NAVIGATING THE CURRENTS OF GREEN HYDROGEN

TOWARDS A HUMAN DEVELOPMENT-CENTRED FRAMEWORK

Knowledge Partners

TIDE CENTRE

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Table of Contents

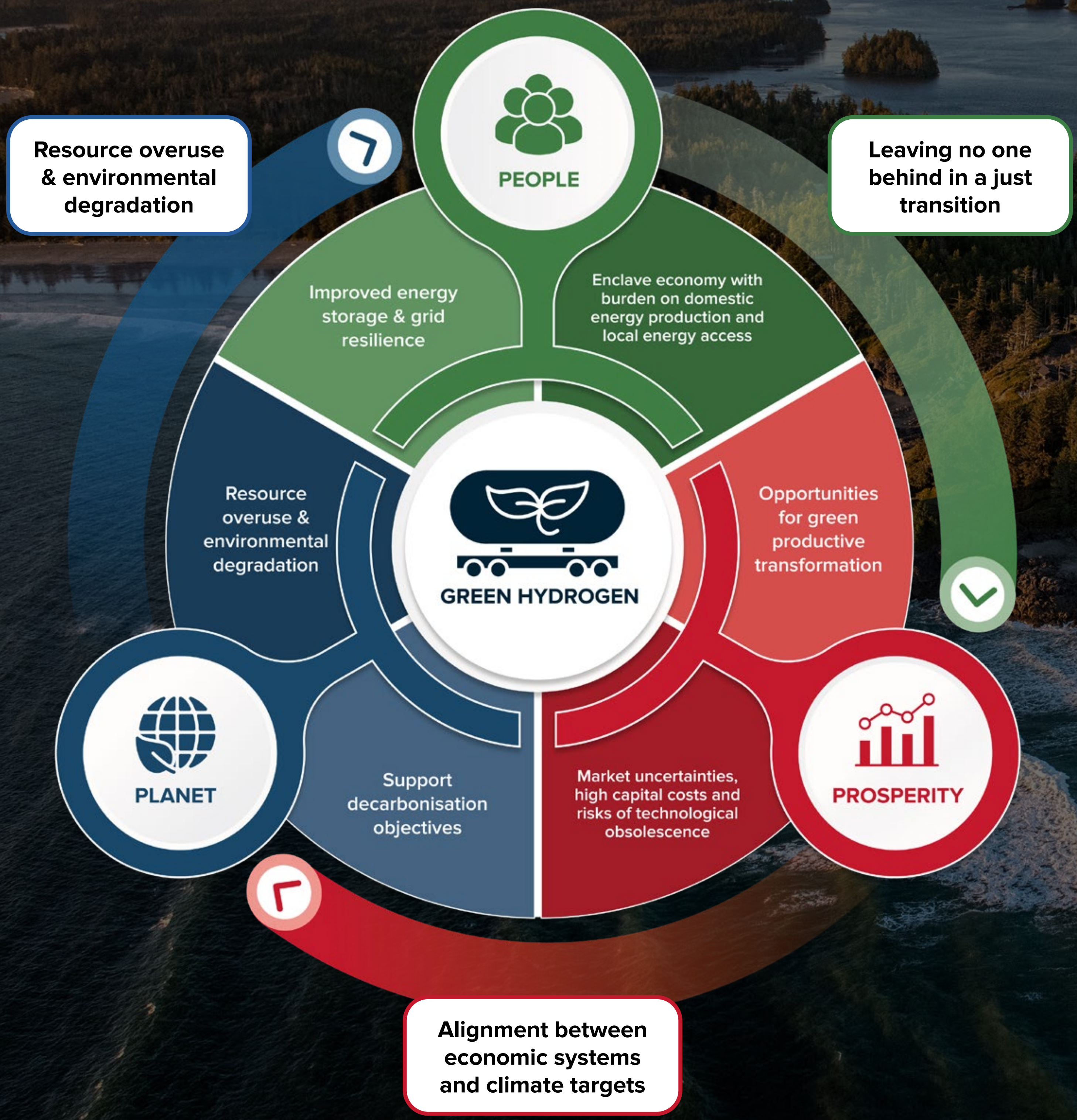
Executive summary and key messages

Although still an emerging technology prone to technological disruption and market uncertainty, green hydrogen is increasingly considered critical to global decarbonization. This is due to its versatility as an energy carrier, its capacity to store energy, and its potential to decarbonize sectors that are hard to electrify, including heavy industry, transport and others.

Green hydrogen represents an interesting opportunity for global development. Developing countries account for the majority of areas where production costs could be lowest (especially in Latin America, the Arab States, and North and Southern Africa). This cost advantage is largely driven by the growing competitiveness of renewable energy technologies, which are essential inputs for green hydrogen production.

At the same time, high levels of uncertainty, risk and technological disruption on both the demand and supply sides of the global green hydrogen sector require strong policymaking. This must see beyond the hype, and strategically allocate time and resources to make consistent links to sustainable development. Otherwise, if left unchecked, the growth of green hydrogen could reproduce extractivist dynamics and historical resource dependencies while failing to deliver long-term gains to producer countries in the Global South.

A careful rethinking of policy approaches to green hydrogen is needed so that this resource truly becomes a tool for sustainability, local development and human prosperity in ways that do not leave—much less push—anyone behind. A '3P' framework emphasizing people, planet and prosperity aligns the growth of green hydrogen with sustainable human development (Table 1). Such a framework not only entails looking at the financial and energy feasibility of green hydrogen projects but also their impact on local energy access, job creation, local ecological priorities and structural change.



PEOPLE

For green hydrogen to contribute to a just transition, its production needs to support—rather than come at the expense of—expanded energy access. In nations where shortfalls in energy access remain a challenge to human development, green hydrogen projects need to align with the priorities of full electrification and a resilient electricity supply.

This can be achieved by requiring investment projects to oversize renewable energy deployment and contribute to grid interconnections and infrastructural build-out. Further agreements can stipulate that the production of domestic renewable energy and green hydrogen should meet domestic energy demand first, with exports limited to excess production.

The creation of domestic green hydrogen sectors should also contribute to up-skilling labour and developing human capital more broadly, with targeted programmes and conditionalities on including local labour across the value chain.

PLANET

Large-scale green hydrogen projects will require significant land, water, energy and infrastructure requirements. If these dimensions are not well managed, green hydrogen projects may contribute to global climate goals while generating adverse environmental impacts and social injustices in the communities and ecosystems where it is produced.

Crucially, green hydrogen strategies should align with each country's ecological priorities and challenges, which can differ widely. Each government seeking to produce green hydrogen should develop strong internal environmental appraisal capabilities to identify risks, develop frameworks to manage potentially scarce resources (such as water) and uphold 'do no harm' principles.

PROSPERITY

Green hydrogen provides four distinct opportunities to promote economic development in the developing world, where we find most areas where it can be produced cost-competitively. But for the green hydrogen economy to support an agenda of sustainable industrialisation and resilience, strategic policy tools and the creation of technological foresight units are needed to reduce exposure to technological obsolescence risks and develop the right types of local linkages, aligned with development needs.

Furthermore, though many countries seek to position themselves as first movers in the green hydrogen sector, given the uncertainty surrounding future market demand and the rapid pace of technological disruptions, a cautious experimental approach may be more appropriate for many fiscally-constrained developing nations, where lessons from early entrants can inform more cost-effective and scalable hydrogen development strategies at more mature stages of the hydrogen learning curve.

Policy Recommendations

Countries developing green hydrogen sectors need to tailor strategies to national priorities and local realities, avoiding one-size-fits-all approaches. They may need to develop strong capabilities around industrial and energy policies to comfortably assess the rewards and risks of green hydrogen strategies, across ecological, social and economic domains. Developing a green agenda should extend beyond countries and international investors. To be successful, it needs to involve multistakeholder consultations with local communities, civil society, the local business community, trade unions and all key development actors. Such actors can play catalytic roles in steering the green hydrogen sector to improve energy access and human well-being.

One recommendation is to publish an annual report on the impact of green hydrogen projects on energy access. Since much of the existing discourse on the link between green hydrogen and energy access remains theoretical, such an effort could assess current and upcoming projects, paying particular attention to contractual and operational arrangements that may either enhance or undermine local energy access. This would help generate early insights that could inform the design of future projects based on consistently prioritizing and improving energy access. Compiling and disseminating a resource that brings together model contracts and legislation—an atlas of best practices—could provide valuable guidance to countries seeking to build robust policy and regulatory frameworks, ultimately strengthening their bargaining position in the hydrogen economy.

There is also scope for assessing the quality of employment generated by green hydrogen projects, with a focus on labour up-skilling and workforce development. Partnering with organizations such as the International Labour Organization (ILO) to support skills development in fields like chemical engineering and other foundational disciplines could further strengthen workforce readiness, particularly in developing countries.

Towards ecological sustainability, dedicated initiatives could promote the reuse and repurposing of decommissioned electrolysis technologies. Applying circular economy principles to manage obsolete equipment would help minimize environmental impacts and contribute to long-term sustainability. Comprehensive lifecycle analysis across the entire green hydrogen value chain—from renewable energy inputs to hydrogen production, storage, transport and end-use—is essential. It could accurately assess the real climate benefits of green hydrogen, identify potential emissions hotspots, and deliver genuine decarbonization outcomes aligned with national and global climate goals.

Table 1.
Summary of the 3P framework for green hydrogen

PEOPLE

OPPORTUNITY

- Expanding energy access, as around 600 million people in the world still lack access to electricity, one of the greatest resources for safe and sustainable livelihoods.
- Creating new decent jobs in renewable energy and up-skilling the labour force in general.

CHALLENGE

- Grid-connected projects with no strong additionality requirements may end up decreasing the total amount of electricity available, with a potentially nefarious effect on energy prices. If not mitigated through social compensation or protection, this could negatively impact consumers and increase energy poverty rates.
- In off-grid projects with dedicated renewable capacity, a key challenge is ensuring they contribute to local energy access, especially in underserved areas. Given high transmission costs, alternative benefit-sharing or support models may be needed to close access gaps.
- A lack of skills could lead to a low number of jobs for local populations and limited up-skilling.

NAVIGATING THE POLICY LEVERS

- Ensuring additionality, with the improvement of grid connections and infrastructure build-out.
- Incentives for the local provision of energy to local communities as part of hydrogen projects.
- Provisions for training, up-skilling and hiring the local labour force across the value chain.
- Clear fiscal and taxation frameworks to ensure sustainability of large-scale green hydrogen projects.

PLANET

OPPORTUNITY

- Decarbonization of several hard-to-abate sectors, especially where carbon emissions are high and electrification options are limited.

CHALLENGE

- Large-scale green hydrogen projects will require significant land, water, energy and infrastructure. They should not be used to address the decarbonization challenge at the expense of other ecological goals related to land degradation, water scarcity, biodiversity loss, etc..

NAVIGATING THE POLICY LEVERS

- Strong environmental appraisal capabilities to align green hydrogen projects with locally defined environmental priorities.

PROSPERITY

OPPORTUNITY

- New form of rent generation, job creation, improvement of the carbon cost competitiveness of various industries, and development of links with other sectors.

CHALLENGE

- Risks of falling into traditional patterns of commodity dependence.
- Risks of debt burdens as the initial investment required to develop a green hydrogen economy is substantial.
- First-mover disadvantages and risks of technological obsolescence if countries develop green hydrogen projects at the height of the learning curve.

NAVIGATING THE POLICY LEVERS

- Integrating green hydrogen in broader development policy with clear and well-defined objectives.
- Creation and reliance on technology foresight units to anticipate potential disruptions and identify opportunities for local linkages in the hydrogen value chain.
- Cautious experimentation through pilot projects and phased investments, rather than large-scale investments at the outset, to allow learning and adaptation based on technological advancements, market developments and regulatory frameworks in early adopting nations.

A DEFINITION OF GREEN HYDROGEN

Green hydrogen is defined as molecular hydrogen (H_2) produced through the electrolysis of water using electricity generated exclusively from renewable energy sources such as solar, wind or hydropower. This process results in negligible direct greenhouse gas emissions, distinguishing it from other forms of low-carbon hydrogen, which may involve fossil fuel-based production with carbon capture and storage. As an energy carrier, green hydrogen offers a technologically versatile pathway to decarbonize sectors where direct electrification is technically or economically unfeasible, including heavy industry, shipping and long-duration energy storage.

01. INTRODUCTION

Green hydrogen, harnessed thoughtfully, can carry nations towards energy and economic transformations. Yet without a clear direction, this process can trigger unintended risks.

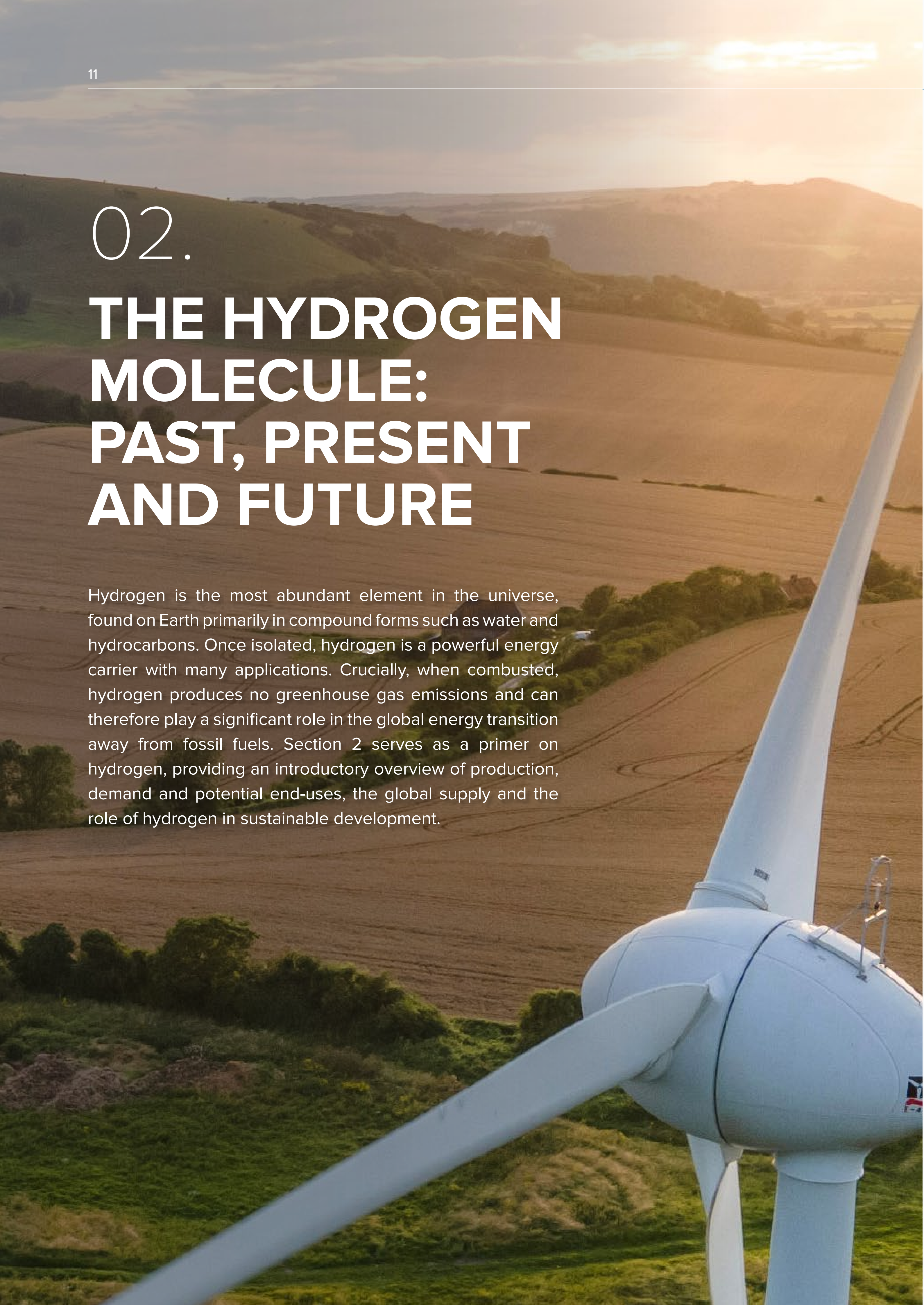
Produced via electrolysis using renewable electricity, green hydrogen holds significant potential to decarbonize myriad end-uses, foster industrial diversification and drive economic prosperity. Its potential for development is especially significant in renewable resource-rich developing countries. Forecasted to be the main production centres of green hydrogen, some of these countries are already developing ambitious strategies to take advantage of this potential opportunity. For this emerging sector to support human development without recreating historical patterns of dependency and extractivism, however, countries must guide it with care. Applying a '3P' or people-planet-prosperity framework can align national capabilities, ecological safeguards and local community voices. It can assess risks and rewards, and inform a strategic course to sustainable, inclusive and resilient development.

While green hydrogen may become a source of opportunity for some countries, policymakers everywhere must consider a range of factors and the implications of dedicating significant time, resources and capital to the sector, along with its potential social, environmental and economic impacts. Green hydrogen development strategies should align to local ecological, social and economic contexts and aspirations, avoiding one-size-fits-all policies. Concurrently, they need to navigate the global energy landscape and geopolitics to prevent the replication of extractivist dynamics. The relationship between green hydrogen and sustainable, human-centred development is highly complex, requiring significant consideration and balancing so that real, tangible benefits accrue for people domestically.

This policy brief, designed for policymakers, provides a technology-agnostic assessment of green hydrogen and its fundamental tenets based on the 3P framework (Figure 1). It covers the main opportunities, key challenges and considerations, and possible solutions, concluding with policy recommendations for key stakeholders.

Figure 1. The 3P framework for green hydrogen: from an extractive to a symbiotic economy

Source : Authors' elaboration



02.

THE HYDROGEN MOLECULE: PAST, PRESENT AND FUTURE

Hydrogen is the most abundant element in the universe, found on Earth primarily in compound forms such as water and hydrocarbons. Once isolated, hydrogen is a powerful energy carrier with many applications. Crucially, when combusted, hydrogen produces no greenhouse gas emissions and can therefore play a significant role in the global energy transition away from fossil fuels. Section 2 serves as a primer on hydrogen, providing an introductory overview of production, demand and potential end-uses, the global supply and the role of hydrogen in sustainable development.

2.1 The many colours of hydrogen: green above all

While global interest in hydrogen has increased significantly in the last few years, commercial production has gone on for over a century, for uses primarily in the chemical, petrochemical and refining sectors. The current wave of interest is not the first time that hydrogen has been perceived as a possible solution to global energy problems. It first garnered attention following the oil crises of the 1970s as a potential vector of energy security (Yap and McLennan 2023).

Hydrogen has traditionally been produced via the steam methane reforming of natural gas or coal or through the gasification of hard or brown coal (Table 2). The resulting products, called ‘grey hydrogen’ and ‘brown/black hydrogen’, respectively, entail significant emissions during production, making both processes environmentally unsustainable. Hydrogen is also produced as a by-product of the chlor-alkali industry—during the electrolysis of brine to produce chlorine and caustic soda—contributing approximately 15 percent of the global hydrogen supply with relatively low additional emissions. Other emerging methods include biogas reforming, where methane from organic waste undergoes reforming to yield hydrogen, and ethanol reforming, which utilizes bioethanol from renewable feedstocks such as sugarcane or starch.

Table 2. Hydrogen production methods

Hydrogen colour	Inputs	Method	Emissions
Black or brown	Coal	Gasification	Very high
Grey	Natural gas	Steam methane reforming	High
Blue	Natural gas	Steam methane reforming with carbon capture and storage	Reduced (varying rates of emissions captured)
Turquoise	Natural gas	Methane pyrolysis (solid carbon byproduct)	Low (solid carbon captured)
Yellow	Water	Electrolysis powered by grid electricity	Variable (depending on grid carbon intensity)
Pink	Water	Electrolysis powered by nuclear electricity	Very low
Green	Water	Electrolysis powered by renewable electricity	Minimal

Ongoing improvements in carbon capture and storage are leading to the possibility of producing 'blue hydrogen', which entails the steam methane reforming of natural gas, with some emissions captured in the production process. While more environmentally sustainable than grey hydrogen, blue hydrogen still generates significant emissions of both carbon dioxide and fugitive methane emissions. Further, carbon capture and storage technology is still in development (de Kleijne et al. 2022). Nonetheless, blue hydrogen is expected to play a significant role in most global decarbonization projections. While a variety of other hydrogen production methods exist,[1] the most important type for global decarbonization is through the electrolysis of water using renewable electricity, yielding 'green hydrogen'.

Green hydrogen is the most sustainable form of hydrogen, with little to no emissions across the entire production value chain.[2] It requires an electrolyser, renewable energy sources (usually solar photovoltaic [PV], wind power, geothermal and/or hydro) and water, yielding hydrogen as well as oxygen as a by-product.

The rest of this policy brief focuses primarily on green hydrogen for several reasons:

- Green hydrogen produces few to no emissions and is therefore the primary choice for global decarbonization where electrification is not an option.
- Ongoing decreases in the cost of renewable energy and electrolysers will further diminish the cost of hydrogen production, unlike more mature production routes, which rely on volatile fossil fuels (Box 1).
- Very high amounts of renewable electricity generation are needed for green hydrogen production. As renewable resource-rich areas are primarily found in developing countries, an important concern is to ensure that the green hydrogen economy supports sustainable development.

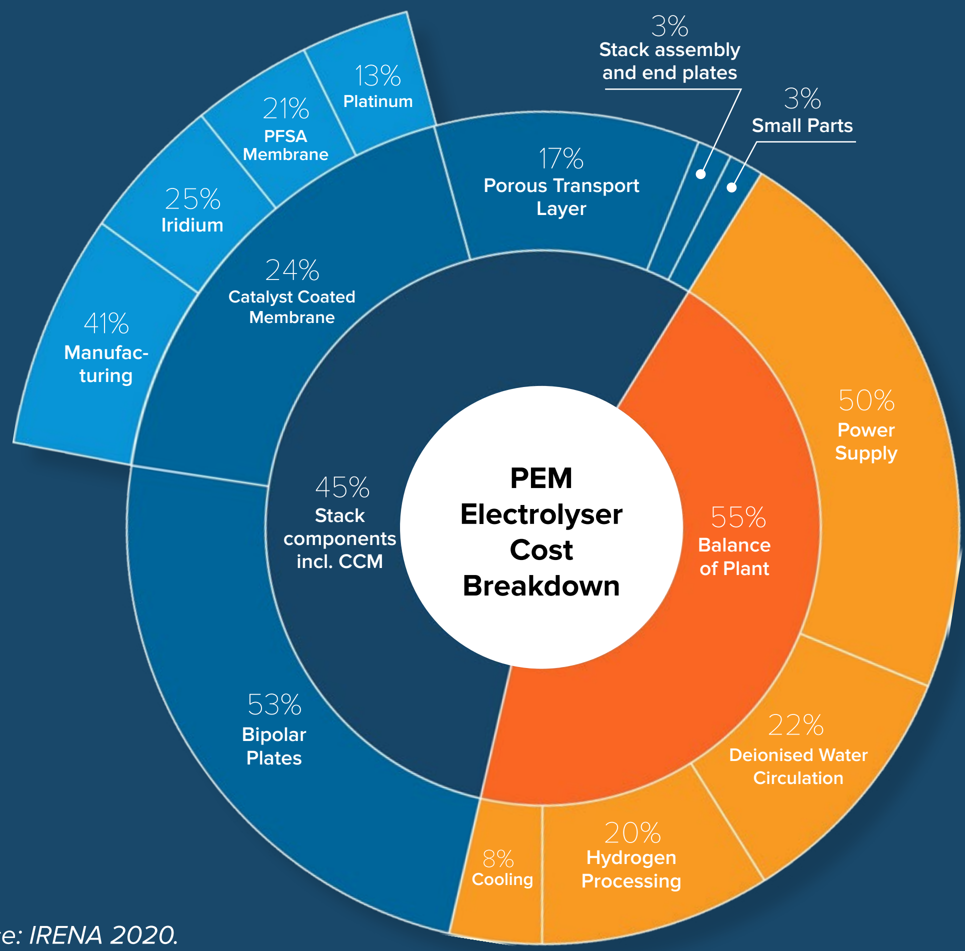
1 *For example, 'pink hydrogen' produced via electrolysis using nuclear-generated electricity or 'turquoise hydrogen' from methane pyrolysis with a solid carbon byproduct.*
2 *The Green Hydrogen Standard defines this as less than 1 kilogram of carbon dioxide per kilogram of hydrogen produced (Green Hydrogen Organisation 2023).*

BOX 1. Hydrogen electrolyser components and cost structures

Significant cost reductions for hydrogen electrolysers can be achieved by addressing both stack components and balance-of-plant systems. Stack costs, driven by expensive critical minerals such as platinum, iridium and titanium in PEM (proton exchange membrane) electrolysers, can be reduced through material innovations and improved design.

Balance-of-plant systems, which include power supplies, cooling systems and gas purification, represent a substantial share of total costs. Standardizing components and optimizing system designs for larger installations can unlock further savings. Power supply systems, in particular, offer significant opportunities for cost reduction through scale-up.

Achieving economies of scale is critical. Ramping up manufacturing to gigawatt levels can reduce electrolyser costs by nearly 50 percent, as seen in other renewable energy technologies, such as solar PV. Larger module sizes and standardized components drive further savings, especially for large-scale projects. Overall, these strategies could reduce electrolyser costs by up to 80 percent over the long term, increasing competitiveness.



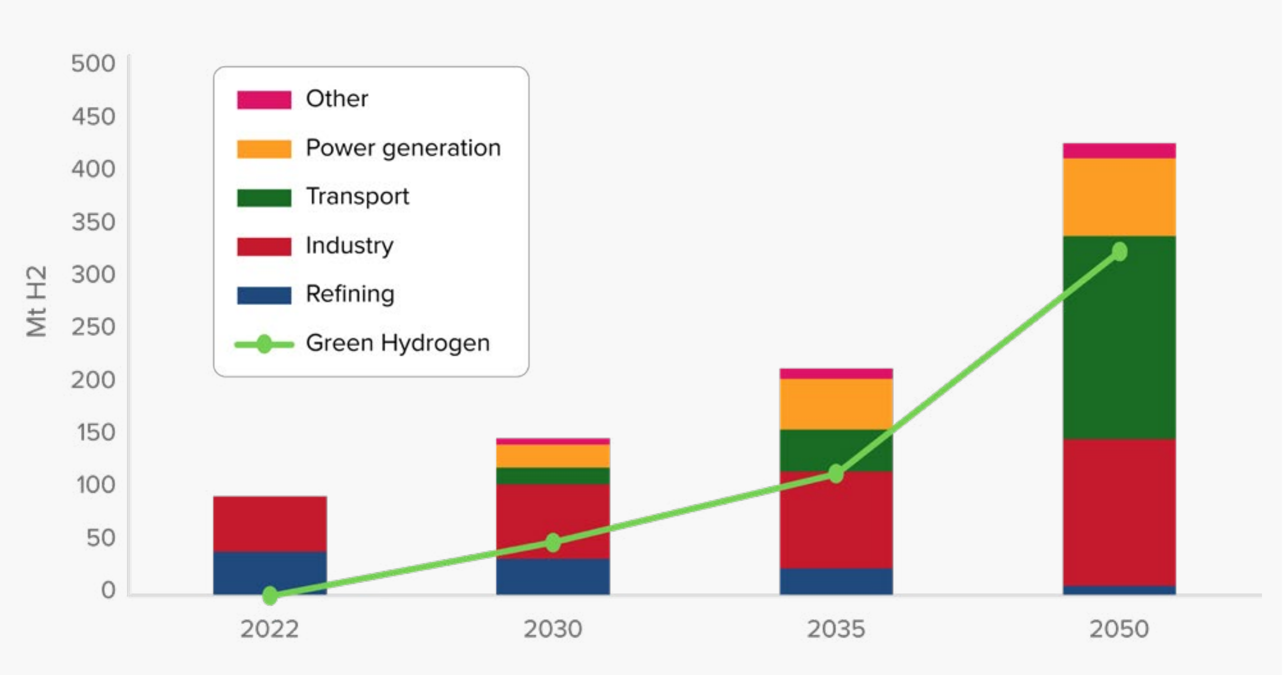
Source: IRENA 2020.

2.2 Green hydrogen and global decarbonization demand and end-uses

Given the increasing urgency to accelerate the global energy transition, green hydrogen has quickly moved to the centre of many decarbonization strategies. It is expected to be a fundamental contributor to achieving the goals of the 2015 Paris Agreement on climate change, which calls for limiting global warming to 2°C and striving for no more than 1.5°C above pre-industrial levels. Interest in hydrogen has exploded in the last few years. As of late 2024, 58 countries (and two regional groups) had created their own hydrogen strategies (IEA 2024b). Prior to 2020, only four countries globally had any national hydrogen strategy at all.

Current annual hydrogen demand totals between 95 and 100 megatons, all of which is used either in the refining and petrochemical or industrial segments, with minimum uptake in new industries. Less than 1 percent of total production is currently low-carbon hydrogen (green or blue), but both the demand and supply of low-carbon hydrogen are expected to significantly escalate in the coming years. In the International Energy Agency's (IEA) 2023 net-zero scenario projections (Figure 2), demand for hydrogen is due to increase to 150 million tons per year by 2030, of which low-carbon hydrogen would provide less than 50 percent. It would rise to 430 million tons per year by 2050, with close to 98 percent provided by low-carbon hydrogen (IEA 2023b).

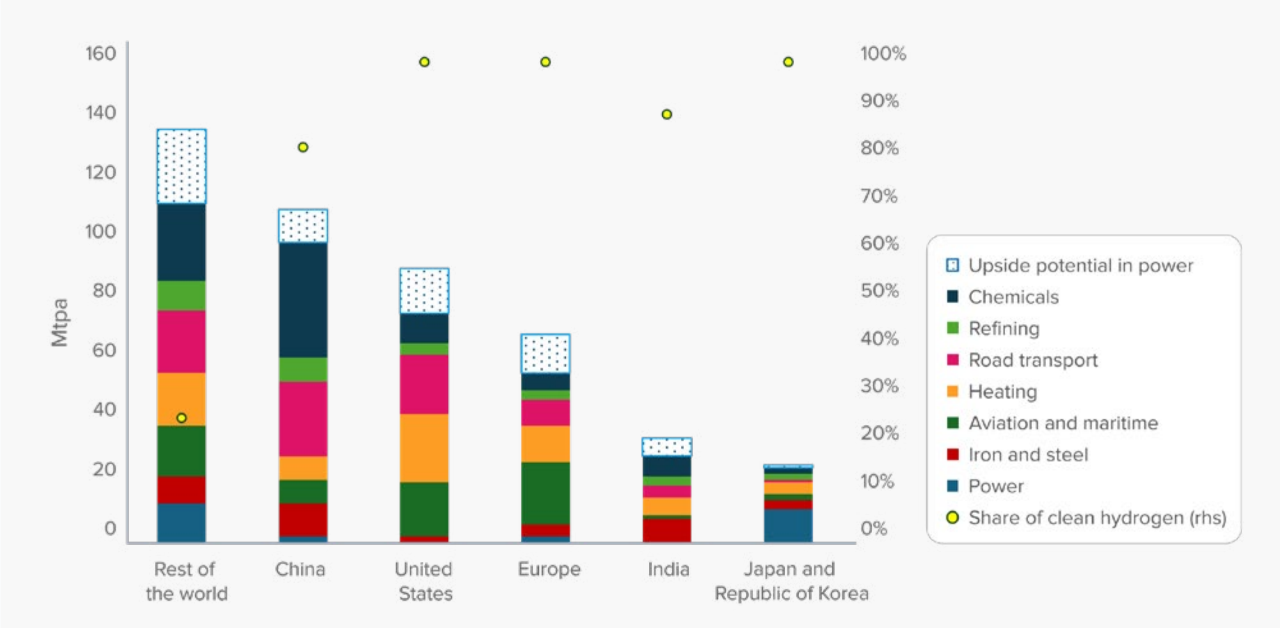
Figure 2. Demand projections for a net-zero scenario



Source : IEA 2023b.

In a different set of projections, by 2050, China, India, Japan, the Republic of Korea, the United States of America and Europe are jointly expected to account for 71 percent of total global hydrogen demand, with the last four relying entirely on low-carbon hydrogen (McKinsey & Company 2024). The industrial, chemical and transportation segments are expected to account for most demand, primarily for power generation and storage, and increasingly less so for the refining industry as fossil fuel use declines (Figure 3).

Figure 3. Hydrogen demand in selected regions by 2050



Source : McKinsey & Company 2024.

Given nascent green hydrogen (and low-carbon) sectors, the economics, efficiency and competitiveness of potential end-uses are still evolving. This has a significant impact on overall demand projections, which have decreased substantially in recent years, especially in the shorter term through 2030. For example, the European Union's Agency for the Cooperation of Energy Regulators recently announced that Europe would not meet its stated demand target of 20 megatons of hydrogen by 2030 (EU-ACER 2024). Significant ranges in demand projections exist due to inherent uncertainty around end-uses, prices and market scale-up. McKinsey & Company's (2024) projections for low-carbon hydrogen usage by 2050 range between 125 and 585 million tons per year.

Uncertainty about end-uses is a major factor in diverging demand forecasts. While hydrogen has been referred to as a "Swiss Army knife of decarbonization" (Power Magazine 2021), it is increasingly clear that use will be limited to a smaller set of sectors than initially anticipated. This is due to both economic and technical considerations. End-uses increasingly have alternative ways to decarbonize, primarily through direct electrification, which can be significantly more efficient and economical. For example, there is no economic case for using hydrogen to heat buildings; heat pumps provide a better value proposition (Rosenow 2023). Electric passenger vehicles have massively outcompeted hydrogen fuel-cell vehicles (MIT Climate n.d.). Increasingly, direct electrification solutions are more attractive even for trains (Hydrogen Insight 2023) and large-scale mining trucks (Hydrogen Insight 2024), both once seen as important markets for low-carbon hydrogen.

These examples highlight the importance of technological innovation and disruption and the effects on the broader hydrogen sector. Nonetheless, there are some uses where, for now, low-carbon hydrogen and its derivatives are seen as essential, although with major variances in technological and commercial maturity, as follows.

Hard-to-abate industrial sectors, including ammonia-based fertilizer, steelmaking, the chemicals sector and others

Table 3. Hydrogen end-use in industrial decarbonization

Sector	Hydrogen usage	Technological maturity	Economic viability	Likelihood of alternative
Fertilizer production	Used to produce ammonia	Mature—widespread technology	Viable—ammonia is a proven process, but costs depend on the hydrogen source	Low—hydrogen is essential as a feedstock, with no direct electrification option
Steelmaking	Replaces coal in the direct reduction of iron	Moderate—pilot plants exist but scaling up is needed	Emerging—high costs due to green hydrogen costs	Low to moderate—some emerging technologies
Feedstock for chemicals	Used in producing methanol and synthetic fuels (power-to-X)	Moderate—existing processes adapt to green hydrogen	Emerging—expensive but essential for decarbonizing chemicals	Low—critical for synthetic fuels and chemicals
Industrial heat	Used as a clean fuel for high-temperature industrial processes	Moderate—technically feasible but underdeveloped at scale	Emerging—competes with cheaper natural gas	Low—limited alternatives for very high-temperature processes

Source: Based on secondary research and stakeholder interviews with industry experts.

The most important prospective use of green hydrogen may be the decarbonization of several hard-to-abate sectors where carbon emissions are high and electrification options limited (Table 3). In several industrial processes, green hydrogen can be used as a feedstock to replace grey hydrogen or fossil fuels. Examples include substituting for natural gas in ammonia-based fertilizer production and uses in steelmaking and cement production. Green hydrogen can also serve as a clean fuel for generating the high-temperature heat needed in industrial processes such as cement production. The steel, cement and chemicals sectors alone currently account for over 30 percent of global carbon dioxide emissions, presenting significant decarbonization potential (Reuters 2024c). Investment lock-ins are a significant problem in capital expenditure-heavy industrial sectors, however. Long-term investment horizons provide little short-term flexibility to make fundamental production switches.

The power sector, especially for power generation and as a form of long-term energy storage

Green hydrogen may play a role in decarbonizing electricity. Excess renewable electricity can be converted into green hydrogen and used for shorter-term grid balancing. But the primary application of green hydrogen may be for long-term storage and use during periods of low renewable energy potential. Beyond its contribution to decarbonization in electricity systems, green hydrogen may make important contributions to greater energy security and energy system resilience (Table 4).

Table 4. Hydrogen end-use in power sector decarbonization

Sector	Hydrogen usage	Technological maturity	Economic viability	Likelihood of alternative
Power generation	Used in turbines or fuel cells for electricity generation	Moderate—gas turbines and fuel cells exist but need scaling up	Limited—less cost-competitive than natural gas	Moderate—batteries and direct renewable power are often more efficient
Energy storage	Used as a long-term energy storage medium for excess renewable power	Early to moderate—demonstration projects in some sectors with some uses advanced	Emerging—expensive infrastructure, round-trip efficiency is low	Low—hydrogen complements batteries for long-duration storage

Source: Based on secondary research and stakeholder interviews with industry experts.

Some types of long-distance transportation, especially shipping and aviation

Another potential key use of green hydrogen is in decarbonizing long-distance transportation, where batteries are less practical due to weight and energy density constraints. Hydrogen fuel cells or green ammonia could power some trucks, buses and ships, providing longer ranges and quicker refuelling than batteries (Table 5).

Table 5. Hydrogen end-uses in transportation sector decarbonization

Sector	Hydrogen usage	Technological maturity	Economic viability	Likelihood of alternative
Aviation	Used to produce synthetic jet fuels (e.g., e-fuels or sustainable aviation fuels)	Moderate—the technology is proven but scaling up production is a challenge	Emerging—costs are high but necessary for net-zero aviation targets	Low—needed for long-haul flights; batteries or hydrogen alone are not feasible
Shipping	Converted to ammonia as a cleaner fuel for large cargo vessels	Emerging—ammonia is promising but still costly with retrofitting needed	Early—trials underway with infrastructure a bottleneck	Low—few viable alternatives for decarbonizing long-haul shipping

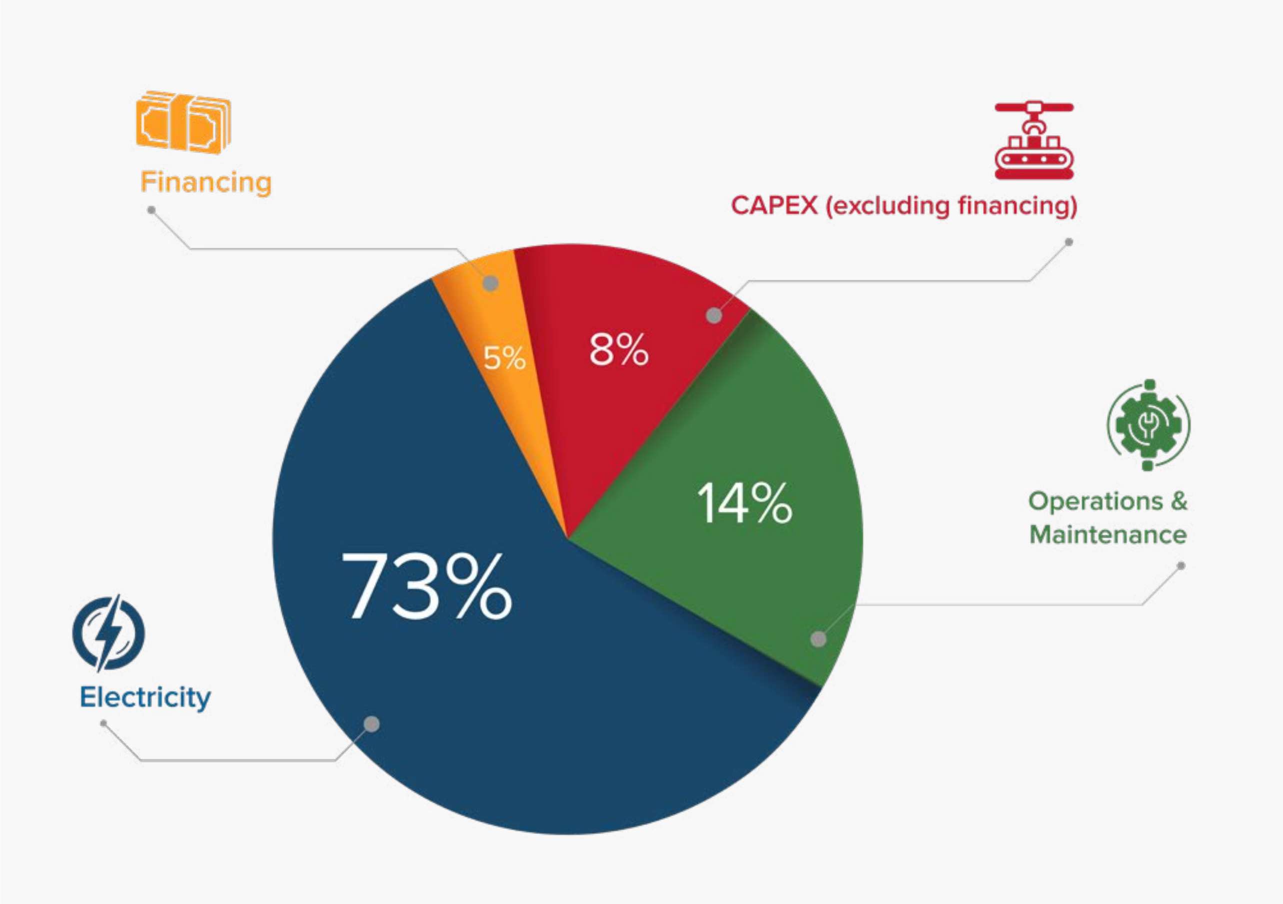
Source: Based on secondary research and stakeholder interviews with industry experts.

2.3 The supply dimension: who, how, where and for how much

While most future global demand for low-carbon hydrogen is expected to come from a small number of already industrialized countries, the supply may be highly geographically dispersed, especially for green hydrogen.

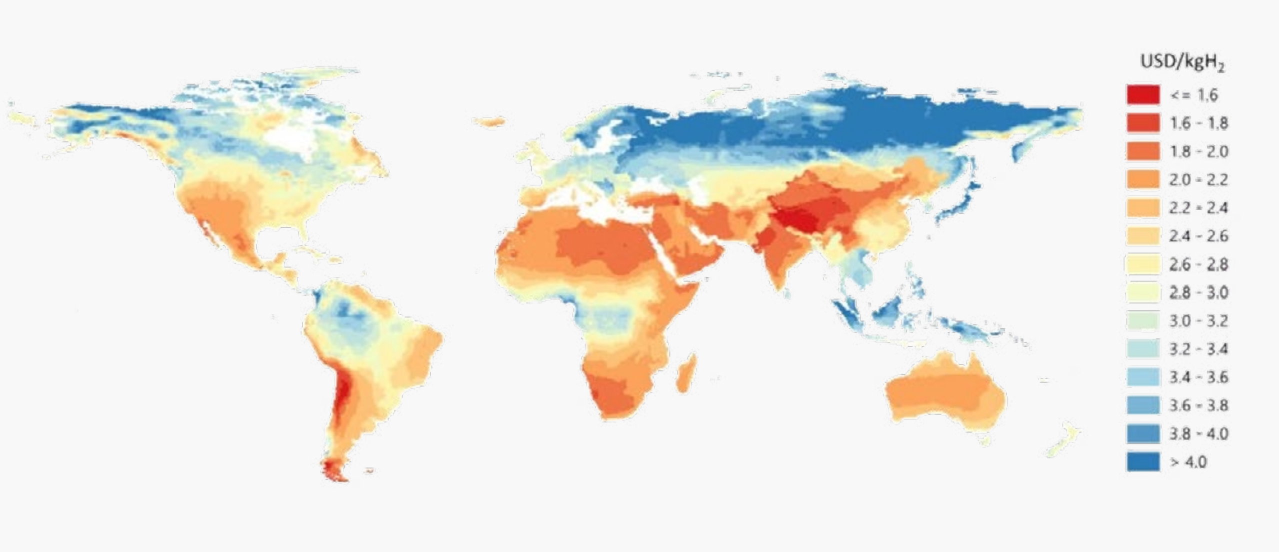
While many factors are fundamental in the levelized cost of hydrogen production—including the cost of capital and capital expenditure on electrolysers and renewable energy sources—large quantities of cheap renewable electricity determine the economics and viability of many projects (Figure 4). High renewable energy potential (especially wind and solar) in many developing countries has made the green hydrogen sector a very attractive new source of economic opportunity (Figure 5). Many countries are looking to capitalize on the expected boom in demand in the coming years.

Figure 4. Cost shares of green hydrogen production, 2019



Source : Wood Mackenzie 2019.

Figure 5. Hydrogen costs from hybrid solar PV and onshore wind systems over the long term



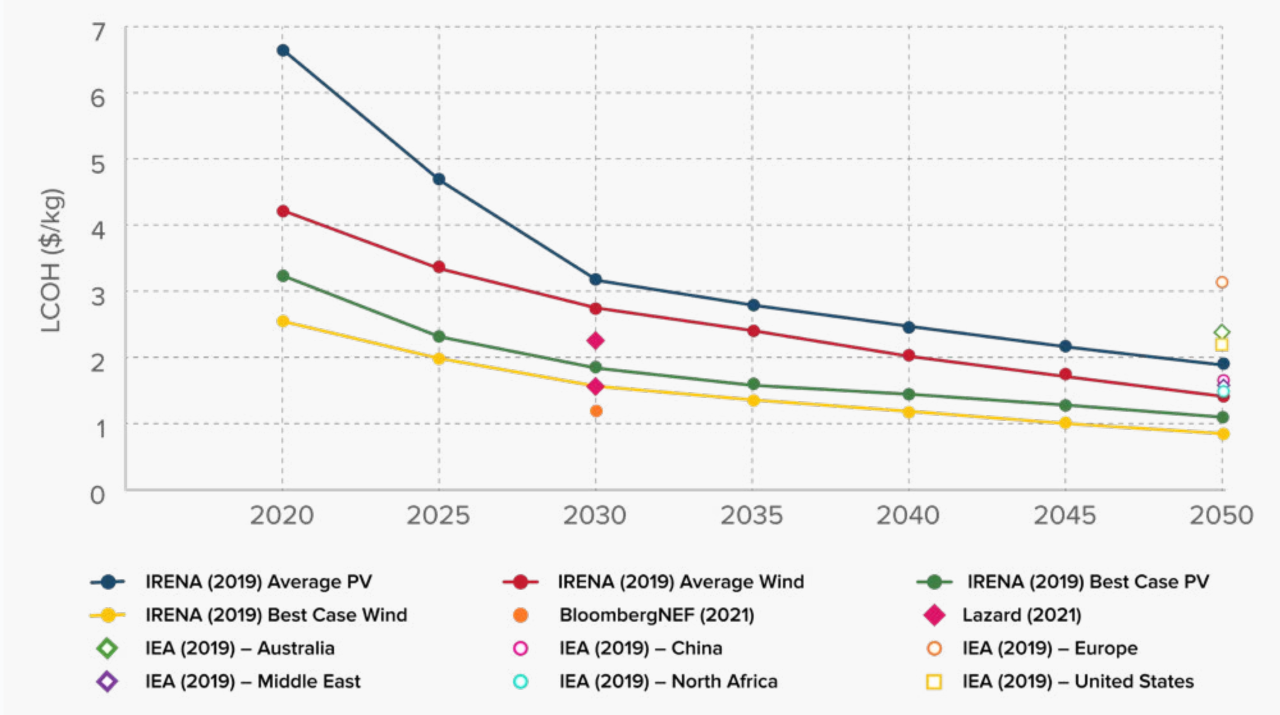
Source : The Economist Impact 2021.

Of the 58 national hydrogen strategies created in the past four years, roughly half are in developing countries, featuring a wide range of ways to leverage domestic potential. Many countries seek to become producers of green hydrogen. As a first step, they focus primarily on exports to global demand centres (primarily in the Global North) but also foresee the localization of the hydrogen economy, including through using domestically produced hydrogen to decarbonize domestic industries or to attract new industries that use green hydrogen as an input. Often these strategies also include developing upstream[3] and downstream[4] links to create new jobs and revenue streams, and contribute to national industrialization.

The cost of producing green hydrogen is still significantly higher than for grey or blue hydrogen, although there is an expectation that costs will decrease significantly in the coming years. Reductions are expected in the costs of electrolysers, especially as technologies further mature. Some further decline in the cost of renewable energy sources is also anticipated. In addition, as demand scales up, additional cost decreases should result from economies of scale and the optimization of production (Figure 6).

3 *For example, the manufacturing of hydrogen electrolysers but also renewable energy equipment, including solar PV panels, wind turbines or battery storage.*
4 *Using green hydrogen in downstream industries, whether to decarbonize existing sectors or attract new industries to the country.*

Figure 6. Cost of green hydrogen production, 2015–2050



Source : Webb et al. 2023.

The green hydrogen sector is still at the initial stages of development. As of the end of 2023, only 1.4 gigawatts of electrolyser capacity was installed globally (primarily in China and Europe) with progress on new projects proceeding more slowly than expected. While the total capacity of announced projects is over 520 gigawatts by 2030, only 4 percent of these initiatives have secured financial investment or are currently under construction (IEA 2024b). The most recent Global Hydrogen Review (ibid.) lists several key issues that have slowed projects or led to cancellations, including:

- Regulatory uncertainty and the slow development of policy frameworks
- Demand uncertainty and the slower-than-expected development of the hydrogen and hydrogen derivatives market
- Financial hurdles and incentive delays for green hydrogen production
- Licensing and permitting issues, including access to utilities (water and electricity) as well as securing the social license to operate
- Operational issues partially inherent in the scale-up of the sector and improvements through learning by doing

Infrastructure is a fundamental component of the hydrogen story, requiring a massive ramp-up of hydrogen pipelines (new and repurposed); blending facilities; hydrogen, ammonia and methanol port infrastructure; and underground storage facilities. Significant capital expenditure will be borne by both the private and public sectors (ibid.).

2.4 This time must be different: avoiding extractivism

The global green hydrogen sector has reached a complicated point in its development. On the one hand, there is significant interest. Massive ambitions to expand the sector are evident in the emergence of national hydrogen strategies and projections of potential end-uses and significant demand increases in coming decades. On the other hand, it has proven difficult for the sector to take-off. The 'chicken and egg problem' of simultaneously scaling up both demand and supply has created significant uncertainties for both producers and consumers. While the hype around green hydrogen seems to have peaked, and more recent analyses have begun revising shorter-term projections downward in terms of both demand and price competitiveness, a market opportunity still clearly exists (ECDPM 2024).

Many developing countries are actively looking to develop their own hydrogen sectors to create new sources of revenue and spur industrialization. Yet the uncertainty of green hydrogen development imposes significant risks on prospective producers. For many developing countries struggling with limited fiscal space, high levels of debt and a lack of human capital, among other challenges, deciding to spend precious time and resources on developing an inherently uncertain sector will require significant coordination, industrial policy planning, technological and market foresight, and solid governance mechanisms. Transparent decision-making, effective regulatory institutions and inclusive stakeholder engagement will be essential to manage risks, prevent elite capture and align green hydrogen development with national priorities and the delivery of broad benefits. Understanding how to navigate complicated currents in the sector is key, as further explained in Section 5.

At its core, green hydrogen, despite its many potentially positive attributes, is still primarily a commodity, one that will overwhelmingly be produced in remote areas with a significant impact on local communities and the environment. In many ways and in many parts of the world, its production and handling may most closely resemble those in the fossil fuel sector, and not only due to similar infrastructure. Avoiding the repetition of past mistakes calls for assessing and learning from past lessons. By creating real local value addition and using the green hydrogen sector for further development, nations can prevent a reoccurrence of the so-called 'pre-source' and resource curse (Cust and Mihalyi 2017.)

The rest of this policy brief assesses these issues based on the pillars of people, planet and prosperity, providing an overview of opportunities, challenges and solutions.

03.

MAKING GREEN HYDROGEN WORK FOR PEOPLE: ENERGY ACCESS, HUMAN CAPITAL AND A JUST TRANSITION

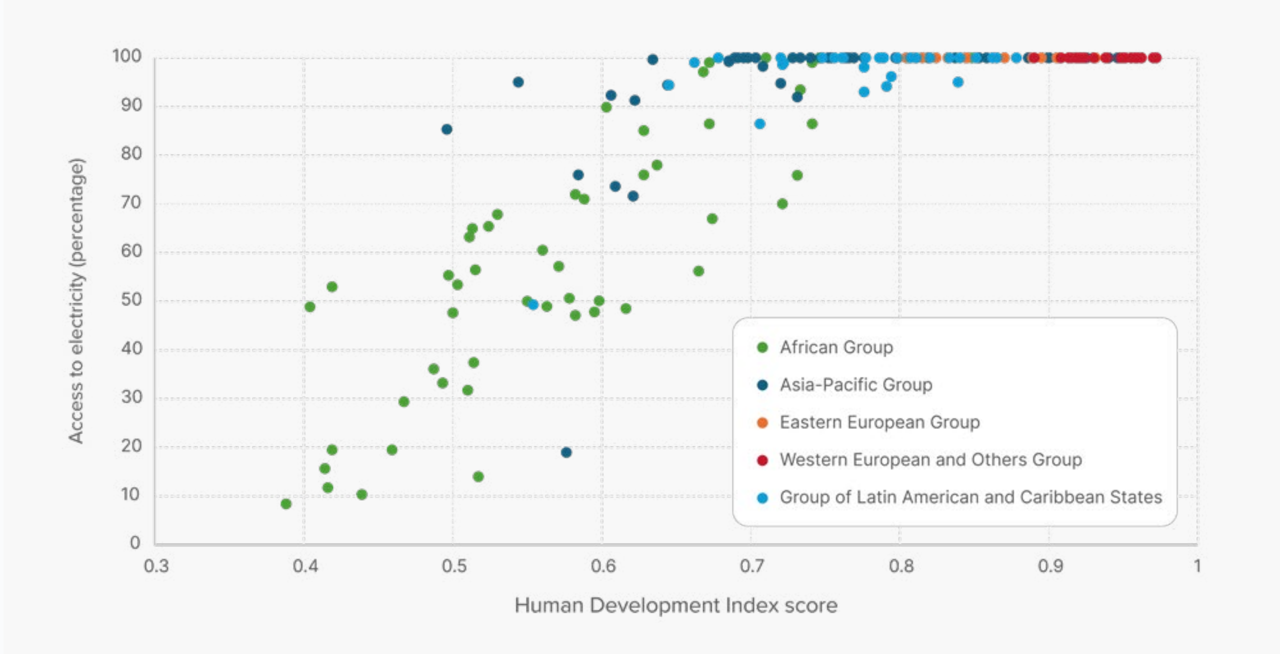
Large-scale green hydrogen sectors may better the lives of local populations in several ways, including through improved energy access, new jobs and opportunities for achieving a just energy transition from fossil fuels. Realizing these gains largely depends on applying the right tools, incentives and investment conditionalities.

3.1 Energy access

Opportunities

Scaling up green hydrogen production can improve energy access in three ways. First, the significant build-out of needed new renewable energy capacity may increase access to electricity, especially in developing countries where universal electrification has not yet been achieved. The link between electrification and improvements in socioeconomic indicators has been widely documented (Figure 7); electricity access is a great equalizer (Public Power 2021).

Figure 7. Access to electricity tracks the Human Development Index



Source : Elaboration based on UNDP 2024 HDI report.

Full electrification is a key global developmental priority. Ongoing efforts entail the expansion of large-scale, centralized grids and smaller, more decentralized off-grid solutions, both of which may be served through green hydrogen projects. Grid-connected electrolysers may feed some electricity back into the grid. Another possibility is where electricity is fed directly to smaller off-grid communities where green hydrogen projects are located.

Second, the development of green hydrogen sectors, both in countries without full electrification and markets with additionality requirements, will necessitate the construction of new renewable energy sources and the larger infrastructure, transmission and power production needed for an integrated hydrogen economy. A large-scale renewable build-out will establish supply chains and links, create skills and enable learning-by-doing effects that lead to easier renewable installations.

For Namibia, which currently has an electrification rate of 56 percent, developing a green hydrogen industry and enhancing energy access are closely linked, as evidenced in the country's Blueprint for Namibia's Green Industrialization (Namibia 2024). Plans for the largest project in the country, the Hyphen, call for building up to 7 gigawatts of solar PV and wind to power 3 gigawatts of electrolysers (Enertrag n.d.). By some accounts, excess electricity from hydrogen projects could decarbonize the entire Namibian grid (Ricardo 2024). While this projection may not yet be substantiated, Namibia is nonetheless rapidly expanding its power production and using interest in the green hydrogen project to attract other investors. The country has opened power generation assets to independent power producers while still providing oversight and financing for transmission and distribution infrastructure (Ammonia Energy 2024). This has already yielded significant new investments, especially in wind power and solar PV assets.

A third key consideration linking green hydrogen and energy access lies in the potential for long-term, large-scale energy storage. This is especially pertinent as countries globally decarbonize their electricity systems, including in eventually using green hydrogen in hydrogen-fired power plants, especially in times of low renewable energy generation or to balance the grid. The storability of hydrogen also has significant implications for energy security, offering possibilities to absorb excess renewable power and support the stability of highly decarbonized electricity grids. In short, green hydrogen, in complementing other forms of energy storage, would decrease emissions and increase energy security and resilience (see Box 2).

Challenges

Despite some opportunities, the green hydrogen sector could potentially have negative consequences on energy access and broader just transition goals. Grid-connected projects with no strong additionality requirements may end up decreasing total electricity available, and even the installation of large-scale new renewable capacity may do little for broader electrification. There might be an effect on energy prices that, if not mitigated through social compensation or protection, could negatively impact consumers and increase energy poverty. Since high renewable capacity is key to decreasing project costs, significant excess electricity would likely not be available for the grid or general population without conditions for the operator to provide it.

Additional large-scale investments may be needed in transmission and distribution infrastructure, which may deter investors and lead to closed-loop systems that do not contribute to local grids and communities. The sector would then have little to no impact on local human development, broader energy access, though it could still contribute to lowering emissions. Moreover, many large-scale green hydrogen projects are expected to operate off-grid, relying on dedicated renewable energy systems. In such cases, the key challenge is making sure that that these projects still contribute to closing the energy access gap, particularly in underserved areas.

BOX 2. Comparing lithium-ion battery and hydrogen storage

While both lithium-ion batteries and hydrogen storage systems (such as salt caverns or ammonia storage) are both used to store energy, they fulfil very different purposes. Lithium-ion batteries store electricity for short periods and are fundamental to grid stability and balancing. Hydrogen storage is primarily in gaseous form, providing a much longer-term storage system for use as needed for industry or power generation. Table 6 summarizes the key characteristics of both energy storage systems.

Table 6. Key characteristics of lithium-ion batteries and hydrogen as storage systems

	Lithium-ion battery	Hydrogen storage
Energy density	200–300 Wh/Kg	33.33 kWh/Kg
Round-trip efficiency	85–95 percent	30–50 percent
Energy loss	Lower, minimal energy losses in conversion	Higher due to electrolysis, compression and conversion losses
Storage duration	Hours to a few days	Days to months
Response time	Milliseconds to minutes	Minutes to hours
Use case	Short-term, daily load balancing, grid stability	Long-term, seasonal storage, heavy industries
Main consumers	Residential, commercial, grid operators, electric vehicles	Industrial sectors (steel, chemicals, etc.), long-haul transport, power generation, seasonal storage, heavy-duty applications
Scale of deployment	Highly scalable, with large global deployment	Emerging, requires significant infrastructure investment
Technological maturity	High—commercialized lithium-ion batteries	High—commercialized salt cavern storage and ammonia storage

Source: IEA 2024c.

A fundamental question especially for developing countries without full electrification relates to the right prioritization, sequencing and overall conditions to ensure the development of the broader energy system. The primary role of green hydrogen in the energy system is expected to be longer term and at a national scale, with little application in terms of improved energy access in the short term and at smaller scales. Smaller-scale transportation of hydrogen to remote or underserved areas may be harder, with significant operational and safety-related issues. And the costs of green hydrogen will also almost certainly remain higher than other possible (albeit less green) alternatives.

Mechanisms such as benefit-sharing schemes or parallel investments in local mini-grids can help ensure that off-grid hydrogen projects support inclusive energy development. At the same time, rather than deploying more complex infrastructure, transportation, storage and fuel cell solutions, direct electrification may be the better option. Small-scale renewable energy schemes deployed with battery storage systems often remain more practical and economically feasible for small-scale requirements.

Navigating the solutions

Countries need to ensure that green hydrogen helps fulfil domestic strategic priorities for energy access, which requires a targeted, context-specific approach. There may be significant variances among countries where full energy access and electrification have still not been achieved (e.g., Kenya, Mauritania, Namibia), where existing energy systems pose challenges (e.g., South Africa), or where energy access is better and other energy transition topics are more pertinent, such as the decarbonization of hard-to-abate sectors (e.g., Australia, Chile).

When it comes to electricity access, grid-connected electrolyser projects especially must provide additionality by integrating brand-new renewable capacity. This is key given scenarios where projects may decrease electricity available for other uses, increase electricity prices and exacerbate energy poverty. Even as the green hydrogen sector should be geared towards broader energy access and electrification and the greening of existing electricity systems, additional social safeguards need to be in place to protect consumers.

Countries should prioritize green hydrogen projects that both contribute to broader electrification and build the stability and resilience of the electricity supply. Such considerations can be included in tenders or by offering incentives for achieving key energy access goals. Countries can also consider reaching agreements with project owners to oversize renewable energy deployment and contribute to improved grid interconnections and infrastructural build-out. At the same time, the impact of green hydrogen on local energy access should not be overestimated, since technical, logistical and economic factors favour electrification for most consumer end-uses.

3.2 Human capital and the just transition

Opportunities

The roll-out of large-scale green hydrogen production facilities and the large quantities of renewable energy required for green hydrogen production will create considerable opportunities for job creation, including through increased demand for workers to install both small- and utility-scale renewables. Renewable energy and energy efficiency create more jobs than legacy fossil-fuel sectors (IEA 2024a), and the broader green hydrogen value chain may have potential to generate significant employment along the value chain, including in renewables production, operations and maintenance, infrastructure development, transportation, research and development, and manufacturing.

Chile's green hydrogen strategy emphasizes the creation of over 100,000 new jobs in both upstream and downstream activities, including the greening of manufacturing. New jobs and local employment are important goals of the strategy (Chile, Ministry of Energy 2020). The European Union estimates that every EUR 1 billion in investment across the green hydrogen value chain creates 20,000 jobs (Ricardo 2024). It is also critical to assess the types of jobs provided to local populations, the proportion filled by non-local workers and experts and the potential for up-skilling. For example, the Hyphen project in Namibia targets 15,000 jobs during the construction phase and 3,000 during operations, with 90 percent fulfilled by local Namibians (ibid).

A significant component is equipping the labour force with the right skills to seamlessly integrate into the hydrogen economy. Many skills are currently not found in developing countries or specific regions in these countries where green hydrogen plans exist. Closing gaps necessitates introducing broader technical, vocational education and training programmes as well as targeted hydrogen-specific courses. These measures may have a positive impact on green hydrogen strategies while also producing significant transferable skills and links to other sectors.

Some existing skills among workers may be repurposed. This holds special significance for existing fossil fuel producers, where a just transition will require retraining and reintegrating workers. In Oman, which has substantial plans to create a green hydrogen sector, there is potential for repurposing existing oil and gas assets and many jobs in the sector, with training providers already offering relevant courses (IEA 2023c). Up-skilling and repurposing are also particularly relevant in countries with strong legacy carbon-intensive and labour-intensive sectors. In South Africa, a just transition is key to avoiding leaving coal-reliant communities behind in a green hydrogen economy.

Challenges

The creation of jobs and skills is not automatic. Significant risks exist. As developing countries often lack the skills needed for large-scale hydrogen or renewable projects, foreign developers may bring in workers to build, manage and administer them, with little local involvement, and therefore also little capacity-building and knowledge absorption. Some international labour is to be expected in most cases but the goal should be for up-skilling and technical skills development to anticipate the needs and uncertainties of the green hydrogen sector (see Section 6). The Hyphen project in Namibia made major announcements regarding jobs but is now unlikely to meet its targets for total jobs created or domestic employment posts.[5]

While many projects centre on creating new jobs and human capital development, the green hydrogen sector, much like other extractive sectors, is primarily capital-intensive. It will not be a mass source of new employment. Although there are opportunities along the value chain, the long-term development perspective of the sector means that scale-up, jobs created and up-skilling may take more time.

As with other location-specific extractive sector projects, historical lessons show a variety of risks and possible failures when it comes to new green hydrogen projects, especially those replacing other sunset industries, and in the context of a just transition. Risks include failing to obtain a social licence to operate, which is consistently a significant issue in industrial project development. Working and engaging closely with the local population, providing timely and transparent information and local benefits, and creating employment opportunities for local communities are crucial to success. Much can be learned from community dialogues on extractive sectors (Korinek and Ramdoo 2017; Lebdioui 2020; Ovadia 2014). These considerations are particularly relevant to green hydrogen projects placed in a few specific locations. If they create enclave economies, they may have significant impacts on equity due to unequal access to job opportunities or benefits.

Navigating the solutions

Provisions must be in place for local labour to deeply engage with all green hydrogen projects, along the entire value chain. At the same time, there should be corresponding programmes and realistic timelines for training and up-skilling local labour. This may involve working with international partners or operators and establishing new training centres, or partnering with existing institutions and broadening training offerings. Broader implications for equity and development opportunities are especially relevant to just transition aims and the prospects for marginalized communities to benefit from new projects.

In South Africa, skills development for the green hydrogen sector features explicitly in the country's Just Energy Transition Partnership. A study from South Africa's Department of Higher Education and Training mapped out close to 140 different possible occupations along the green hydrogen value chain, identifying 74 necessary degree programmes (South Africa, Department of Higher Education and Training et al. 2024). The country already offers 50 of these but additional technical and vocational courses as well as international partnerships and 'train the trainer' programmes are needed to increase skill levels.

Parallels between the hydrogen and extractives sectors imply that learning from past lessons is key, including to uphold fundamental principles of accountability and transparency in project development and apply good governance and redistributive policies so benefits are widely shared.

5 Expert interviews from private sector, academia and international organizations.

04.

ENSURING RESPECT FOR OUR PLANET: DECARBONIZATION WITHOUT ENVIRONMENTAL DEGRADATION

The primary and most important promise of green hydrogen is to play a potentially transformative role in the global energy transition away from fossil fuels, as described in Section 2. Yet the energy transition may also be at the heart of broader ecological sustainability, which addresses a series of ecological challenges and goes beyond decarbonization (Chang et al. 2024). While the existential threat posed by climate change has helped to fuel fruitful discussions on sustainability, it has also contributed to what some have described as carbon reductionism.[6] 'Greening' is often used as a synonym for the transition to renewable energy even as decarbonizing the economy solves only one of the many dimensions of the environmental crisis.

Section 4 assesses resource sustainability more broadly, focusing on land use and the unsustainable exploitation of renewable resources, especially the overuse of water, as well as atmospheric factors. It also looks at the use of important non-renewable resources, namely, the critical minerals required across the hydrogen value chain.

4.1 Resource sustainability: land, water, air

Opportunities

The most important prospective use of green hydrogen is in decarbonizing several hard-to-abate sectors, especially where carbon emissions are high and electrification options are limited. This may lead to significant reductions in greenhouse gas emissions globally and locally (Dagnachew and Solf 2024).

Challenges

A significant factor in developing large-scale hydrogen projects, much like other extractive projects, is the requirement for land for the electrolyser, water supply system and transportation infrastructure (among other elements), and, primarily, renewable energy sources (Table 7).

Table 7. Land-use requirements

Land needed for	Size of required land
Onshore wind	From 8.4 square metres to a maximum of 247 square metres per megawatt hour
Ground mounted solar PV	20 square metres per kilowatt
Electrolyser	0.048 to 0.095 square metres per kilowatt

Source : International PtX Hub 2024a, based on Heinemann and Mendelevitch 2021; Lebling et al. 2022 and Ritchie 2022

Requirements and impacts on land use differ among regions. In areas with better solar potential and higher capacity, less solar PV build-out is needed. In western Australia or Namibia, where solar radiation is high, land use per kilogram of hydrogen would be significantly smaller than in Northern Europe, which receives much less sunlight. Similarly, regions with better wind potential and higher capacity (e.g., the Magallanes Province of southern Chile) will require less renewable capacity build-out.

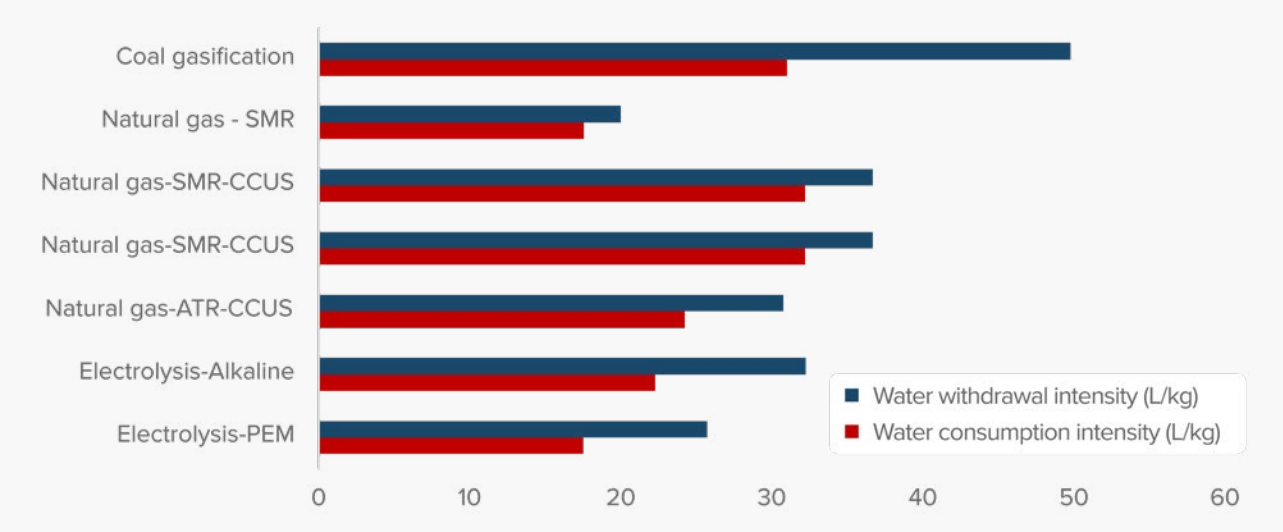
Levels of land use and locations selected have significant implications for local biodiversity and degrees of disruption. While environmental impact assessments are key to preventing damages from any renewable roll-out, inherently, some impacts on local flora, fauna and biodiversity are likely. Minimizing impacts from green hydrogen projects requires careful consideration of local biodiversity hotspots.

In Namibia, a local environmental group has claimed that the massive 4,000-square-kilometre Hyphen project, expected to be located in the Tsau Khaeb National Park, would cause catastrophic and irreversible damages. The region accounts for only 3 percent of Namibia's total land but 25 percent of its plant species, some of which are only found in the park (Namibian Chamber of Environment 2024). A large green hydrogen project in western Australia will result in significant clearance of vegetation, which may have an impact on local biodiversity (Microgrid Media 2024). As with any industrial production, large-scale land-use requirements call for all steps of the process to consider local environmental degradation and biodiversity protection (in addition to any communities living or working in the areas). Projects should take all steps necessary to prevent significant damage to local environments.

Water use in green hydrogen production is a major emerging topic. While production is foreseen in areas with the highest renewable energy potential, these often coincide with some of the most water-stressed parts of the world. Green hydrogen electrolysis requires significant amounts of clean water (IRENA 2023), and assessments are needed to avoid increased water scarcity and competition with other water uses.

IRENA (2023) finds that current annual water withdrawals for hydrogen production (primarily brown and grey) amount to 2.2 billion cubic metres. This is due to increase to 7.3 billion cubic metres by 2040 (a mix of green and blue) and 12.1 billion cubic metres by 2050 (almost all green). While all hydrogen production requires significant volumes of water, green hydrogen (both PEM and alkaline) has the lowest water withdrawal and consumption rates.

Figure 8. A summary of water withdrawal and consumption intensities by hydrogen production technology



Meaning of acronyms
- *SMR - Steam Methane Reforming*
- *CCUS - Carbon Capture, Utilization, and Storage*
- *ATR - Autothermal Reforming*
- *AEL - Alkaline Electrolysis*
- *PEM - Proton Exchange Membrane Electrolysis*

Source : IRENA 2023.

Requirements are significantly higher for saltwater, however, which requires desalination before use as an electrolyser. Roughly 83 kilograms of saltwater may be required to produce 35 kilograms of desalinated water that can then be used to produce 1 kilogram of green hydrogen through electrolysis (International PtX Hub 2024b). This process also yields 48 kilograms of brine, which can have adverse effects on local water sources and soils, potentially impacting food security and biodiversity (Gischler et al. 2023). Desalination plants also need renewable energy, further increasing land-use requirements and other environmental considerations associated with clean energy deployment. While surface water from lakes or rivers or groundwater require only 0.37 to 0.48 kilowatt hour per cubic metre for desalination, seawater requires 2.58 to 8.5 kilowatt hour per cubic metre, a significant increase.

Other discharges can occur in producing hydrogen derivatives, such as ammonia or methanol, including catalysts and other chemicals that can harm the environment, potentially contaminating water sources and soils during production and transportation if not handled properly.

Air-related and atmospheric concerns are other factors. While green hydrogen itself does not produce direct emissions, its combustion, like any combustion reaction that heats air to high temperatures, creates harmful pollutants called nitrogen oxides. These are linked to smog, acid rain and damaging health impacts such as asthma and respiratory infections. Recent studies have shown that hydrogen may exacerbate the effects of certain greenhouse gases, including methane, ozone, stratospheric water vapour and aerosols (Sand et al. 2023). It may increase the ability of methane to linger in the atmosphere. Although research is still ongoing, some indications suggest that methane contributes to global warming much more significantly than the same quantities of carbon dioxide emissions (Lakhani 2023). The production and transportation of hydrogen requires rigourous safety and assurance measures to prevent fugitive methane emissions.

Navigating the solutions

The environmentally friendly nature of green hydrogen should not blind policymakers to the imperative for strong environmental regulatory frameworks and safeguards for all projects. One priority may involve strengthening the capacity of local institutions to conduct environmental assessments, including through dedicated units deeply immersed in the local context and international collaboration on best practices. Bolstering environmental appraisal capabilities locally helps define the suitability of green hydrogen based on local environmental priorities, recognizing that the concept of sustainability is highly dynamic across time and space.

To mitigate project impacts, environmental policies should enforce rigorous assessments and regulations to protect ecosystems, particularly in areas of high ecological value. This includes preserving natural habitats, minimizing land degradation and locating renewable energy projects away from critical wildlife corridors and sensitive landscapes.

Strong water management tools and frameworks help to uphold sustainable development and 'do no harm' principles (e.g., water and wastewater management requirements for hydrogen in western Australia). If desalination is used to produce green hydrogen (as in Algeria and Saudi Arabia, for instance), countries should follow appropriate environmental studies and international standards on the appropriate discharge of water and wastewater. In water-stressed areas, compelling project developers to oversize desalination capacity may be a possibility to prevent impacts on the water use of existing communities. The Office Chérifien des Phosphates (OCP) Group OCP project in Morocco, for instance, has sought to build excess desalination capacity to supply its workforce (Ricardo 2024).

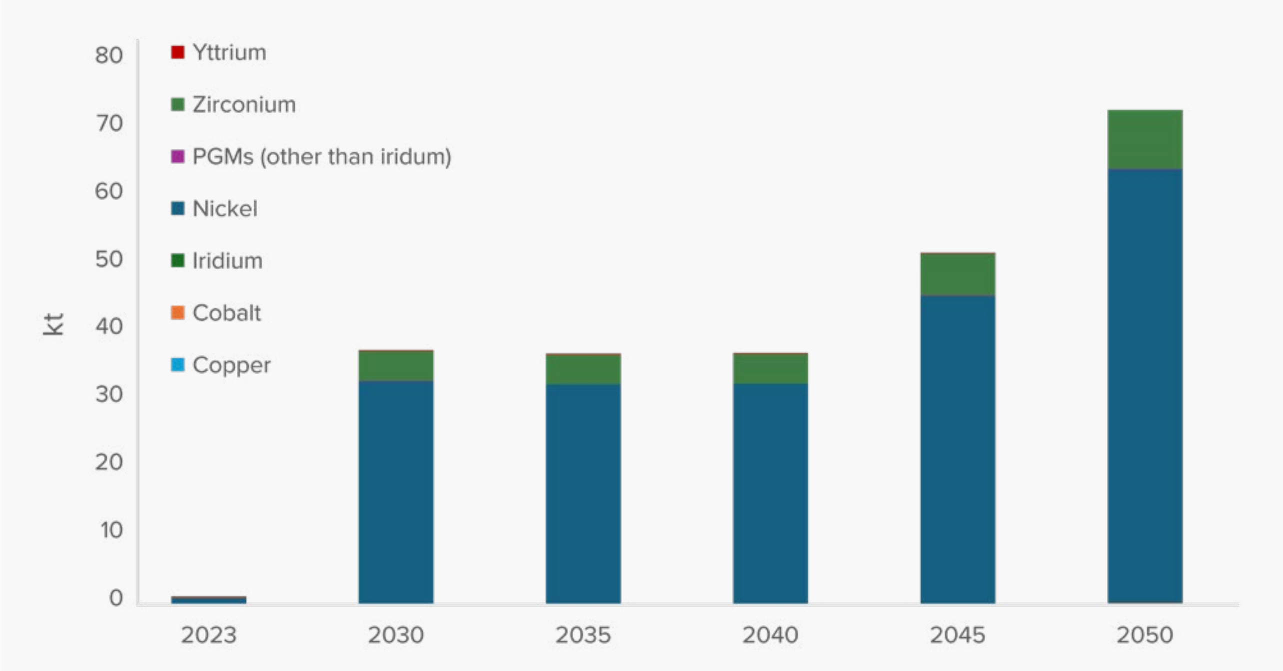
4.2 Critical minerals

Opportunities

Many parts of the green hydrogen value chain will require increasingly large amounts of a broad range of critical raw minerals. This presents an opportunity for countries with mineral deposits or existing production to capture greater value.

A number of critical minerals are in electrolysers. PEM electrolysers require platinum group metals, including iridium; alkaline electrolysers depend on nickel. Fuel cells, which convert hydrogen into electricity, will increase demand for platinum and palladium. Other essential minerals, across the value chain, include copper, cobalt, zirconium and some rare earth elements (Figure 9).

Figure 9. Critical mineral demand for hydrogen technologies



Source: IEA 2024c. Note: All values are for a stated policy scenario. PGMs refer to Platinum Group Metals

Many minerals for green hydrogen technologies are geographically concentrated. For example, South Africa and Zimbabwe jointly account for 41 percent of global palladium production and 66 percent of global platinum production, with South Africa leading on iridium production globally (USGS 2024d). Indonesia and the Philippines jointly account for 61 percent of nickel production (USGS 2024c) and the Democratic Republic of the Congo for 74 percent of global cobalt production (USGS 2024a). Peru and Chile produce 35 percent of copper output (USGS 2024b).

Challenges

Many issues in other extractive sectors in terms of resource sustainability largely apply to critical minerals. Land-use concerns, environmental degradation, and water stress and contamination have all occurred in mining operations globally. Fears persist around the massive scale-up of mining needed to meet demand for energy transition technologies.

While almost all critical minerals for green hydrogen are in various developing countries, processing stages most often are not. The majority of critical minerals is processed in China closer to downstream industries (Zhou 2024). While this tendency has been changing for some minerals (e.g., nickel processing in Indonesia), supply and demand for global critical minerals has become a source of significant geopolitical tensions and competition. Developing countries looking to maximize value must consider these issues.

Navigating the solutions

Critical mineral requirements must be considered holistically, along the green hydrogen value chain, to avoid limiting sector growth. While increased demand may present an opportunity for critical mineral-producing or processing countries to expand production, this should not come at the expense of environmental, social and governance considerations.

Countries looking to further develop critical mineral sectors may concurrently explore investments in exploration, international collaboration and measures to attract investment, such as through improvements in permitting and licensing, regulatory and fiscal regimes—while striving to create longer-term local benefits. A focus on circularity and sustainability is needed, including through more investment in minerals recycling and secondary recovery to decrease pressure on primary production.

Avoiding historical extractivist patterns and dependencies requires safeguards against scenarios where producer countries become sacrifice zones for the energy transition in the Global North. To reduce dependency on resource-intensive supply chains and mitigate risks of replicating extractivist models, countries should explore alternative production pathways—such as agro-produced ethanol reforming and biogas reforming. These bio-based options can complement mineral-intensive hydrogen technologies by leveraging agricultural residues and organic waste, offering more localized, lower-carbon hydrogen production while supporting rural economies and energy diversification.

6 *On the danger of carbon reductionism, see Kassem and Estevez (2022) and Chang, Lebdioui and Albertone (2024).*

05.

A LEVER FOR SHARED PROSPERITY: AVOIDING ENCLAVES AND RISKS OF TECHNOLOGICAL OBSOLESCENCE

The prospects of a green hydrogen economy have captivated countries across the world, particularly in regions with abundant renewable energy potential. For many developing nations, green hydrogen presents a potential opportunity for economic growth, not only through exports but also through structural transformation and the development of new industrial linkages, value addition and industrial upgrading.

As nations look to harness this opportunity, however, they must carefully navigate the risks of falling into extractivist models and traditional patterns of commodity dependence and technological obsolescence. Green hydrogen plans need to be carefully integrated within broader inclusive development policies.

5.1 Structural transformation and economic diversification

Opportunities

The green hydrogen sector provides three main economic opportunities for producing nations:

(i) Financial benefits from exports, including export revenues and foreign exchange generation.

(ii) The improved carbon cost-competitiveness of existing industries through decarbonization, particularly those reliant on fossil fuels that are increasingly targeted by carbon tax mechanisms globally.

(iii) New investments in energy-intensive industries that can rely on existing capacity for producing low-cost and clean hydrogen. In addition to retrofitting existing industries, the availability of low-cost green hydrogen can attract businesses in entirely new industries that find it profitable to rely on domestic hydrogen production. This process advances economic diversification and reduces dependency on traditional commodity exports.

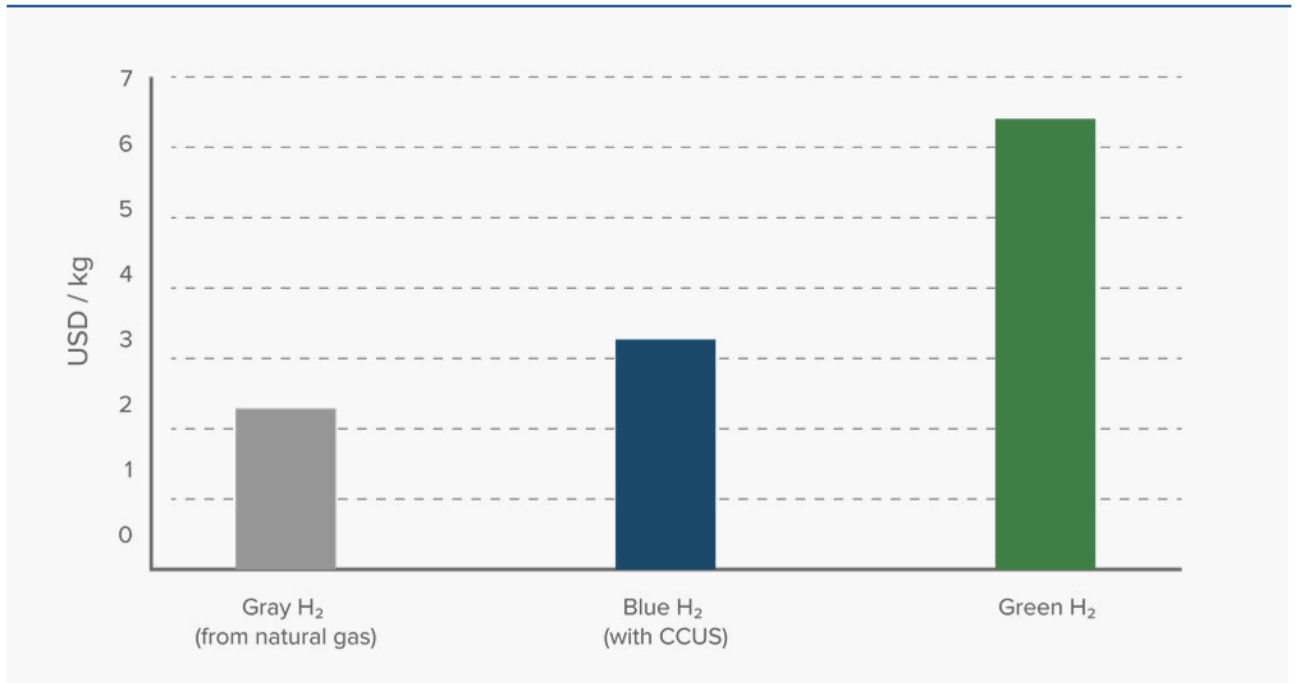
Challenges

The path to a development-oriented hydrogen economy presents some challenges for developing countries. While green hydrogen exports may produce economic growth, countries that do not take measures to avoid past patterns of resource extraction risk becoming mere suppliers of raw hydrogen, with little value addition to support domestic job creation and industrial transformation.

Two thirds of planned investments in the hydrogen sector are already concentrated in industrialized regions, such as East Asia, Europe and North America. Developing nations to date mainly serve as raw material exporters (IRENA 2022a; Lebdioui 2024). This divide echoes historical relationships of resource extraction, where value addition occurs outside the region of production, leading to limited local economic benefits. Developing nations seeking to benefit from the hydrogen sector must avoid becoming enclaves for hydrogen production while missing out on the broader economic gains of industrialization and technological advancement. For hydrogen investments to help build a resilient, diversified economy, they must contribute to local value chains, infrastructure development and job creation.

The green hydrogen sector is still at an early stage of development, with many uncertainties surrounding its technological and market viability. Innovations are rapidly emerging but with no clear pathway to profitability or technological dominance. Market demand is expected to grow, yet the long-term outlook remains unclear as green hydrogen is still the most expensive source of hydrogen, especially compared to fossil fuel-based hydrogen sources, as shown in Figure 10. Costs for existing grey hydrogen plants remain the lowest across all regions (new plants are slightly higher due to construction and technology upgrades). Blue hydrogen costs tend to be consistently higher than grey hydrogen but significantly lower than green hydrogen.[7]

Figure 10. Average production costs of different types of hydrogen (2023)

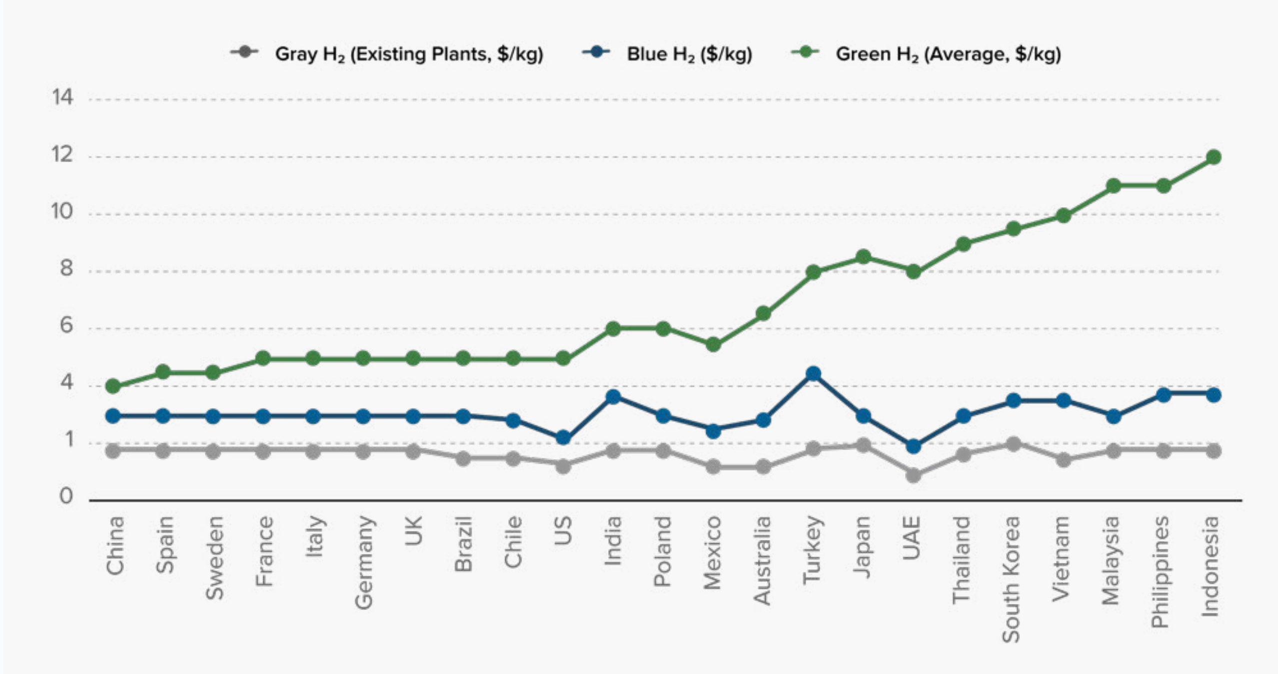


Source : Authors' elaboration based on BloombergNEF data.

Looking beyond global averages, the cost differential between green and grey hydrogen varies widely across nations (Figure 11). The cost of green hydrogen fluctuates the most, between $4.5 and $12 per kilogram, reflecting differing production costs likely influenced by renewable energy availability, infrastructure and other local economic factors. Brazil, China, Italy and Spain have some of the world's lowest differentials between green and grey hydrogen costs (less than $4 per kilogram). In Indonesia, Malaysia, Thailand, United Arab Emirates and Viet Nam, the differential surpasses $7 per kilogram, which raises important questions about the future cost-competitiveness of green hydrogen production.

7 From 2030, findings suggest that producing green hydrogen in a new plant could be as much as 18 percent cheaper than continuing to run an existing gray hydrogen plant in five major economies around the world (BloombergNEF 2023).

Figure 11. Estimated differentials in the levelized cost of hydrogen by energy source and market (average US dollars per kilogram in 2023)



Source : Authors' elaboration and estimations based on BloombergNEF data.

The imperative for cost reduction in green hydrogen production creates the risk of technological obsolescence, where current production technologies could be displaced by more cost-effective or sustainable alternatives in the near future. For example, recent breakthroughs in Boston Steel's production of green steel directly from electricity could potentially bypass the need for hydrogen in steel production. This highlights the value of careful foresight and adaptability in navigating the technological landscape.

Navigating the solutions

Directionality: integrating green hydrogen in broader industrial policy

For the green hydrogen sector to contribute meaningfully to human development, it must be integrated into a broader strategic planning process, with interministerial coordination and clear objectives for how it can drive core economic objectives, such as job creation, economic diversification and technological upgrading.

Countries that have successfully developed low-carbon technology manufacturing supply chains, such as those exporting solar panels and wind turbines, have done so through proactive public policies that shape land use, labour costs and capital allocation. These policies have fostered necessary productive capabilities to manufacture advanced technologies domestically, even when resource endowments were not favourable. Applying the same policy approach to the green hydrogen sector could harness its benefits for the domestic economy.

Promoting a socially inclusive hydrogen economy requires a multidimensional, proactive policy approach, based on careful coordination of energy, fiscal, industrial, skills development and labour market policies. Policymakers should consider creating national agencies dedicated to skills retraining and technological readiness to prepare local workers and industries for participation in the hydrogen economy.

Technological foresight

Given considerable scope for technological disruption in both the production and consumption of green hydrogen, countries must find ways to better assess exposure to obsolescence risks. A long-term outlook is essential, as the technological landscape remains fluid. Substitute technologies could emerge to improve hydrogen production (e.g., new generation electrolysers) or replace hydrogen in key sectors, such as green steel production.

Countries may find it useful to create and strengthen technological foresight units within ministries of energy, industry, or science and innovation to anticipate potential disruptions and identify opportunities for local links in the hydrogen value chain. Policymakers should be prepared to adapt to technological changes and prioritize versatile green hydrogen production systems to remain competitive in the global green hydrogen market.

Cautious experimentation: first-mover (dis)advantages at the height of the learning curve

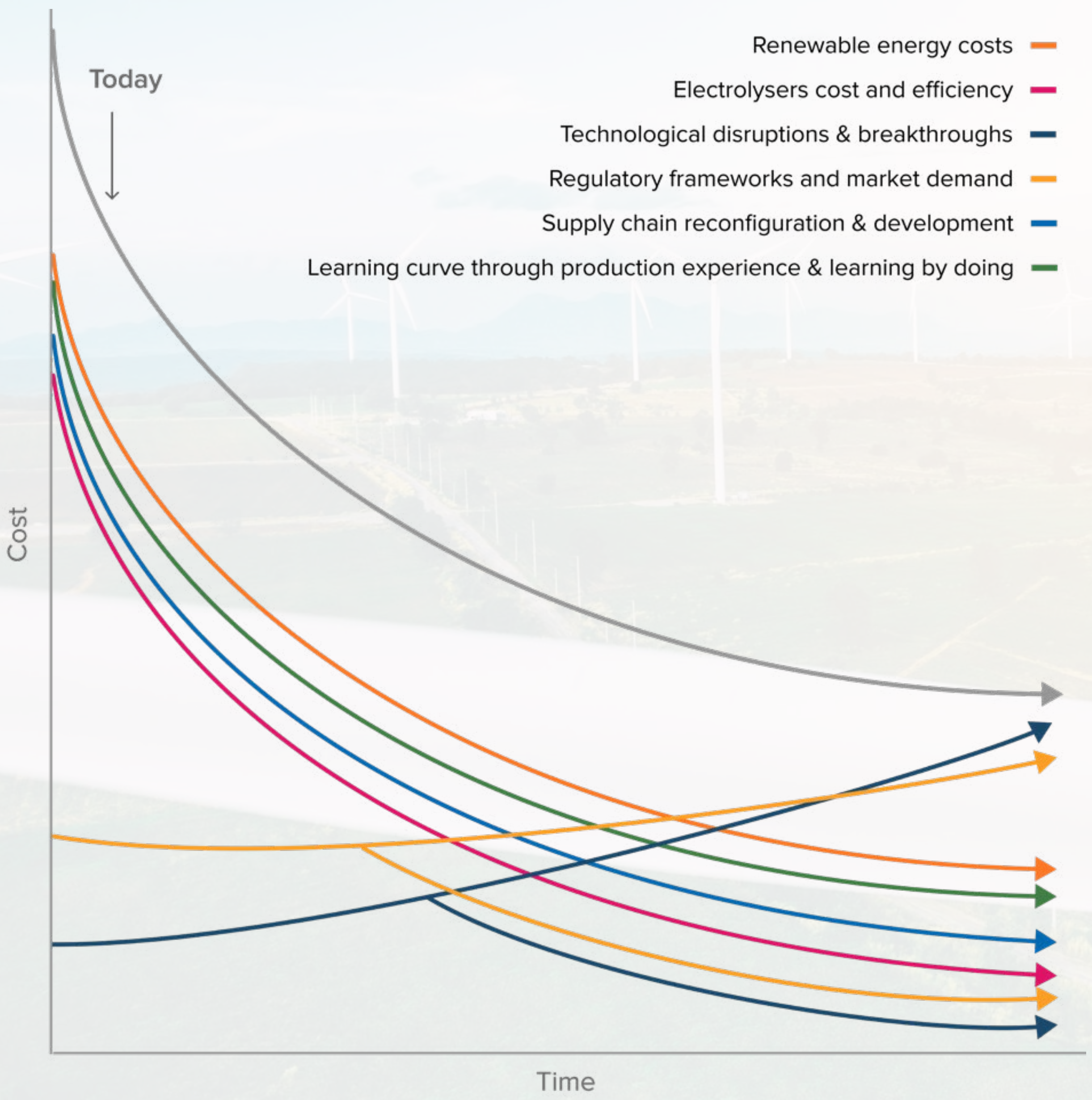
The development of new technologies, including green hydrogen, follows a learning curve. As companies and industries produce more of a given technology, they gain experience, improve efficiencies and adopt innovations, all of which help to reduce production costs over time. The learning curve for green hydrogen is still in its early stages. Costs are high, and technological and market uncertainties are considerable (Figure 12.) Although many countries are eager to position themselves as first-movers, the benefits are not always clear.

First-movers typically aim to capture early market share, build technological capabilities and establish strategic partnerships before competitors. The uncertainties of future market demand and the rapid pace of technological advancement, however, pose significant risks to early entrants in the green hydrogen sector, especially in countries with limited fiscal space. Countries that jump into hydrogen development too quickly may find themselves investing heavily in technologies (e.g., alkaline and PEM electrolysis) undergoing rapid innovation or infrastructure that could quickly become obsolete.

A cautious, experimental approach may be more appropriate. Observing technological advancements, market developments, regulatory frameworks and lessons from early entrants could eventually inform more cost-effective and scalable hydrogen development strategies. As part of an experimental approach, countries might find it useful to pursue pilot projects, phased investments and the gradual scaling up of hydrogen technologies rather than plunging into large-scale investments at the outset.

A more cautious approach allows flexibility, giving governments and industries a chance to reassess the viability and cost-effectiveness of green hydrogen as the technology evolves in a more mature, predictable market. Furthermore, similar to the fossil fuel sector, future market shares in low emissions fuels such as hydrogen are likely to be driven more by production costs than early market penetration, especially in scenarios where green hydrogen demand will be large enough to accommodate various producers in different regions.

Figure 12. The green hydrogen cost curve: drivers and prospects



Renewable energy costs

Electricity accounts for roughly three quarters of green hydrogen production costs, making the long-term decrease in the cost of renewables key for the cost-competitiveness of green hydrogen. Renewable costs are expected to continue to decline (between 2010 and 2020, the price of solar PV fell by 85 percent), but competing demand for renewable generation capacity and critical mineral supply bottlenecks could limit capacity available for green hydrogen production.

Source : Authors' elaboration

Electrolyser costs and efficiency

Electrolyser costs are expected to significantly drop by 2030, within a range of 30 to 85 percent across different types of electrolysis technology. Concurrently, supply chain constraints, critical mineral shortages, technological challenges, performance bottlenecks and overestimations of cost reductions could decrease cost reduction rates.

Supply chain reconfiguration and development

The reconfiguration and development of new supply chains for green hydrogen production components are key to achieving secure supplies and avoiding material shortages as production scales up. Risks, including geopolitical tensions, trade tariff escalations and a lack of government support mechanisms, could affect production scale-up and a deepening of economies of scale.

Learning curve through production experience and learning-by-doing

The accumulation of knowledge, industrial experience and learning-by-doing could increase the competitiveness of green hydrogen production. For instance, learning rates for electrolysers were estimated to be in the range of 25 to 30 percent for both alkaline and PEM electrolysis. Concurrently, many new jobs could be created, requiring significant up-skilling and training to provide an adequate labour supply and avoid interruptions in the growth of the sector.

Regulatory frameworks and market demand

Future demand for green hydrogen hinges on regulatory frameworks and support mechanisms. Over 50 countries have adopted hydrogen strategies since 2020, but uptake requires further regulatory frameworks, new standards and certifications, and policy incentives to reduce markets risks that could hinder investment. Inadequate policy support, the lack of a clear long-term vision or policy shifts could create market uncertainties for both producers and consumers of green hydrogen.

Technological disruptions and breakthroughs

Future technological breakthroughs will determine potential end-uses and the cost-competitiveness of green hydrogen, either by increasing demand (for example, for industrial uses, maritime transport or aviation) or disrupting it (for example, through innovations that lead to electrification solutions for hard-to-abate sectors, such as steel).

5.2 Fiscal sustainability and debt considerations

Opportunities

Financing green hydrogen projects requires careful consideration of a nation's financial health and development priorities. Using public funds may signal a strong national commitment to green hydrogen and help attract private and international investors. Yet allocating existing public resources or even borrowing funds could further strain fiscal space in countries where it may already be limited. Alternative financing models such as public-private partnerships may be more appropriate. For example, countries could offer land, regulatory concessions or co-financing arrangements in exchange for equity or local benefits, while private or foreign partners lead on capital investment.

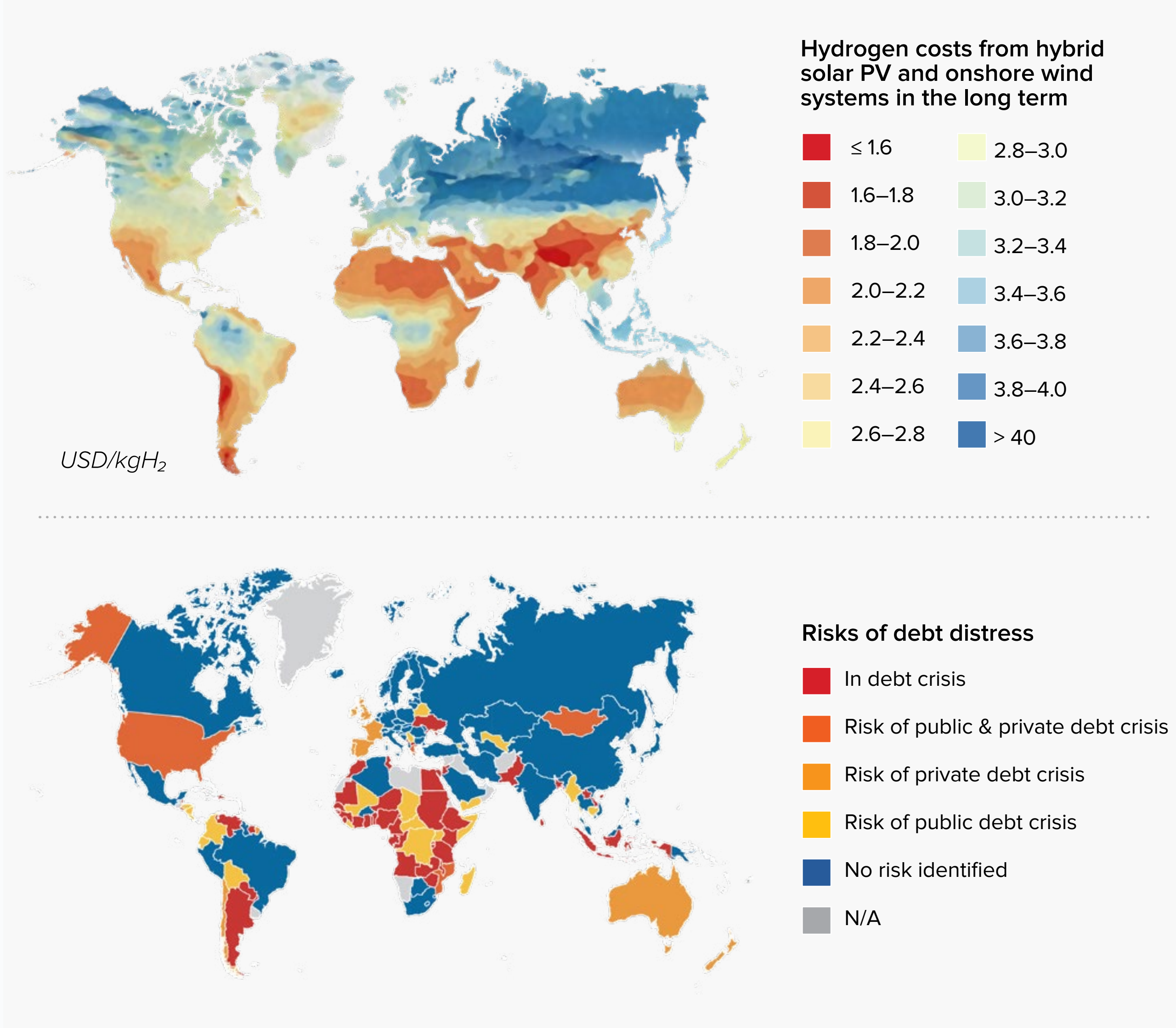
Challenges

The initial investment required to develop a green hydrogen economy is substantial (Figure 13). High production costs, including the need for substantial infrastructure, and the current lack of cost-competitiveness compared to alternatives pose substantial financial risks, particularly for fiscally constrained developing nations. A recent study highlighted that producing green hydrogen remains prohibitively expensive, with costs ranging between $500 and $1,250 per ton of carbon dioxide reduced (Shafiee and Schrag 2024). This is much higher than the costs of removing a ton a carbon through carbon capture and storage (Shafiee and Schrag 2024).

Furthermore, significant technological and market uncertainties constrain the developmental value proposition of investing in green hydrogen. These investments come with low expected rents, raising questions about the long-term reinvestment potential, and whether investments will translate into redistributive measures and sustainable development for local communities. Green hydrogen production, still far from achieving cost-competitiveness, is highly unlikely to generate profits comparable to those of fossil fuels today.

Resorting to external borrowing to finance green hydrogen projects may place additional pressure on government finances (Weidlich 2023). Scarce fiscal resource might be drawn away from critical areas such as healthcare of education that offer a higher return on investment, including in terms of human well-being. Inequities in borrowing practices can worsen fiscal pressures and even disparities in energy access. Despite significant labour, land and construction cost advantages, developing countries often pay more for renewable energy projects than countries in Europe and North America, for reasons that include higher financing costs (Figure 14; Lebdioui 2024).

Figure 13. Hydrogen costs from hybrid solar PV and onshore wind systems in the long term (top), and risks of debt distress (bottom)

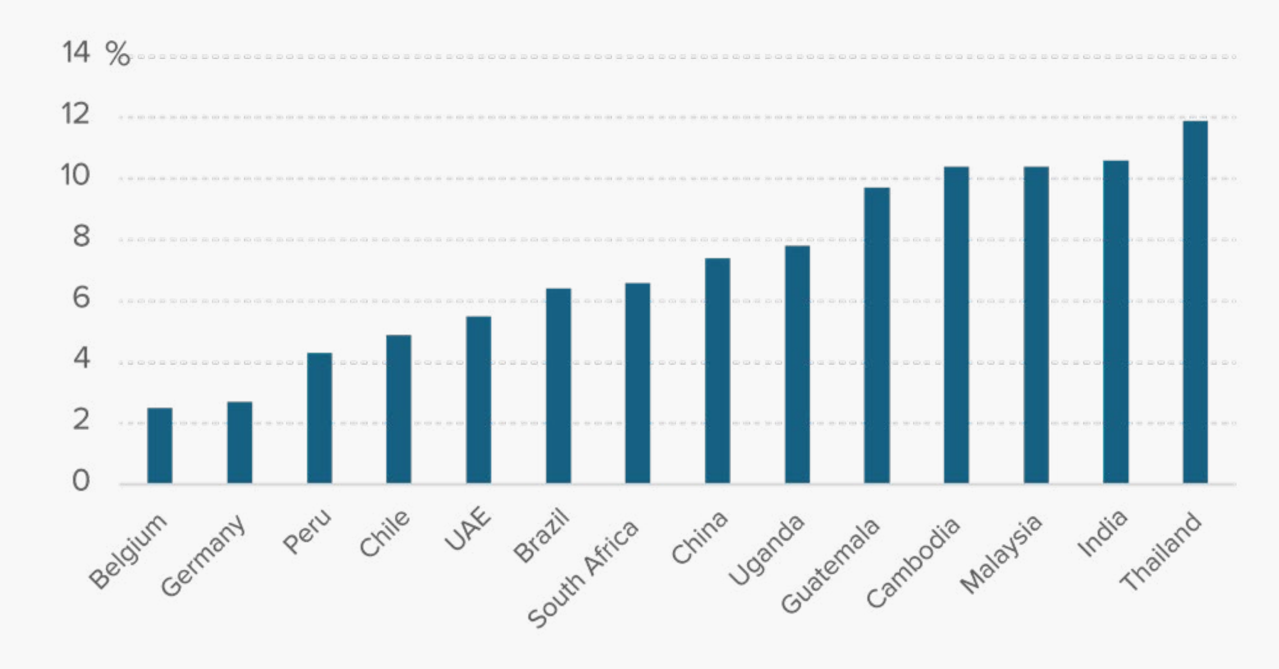


Source : Debt Justice Data Portal, IEA.

In Africa, for instance, the cost of capital for renewable energy projects is even higher than for fossil fuel investments, implying that the continent may miss out on boosting green electricity production by 35 percent under a 2°C transition pathway (Ameli et al. 2021). In India, the cost and terms of debt can add an astounding 24 to 32 percent to the cost of utility-scale wind and solar PV projects (Nelson and Shrimali 2014).

While it is often assumed that renewable energy investments are first and foremost driven by natural conditions, capital has not moved towards areas with the highest potential[8] and greatest need to close the energy access gap. In contrast to non-renewable resources, criteria beyond resource availability influence renewable energy investment (Lebdioui 2024).[9]

Figure 14. Weighted average cost of capital for solar PV projects at 2017 interest rates



Source : Authors' elaboration based on Steffen 2020.

Navigating the solutions

Solutions to mitigate risks in green hydrogen finance have typically involved blended finance models (combined public and private investments to share risks), concessional financing from multilateral development banks and international financial organizations, and de-risking measures and other guarantees to make projects more attractive to investors. For instance, Chile's green hydrogen plan is partly financed by a $245-million investment from the European Investment Bank and KfW Development Bank, a $150 million loan from the World Bank and a $400 million loan from the Inter-American Development Bank (Reuters 2024a). The European Union recently pledged to give South Africa two grants of about $35 million to accelerate its green hydrogen plans (Reuters 2024b).

The de-risking agenda is increasingly prominent in discussions on mobilizing private finance for green hydrogen. Yet there are reasons to be concerned where the role of the State is predominantly to 'escort' private capital towards green investments. Gabor (2023) explains that the de-risking State orients private capital to achieve public policy priorities by tinkering with risks/returns on private investments in sovereign bonds, currency, social infrastructure, and most recently, green industries, leading to a state-capital relationship where capital dominates (Gabor 2023). Development by de-risking poses severe limitations as it is not embedded within an autonomous strategic vision of the State. It structurally weakens the ability of the State to discipline private capital into pursuing green industrialization while enabling new green rules to be written by powerful investors and countries in the Global North (Gabor and Sylla 2023).

There are other ways to navigate the opportunities and risks of investing public funds in green hydrogen projects. A strategically cautious approach includes restricting public investment to the renewables-based electricity generation segment of hydrogen projects. By separating the financing of renewables-based electricity provision and electrolysis, countries can limit risks in green hydrogen production to renewable energy production, for which alternative demand sources exist. Investing in renewables generates a wide range of benefits and multiplier effects,[10] and increases the attractiveness of green hydrogen to investors whose projects can rely on a more stable supply.

It is generally prudent for developing countries to avoid allocating scarce public funds to high-risk green hydrogen ventures. Private investors and high-income nations with greater financial flexibility and a higher capacity to absorb potential losses should lead initial investments. This approach allows the distribution of the substantial costs of the early stages of technology development and market formation. By shouldering the financial burden, international partners can facilitate the advancement of green hydrogen technologies, driving down costs through economies of scale and technological innovation, and paving the way for safer investments in the future.

Once the technology matures and green hydrogen becomes more economically viable, developing nations can participate with reduced financial risk. This strategy not only safeguards the limited fiscal resources of developing countries but also enables them to benefit from the maturation of the learning curve, following technological advancements and market developments. Allowing richer partners to subsidize the costs of the first-mover disadvantage in green hydrogen development effectively promotes global technological progress while protecting the fiscal stability of developing economies.

In sum, a balanced approach where countries leverage a mix of public investment, borrowed funds under favourable terms and private sector participation might not suffice. A more cautious and strategic approach is required to reduce exposure to risks associated with green hydrogen projects while increasing public benefits from them. Thorough strategic fiscal participation, feasibility studies, transparent financial planning and stakeholder engagement, countries can steer investments in green hydrogen so they contribute positively to the nation's development goals without compromising financial stability.

8 UNDP's De-risking Renewable Energy Investment (DREI) Framework offers a structured approach to addressing these barriers by combining policy de-risking instruments.

9 Africa has almost unlimited potential for solar capacity (10 terawatts), abundant hydro (350 gigawatts), wind (110 gigawatts), and geothermal energy sources (15 gigawatts), with some estimates that Africa holds 39 percent of the world's renewable energy potential, more than any other continent (IRENA 2022a).

06.

CONCLUSION: HOW COUNTRIES CAN STEER GREEN HYDROGEN AT THE RIGHT SPEED, TIME, AND IN THE RIGHT DIRECTION

As hydrogen gains momentum globally, developing nations must take proactive steps to navigate this new frontier. Countries need to move forward at the right speed and time, and in the right direction. The hydrogen economy holds immense potential, but its trajectory will depend on policies making it a driver of human development rather than another chapter in the history of resource exploitation and extractivism. The route that countries should take largely depends on their starting point and intended destination.

This concluding section summarizes key reflections on the social, ecological and economic dimensions of green hydrogen development. It outlines recommendations to avoid past mistakes and seize future opportunities.

Moving beyond extractivism by harnessing energy resources to drive inclusive growth and promote social equity

Green hydrogen must not become an enclave economy that marginalizes communities or exacerbates inequality. **Decades of research have shown the dangers of the so-called 'resource curse', where natural wealth enriches a few while leaving the majority behind.** Countries now have the tools to avoid this scenario through well-designed policies for social inclusion. Skills development, labour market policies and welfare frameworks will prepare local populations to participate in the hydrogen economy. Job creation strategies could prioritize workforce training in green hydrogen technologies, including to support workers from fossil fuel industries to transition to new roles. Renewable energy additionality in green hydrogen projects will help avoid additional burdens on the domestic electricity system that could leave (or even push) local communities behind on energy access, despite it being among the greatest enablers of socioeconomic development. Addressing potential social disparities requires fostering inclusive development overall, with benefits reaching all citizens, particularly vulnerable groups.

Sustainability implies ensuring green hydrogen's environmental footprint for both consuming and producing nations

Green hydrogen is often touted as a clean energy solution but its production carries significant ecological and environmental risks. Its reliance on renewable electricity requires vast amounts of land and water, while the production of electrolysers and associated technologies depends on critical minerals such as lithium, cobalt and nickel. These resources often come from environmentally sensitive regions, raising concerns about biodiversity loss, water stress and mining-induced degradation. Countries should adopt policies that prioritize the sustainable management of these resources, incorporating lessons learned from past extractive industries. **For green hydrogen to be truly sustainable, a more limited environmental footprint at the consumption stage in one nation should not come at the expense of environmental damages at the production stage in another.**

Each country's unique ecosystem can offer specific advantages in addressing the challenges of green hydrogen. For instance, nations with abundant solar or wind energy potential can tailor their hydrogen strategies to leverage these natural assets. Countries with robust biodiversity might draw on bio-inspired innovations to enhance energy efficiency and minimize environmental harm (Lebdioui 2022). Tailored approaches that integrate socio-environmental contexts will help align hydrogen development with ecological preservation.

10 As explained by the United Nations, investments in renewable energy will pay off. The reduction of pollution and climate impacts alone could save the world up to $4.2 trillion per year by 2030.

Implementing productive development policies to seize a green hydrogen window of opportunity have temporal implications

Driving economic transformation through green hydrogen will require more than a narrow focus on energy production. Given limited fiscal rent opportunities, countries need to embed hydrogen strategies in broader productive transformation policies, ensuring that hydrogen becomes a lever for sustainable development. Local value addition and linkage development—such as in manufacturing electrolysers, building hydrogen infrastructure and exporting expertise—offer important avenues forward but need to be carefully assessed given expected technological disruptions in green hydrogen production processes. Nations seeking to make the most of green hydrogen as an opportunity for industrialization and social inclusion need to integrate the technology at the core of a joined-up policy approach. This involves coordinated energy, industrial, innovation, environmental, fiscal, and skills, welfare and labour market policies.

Temporal considerations are critical. **Windows of opportunity exist for hydrogen-based industrialization but in many ways are still opening. Considerable benefits may come from cautious and gradual approaches that allow time for market and technological uncertainties to subside.** While some advocate for first-mover advantages in the hydrogen sector, the benefits are not always clear. Early adopters risk locking into obsolete technologies or oversaturating niche markets, while later entrants can capitalize on technological advancements and falling production costs. A ‘first-follower’ or ‘second-mover’ approach may be advantageous, particularly for fiscally constrained developing nations aiming to develop cost-competitive green hydrogen production as global demand grows. Countries should carefully evaluate the timing of their entry to balance short-term gains with long-term sustainability.

Financing and debt sustainability: a strategically cautious approach to using public funds and transferring financial risks to those who can afford it

Financing green hydrogen projects requires careful consideration of a nation's fiscal situation and priorities. Many developing countries have constrained budgets, limiting the scale of investment without external financing. Additional borrowing can exacerbate debt levels, however, potentially leading to financial instability.

Developing nations may find it useful to adopt a strategically cautious approach, focused on financing the least risky segments of renewable energy value chains, while high-income nations and private partners subsidize the costs of the first-mover disadvantage in green hydrogen development. Private investors and high-income nations with greater financial flexibility and a higher capacity to absorb potential losses should lead initial investments in green hydrogen. This approach distributes the substantial costs of the early stages of technology development and market formation. **By shouldering the financial burden, international partners can facilitate advances in green hydrogen technologies, driving down costs through economies of scale and technological innovation, and paving the way for safer future investments.**

Through strategic fiscal participation that avoids additional debt and builds on transparent financial planning, countries can harness the positive contributions of investments in green hydrogen for national development goals without compromising financial stability.

Taking into account geopolitical implications

The geopolitical dimensions of green hydrogen demand and supply chains deserve greater attention. Green hydrogen stands to have profound impacts on established socioeconomic, technological and geopolitical trends around the world. **At the same time, regional energy policies, resource dependencies, international trade dynamics and the internal politics of nations that are major consumer markets and energy players will deeply influence hydrogen production and trade.** Nations rich in renewable energy resources, for instance, may become key exporters of green hydrogen, reshaping global energy markets and trade relations. Dependencies on critical minerals required for hydrogen technologies could introduce new vulnerabilities, and fossil fuel exporting countries that perceive a competitive threat from green hydrogen may delay the deployment of this technology. Furthermore, with falling renewable energy costs but persistently high costs for transporting hydrogen, the production of green hydrogen entails significant supply chain reorganization that is likely to further regionalize energy relations (IRENA 2022b). Countries will need to develop strategies to navigate geopolitical complexities, minimize exposure to risks and secure their place in future hydrogen markets.

Charting a human-centred course: different starting points, destinations and routes forward

Green hydrogen offers both opportunities and challenges for developing nations. With the right policies, it can drive inclusive growth, ecological sustainability and economic transformation. Poorly designed strategies, however, risk repeating past mistakes, leading to enclave economies, technological obsolescence or even a new resource curse. To avoid this scenario, countries should in general adopt a strategic, holistic approach integrating hydrogen development into broader industrial and social policies. **For green hydrogen to fully support human development, each country should also pursue policies tailored to its unique context and ambitions.** These should align hydrogen strategies with national social conditions, environmental priorities and economic transformation needs.

Given diverse starting points and wide-ranging environmental, energy, social and economic goals, countries need to clearly define and prioritize their objectives. When policy goals are overly broad or numerous, strategies risk losing focus, making implementation more complex and reducing the likelihood of success. Policies with multiple simultaneous targets are also more difficult to evaluate effectively, potentially hindering the ability to measure progress and adapt strategies as needed.

In conclusion, whether green hydrogen becomes a tool for prosperity or a source of further socioeconomic pressure and conflict lies in the hands of policymakers. Navigating this journey is a test of governance and a defining moment in the pursuit of global sustainability.

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