heating, 1 kJ of hydrogen replacing 1 kJ of natural gas avoids 7.28 gCO_2 of direct CO_2 emissions (based on LHV values of hydrogen and methane molecules). Similarly, hydrogen-based process can replace fossil-based processes, with no direct emissions. In this case, abated emissions are calculated on a counterfactual supply trajectory based on the carbon content of fossil-based products. For instance, in steelmaking, coal can be replaced by hydrogen-based direct reduction process, avoiding 1.9kgCO_2 that would have been otherwise emitted via conventional coal-based process to produce 1 kg steel. Summing up the avoided emissions for each sector gives the overall decarbonization potential of hydrogen

Sectors			Role of clean hydrogen	Timing		
				2030+	2040+	Comments
Industry	**Steel**	H	**Reduction agent** for DRI or BF-BOF and for high temperatures	✓	✓	**Voluntary demand,** but long assert replacement times
Industry	**Ammonia**	H	Feedstock to **produce ammonia**	✓	✓	**Ease of asset replacement,** as H_2 is already used
Industry	**Methanol**	H	Feedstock to **produce methanol**	✓	✓	
Industry	**Refining**	H	Feedstock for **hydro-cracking and -treating**	✓	✓	
Industry	**Other chemicals**	M	Feedstock and / or fuel for **steam cracking**	—	—	Depending on **economics** (vs. e-cracking)
Industry	**Cement**	M	**Booster fuel** to increase calorific value	✗	—	**Unfavorable short-term econimics** (vs. biomass used)
Industry	**Other Industry**[1]	L	Most can be **direectly electrifies / niche applocations**	✗	—	Depending on **economics**
Mobility	**Road freight**	H	Fuel in **heavy-duty long-haul** transport	✓	✓	**Voluntary demand** and **favorable economics**
Mobility	**Shipping**	H	Fuel in international shipping in the form of **H2, ammonia** or **methanol**	—	✓	Lack of **technology alignment and maturity**
Mobility	**Aviation**	H	**Direct use** or as **feedstock** to produce **Sustainable Aviation Fuel** (SAF)	✓	✓	**Regulatory pressure** (EU) and **no asset changes** needed
Mobility	**Cars**	L	**Electrification possible** and more economic	✗	✗	
Mobility	**Trains**	M	Fuel to **replace diesel engine trains** in long-haul transport	✗	—	
Build	**Residential**	L	Heating alternative in case of **economic limitations of electrification** (e.ge., high cost to electrify buildings with poor insulation)	✗	—	Expected to **first start in areas where electrification is economic**
Build	**Commercial**	L		✗	—	
Power[2]		M	Balance intermittency from renewables through **storage**	✗	—	Required **when renewables reach high share in the mix**

Notes: 1 Incl. Non-ferrous metals, food, paper, pulp, glass, ceramics, wood, machinery, agriculture, textile and manufacturing;
2 Also in the form of ammonia;

Table 1: Demand per sector, where and when

Source: DCSP analysis based on (International Energy Agency (IEA), 2021))

The global emergence of hydrogen supply

The Green Hydrogen Market Outlook by the DCSP[3] shows that the clean hydrogen market will steadily grow from US$640 billion in annual revenue in 2030 to US$1.41 trillion in 2050. Until 2030, market growth is underpinned by the greening of current demand (95 MtH_{2eq}). Projects initially depend on public support to breakeven, as illustrated by the first major schemes such as the European Union (EU) Fit-for-55 package (EU Policies Green Deal, 2022) and IPCEI (Important Projects of Common European Interest) funding program (European Commission, 2020), the German H2Global mechanism (H2Global Stiftung) and Power-to-X (PtX) funds (KfW Entwicklungsbank), or the US Inflation Reduction Act (The White House, 2022).

Green hydrogen will dominate the supply mix from the beginning and reaches 85% of the market (above 500 MtH_{2eq}) by 2050, becoming over time the most competitive clean hydrogen technology (Figure 2). Blue hydrogen will be a useful transition technology to build up demand or as a complementary solution to facilitate the emergence of the hydrogen economy, especially in regions that can leverage natural gas reserves such as the Middle East, North Africa, North America, and Australia, with production peaking in 2040 at almost 125 MtH_{2eq} (30% of supply). Blue hydrogen will be ultimately crowded out by rising competitiveness of green hydrogen and increasingly tight environmental constraints regarding unabated methane and CO_2 emissions.

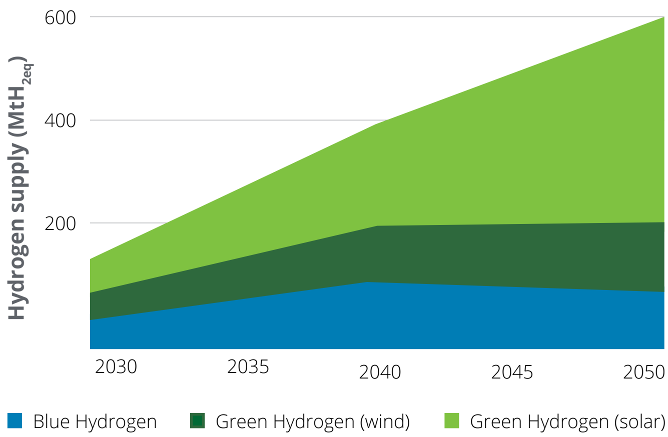


Figure 2: Global clean hydrogen production evolution between 2030 and 2050 by technology type[4]

For many clean hydrogen solutions to emerge, a significant cost disadvantage to grey alternatives must be overcome. For example, EU green hydrogen adoption in ammonia production is expected to not be competitive by 2030 if natural gas prices recover in the coming years (as per International Energy Agency's EU natural gas price outlook in the latest world energy outlook scenarios (International Energy Agency (IEA), 2022c)) and no additional regulatory incentives are created. Therefore, a set of success factors are needed to help promote and accelerate this development.

[3] The following results are based on the results of the DCSP global hydrogen trade model, HyPE.
[4] DCSP analysis based on its international hydrogen trade model, HyPE

Success factors for the hydrogen transformation

Five success factors

There are five factors that are needed to accelerate the deployment of clean hydrogen:

1. **Demand:** The industry needs consolidated, voluntary demand that then in turn starts to stimulate regulated demand. This could happen through new green value propositions and "book and claim" schemes (Pechstein, Bullerdiek, & Kaltschmitt, 2020).
2. **Regulations:** A new nomenclature of the Hydrogen Emission Intensity Index (HEII) is needed. The industry could benefit from simple, synchronized regulations across demand and supply and fast releases of permits.
3. **Technology:** For the demand side, research and development is needed for the maturation versus alignment on required technologies and fuels. Furthermore, the supply side needs to be developed with the scaling up of supply chains.
4. **Assets and infrastructure:** Asset reuse should be maximized with faster asset change cycles. More focus needs to be put on the infrastructure.
5. **Collaboration:** New commercial and business models are needed, and a focus should be put on the acquisition of talent.

Hydrogen hubs

The conditions discussed to accelerate hydrogen development at scale can be brought together by forming hubs. This concept has been proven successful throughout history and can again serve as an accelerator for the industry transformation. Hubs can be defined simply as geographic areas with sufficient low-cost resources to produce clean hydrogen and/or critical mass of clustered off-takers, favorable regulatory environment, and willingness to collaborate to help drive down costs of the hydrogen value chain through economies of scale and reduced infrastructure needs.

There are three forms of hydrogen hubs emerging:

- **Supply and demand hubs** are expected to play a big role in activating hydrogen deployment at local scale by creating supply chains and bringing down costs. These hubs will likely emerge in regions where sufficient local supply of clean hydrogen can be developed economically to meet demand of large local industrial customers. Density minimizes transportation complexity and costs (e.g., no need to ship over long distances), and maximizes economies of scale and governments are willing to facilitate supply and demand development through transparent regulation, standards, and frameworks. Asset sharing, synergies, and willingness to collaborate across sectors will be a major factor.
- **Supply-led hubs** are likely to evolve in regions like the Middle East or US Gulf Coast where the scale of production capacity exceeds local demand, and/or where the economics can compete in certain export markets with a higher willingness to pay due to lack of alternatives or overall dearth in supply. There is an important debate that is emerging around social license and the importance of using hydrogen to improve the social welfare of countries and prioritizing that versus exporting it. This is a valid argument which countries and governments are raising in their national plans.
- **Demand-led hubs** are geographies with a structural domestic supply shortage due to lack of renewables, natural gas, or CO_2 storage capacity. Examples here are Japan and South Korea who are switching from Liquid Natural Gas (LNG) dependence towards hydrogen, with some ability to produce it locally at smaller scales. We see bi-lateral trades emerging first, with potential for some of these demand centers and offtakes to invest in supply as mentioned before.

Hubs by definition require a new approach to ecosystem collaboration, requiring companies across sectors (even former competitors) to collaborate and sometimes share infrastructure, leading to "co-opetition" amongst hub members that can accelerate innovation and scale mutual benefits. Here, the five success factors come together forming a true catalyst of industry transformation.

As outlined, policy and regulation can play a crucial role as accelerator to the hydrogen transformation. Thus, the final section is dedicated to a policy overview and recommendations for future policy instruments.

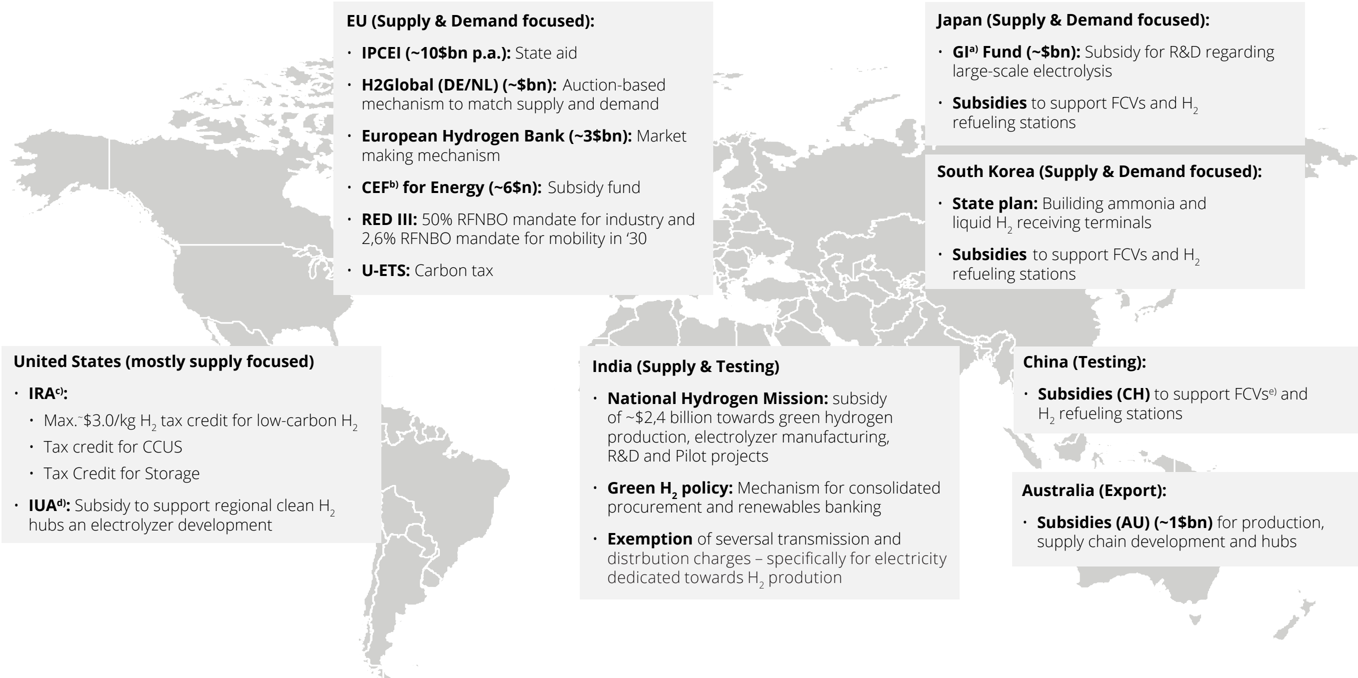
Geographical and policy aspects

Different emerging policy archetypes

Decisive policy support is needed to scale up the clean hydrogen economy and help ensure that green hydrogen plays its needed role on the path to net-zero. To date, over 130 countries (83% of global carbon emissions) have announced national net-zero targets (Net Zero Tracker, 2022). However, according to International Energy Agency (IEA), clean hydrogen projects announced worldwide would at best provide a collective production capacity of only 44 MtH_{2eq} by 2030 (International Energy Agency (IEA), 2022b), a quarter of the demand scenario. Active policy support will be needed at least until the mid-2030s, when green hydrogen technologies could catch up with fossil-based alternatives in terms of costs. Currently, the production cost of grey hydrogen does not sufficiently reflect its impact on climate. Targeted policy support to green hydrogen is therefore crucial to ensure the first projects can compete on a level playing field and enter the market.

- **Demand- and supply-side focus:** The EU, for example, is deploying demand-side mandates such as RED III and carbon pricing (EU-ETS) to make green hydrogen competitive with grey alternatives, as well as supply side subsidies (e.g., IPCEI) to ensure security of supply through local production (European Commission, 2022). Additional mechanisms are currently still being defined (e.g., Hydrogen Bank) (EU Publications, 2021).
- **Supply side focus:** The US has recently deployed the Infrastructure and Investment Jobs Act (IIJA) (The White House, 2022) and Inflation Reduction Act (IRA) (The White House, 2022), which provide (tax) incentives for producers of low-carbon molecules, including hydrogen. It provides a tax credit of US$0.6 – 3 per kg for clean hydrogen, providing a significant push for producers to move post-Final Investment Decision and proceed with implementation. The scale and generous support of the IRA impacts global market dynamics, attracting (and shifting) investments from other regions. The IRA benefits can even make US green hydrogen export to the EU (including transport and cracking) competitive in comparison with EU locally produced green hydrogen. Other regions are therefore working to respond with new measures to maintain competitiveness.
- **Export-driven:** Australia is providing supply-side subsidies for blue and green hydrogen production and hub development (approximately US$200 million/AU$300 million national (Clean Energy Finance Corporation, 2022) and US$335 million/AU$500 million regional funds (energy.gov.au, 2022), plus further local incentives, such as a 90% exemption from water costs for green hydrogen production, announced by New South Wales with additional regional incentives (e.g., New South Wales announced up to 90% exemption of electricity cost for green hydrogen production (NSW Government, 2022)). While the focus started on stimulating export driven by the availability of low-cost (renewable) resources, focus on local demand is picking up, with some delays in the export projects.
- **Testing:** China is currently starting to grant demand-side subsidies to the mobility segment (International Energy Agency (IEA), 2022e), and India is exempting renewables for green hydrogen from transmission and distribution charges and drafting demand obligations for some sectors (International Energy Agency (IEA), 2022d). More clarity on their approaches is expected to emerge in the next years.

Overall, while regulatory incentives are not mature yet and policy support is necessary for large-scale change, there are existing policies today that can help drive investments and change.



Notes: List of regulatory instruments is not exhaustive, but only includes highlights; a) Connecting Europe Facility; b) Inflation Reduction Act; amount depends on total lifecycle CO_2 emissions; c) Fuel cell vehicles; d) Green innovation; e) Contracts for Difference

Figure 3: Overview on regulatory archetypes by region

Source: Deloitte analysis

Recommendations for future policy developments

Policy attention should focus on three components: (1) **Creating a business case**. Use of targeted policy instruments (e.g., mandatory green premiums, Carbon-Contracts-for-Differences, tax credits, and offtake contracts) may reduce the cost-difference between clean and polluting technologies. Long-term offtake mechanisms (such as the German H2Global) can substantially mitigate projects risks, bridge the gap between price and willingness to pay, and strengthen price stability; (2) **Laying the foundations for a climate-oriented market structuring**. A robust and shared certification process for clean hydrogen will be decisive to help ensure transparency and avoid technological lock-ins. International cooperation to implement national strategies will also be needed to help ensure level playing field, strengthen synergies with development and climate objectives and promote strong local content. (3) **Building long-term resilience**. The award of public support (e.g., EU Global Gateway), and more broadly the establishment of energy relationships, should integrate diversification and inclusion targets to foster regional integration. Fair development implies that developing and emerging countries capture parts of the global value chain. More broadly, economic development based on political stability and human rights should be promoted.

Adopting a terminology that goes beyond a binary color classification, can help to encourage investments and emission reduction. A possible approach to create immediate impacts and bridge the gap while long term investments are being ramped up could be the adoption of the Hydrogen Emission Index (HEII): The HEII takes into account both emission and economic considerations of different hydrogen production technologies. Depending on regional specifics, a more economically viable solution could be found that still provides a significant reduction in carbon intensity in the short term while shifting down the cost curve of cleaner solutions. For example, developing electrolysis-based hydrogen production and initially blending both renewable and carbon-intensive electricity can increase the load factor of electrolyzers and operate at lower production cost while reducing emission intensity and addressing demand. Over time, while capacity is being built, assets and infrastructure will move down the cost curve (e.g., electrolyzers), which also reduces the production cost of hydrogen projects with a lower HEII. This needs to be supplemented by policies that strongly encourage increased adoption of lower-emission intensity technologies (i.e., moving to a lower acceptable HEII) within a clear timeframe. Industry leaders and governments need to come together to detail, refine and align on such an approach, as well as develop assurance mechanisms.

References

Britannica. (2022). Retrieved from https://www.britannica.com/science/hydrogen

Clean Energy Finance Corporation. (2022). Retrieved from Advancing Hydrogen Fund: https://www.cefc.com.au/where-we-invest/special-investment-programs/advancing-hydrogen-fund/

DNV. (2022). Retrieved from Energy Transition Outlook 2022: https://www.dnv.com/energy-transition-outlook/download.html

energy.gov.au. (2022). Retrieved from https://www.energy.gov.au/news-media/news/500m-establish-powering-australia-technology-fund-through-cefc

EU Policies Green Deal. (2022). Retrieved from Fit-for-55: The EU plan for a green transition: https://www.consilium.europa.eu/en/policies/green-deal/fit-for-55-the-eu-plan-for-a-green-transition/

EU Publications. (2021). Retrieved from EUR-Lex: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32003L0087

European Commission. (2020). Retrieved from IPCEIs on hydrogen: https://single-market-economy.ec.europa.eu/industry/strategy/hydrogen/ipceis-hydrogen_en

European Commission. (2022). Retrieved from Renewable Energy Directive: https://energy.ec.europa.eu/topics/renewable-energy/renewable-energy-directive-targets-and-rules/renewable-energy-directive_en

H2Global Stiftung. (n.d.). Retrieved from h2-global: https://www.h2-global.de/

Hydrogen4EU. (2022). Retrieved from Hydrogen4EU - Charting pathways to enable net zero: https://www.hydrogen4eu.com/_files/ugd/2c85cf_e934420068d44268aac2ef0d65a01a66.pdf

International Energy Agency (IEA). (2021). Retrieved from Net Zero by 2050: https://www.iea.org/reports/net-zero-by-2050

International Energy Agency (IEA). (2022a). Retrieved from Hydrogen: Energy system overview: https://www.iea.org/reports/hydrogen

International Energy Agency (IEA). (2022b). Retrieved from Hydrogen Projects Database: https://www.iea.org/data-and-statistics/data-product/hydrogen-projects-database

International Energy Agency (IEA). (2022c). Retrieved from World Energy Outlook 2022: https://www.iea.org/reports/world-energy-outlook-2022

International Energy Agency (IEA). (2022d). Retrieved from National Hydrogen Mission: https://www.iea.org/policies/13949-national-hydrogen-mission

International Energy Agency (IEA). (2022e). Retrieved from Hydrogen Industry Development Plan (2021-2035): https://www.iea.org/policies/16977-hydrogen-industry-development-plan-2021-2035

International Renewable Energy Agency (IRENA). (2022a). Retrieved from Geopolitics of the Energy Transformation: The Hydrogen Factor: https://www.irena.org/publications/2022/Jan/Geopolitics-of-the-Energy-Transformation-Hydrogen

International Renewable Energy Agency (IRENA). (2022b). Retrieved from Geopolitics of the Energy Transformation: The Hydrogen Factor: https://www.irena.org/publications/2022/Jan/Geopolitics-of-the-Energy-Transformation-Hydrogen

KfW Entwicklungsbank. (n.d.). Retrieved from Integrated financing for green hydrogen - a perfect fit and from a single source: https://www.kfw-entwicklungsbank.de/Our-topics/PtX/

National Grid. (2022a). Retrieved from https://www.nationalgrid.com/stories/energy-explained/what-is-hydrogen

National Grid. (2022b). Retrieved from https://www.nationalgrid.com/stories/energy-explained/hydrogen-colour-spectrum

Net Zero Tracker. (2022). Retrieved from https://zerotracker.net/

NSW Government. (2022). Retrieved from NSW Climate and Energy Action: https://www.energy.nsw.gov.au/nsw-plans-and-progress/government-strategies-and-frameworks/nsw-hydrogen-strategy

Pechstein, J., Bullerdiek, N., & Kaltschmitt, M. (2020). A "book and Claim"-Approach to account for sustainable aviation fuels in the EU-ETS–Development of a basic concept. Energy policy.

Seck, G., Hache, E., Sabathier, J., Guedes, F., Reigstad, G., Straus, J., ... Cabot, C. (2022). Hydrogen and the Decarbonization of the Energy System in Europe in 2050: A Detailed Model-Based Analysis. Renewable and Sustainable Energy Reviews. doi: https://dx.doi.org/10.1016/j.rser.2022.112779

The White House. (2022). Retrieved from Inflation Reduction Act Guidebook: https://www.whitehouse.gov/cleanenergy/inflation-reduction-act-guidebook/

The White House. (2022). Retrieved from President Biden's Bipartisan Infrastructure Law: https://www.whitehouse.gov/bipartisan-infrastructure-law/

Authors

Tarek Helmi
Partner | Future of Energy Leader
thelmi@deloitte.nl

Bernhard Lorentz
Partner | Global Consulting
Sustainability & Climate Strategy Leader
blorentz@deloitte.de

Thomas Schlaak
Partner | Global Power, Utilities &
Renewables Leader
tschlaak@deloitte.de

Johannes Trüby
Partner | Economic Advisory
jtruby@deloitte.fr