REPORT

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THE ROLE OF GREEN HYDROGEN IN A JUST, PARIS-COMPATIBLE TRANSITION

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THE ROLE OF GREEN HYDROGEN IN A JUST, PARIS-COMPATIBLE TRANSITION

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ABBREVIATIONS

CBAM	Carbon Border Adjustment Mechanism
CCS	Carbon capture and storage
CCUS	Carbon capture, utilisation, and storage
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
DFI	Development finance institution
DRI	Direct reduction iron
EBRD	European Bank for Reconstruction and Development
EIB	European Investment Bank
EJ	Exajoule
EOR	Enhanced oil recovery
EU	European Union
ESG	Environment, Social, and Corporate Governance
FPIC	Free, Prior, and Informed Consent
GDP	Gross domestic product
GHG	Greenhouse Gas
GW	Gigawatt
G7	Group of 7
H4D	Hydrogen for Development
IEA	International Energy Agency
IMF	International Monetary Fund
IMO	International Maritime Organisation
IRENA	International Renewable Energy Agency
KfW	Kreditanstalt für Wiederaufbau - German Development Bank
Km	Kilometer
LCOE	Levelised cost of electricity
LNG	Liquefied natural gas
m^3	Cubic meters
MDB	Multilateral Development Bank
Mt	Megatonnes
PEM	Proton exchange membrane
PV	Photovoltaic
RE	Renewable energy
R&D	Research and Development
SOEC	Solid oxide electrolysis cells
SDG	Sustainable Development Goal
TFC	Total final consumption
TW	Terawatt
UN	United Nations
USD	United States Dollar

01 INTRODUCTION AND OBJECTIVES

To meet the goals of the Paris Agreement, strong shifts in the energy sector are essential. In a 1.5°C-compatible world, fossil fuel production and consumption needs to end. According to the IEA, no additional investment in fossil fuel production is required for a pathway towards net-zero by 2050 (IEA, 2021d). This means that fossil fuel infrastructure needs to be decommissioned, often before its technical lifetime, and alternative revenue and energy sources developed (IEA, 2022e). The declining global demand for fossil fuels and rising demand for renewables and zero emission alternatives will change the global geoeconomic and geopolitical landscape. While fossil fuel exporters face rising stranded asset risk and need to find alternative sources of income and diversify exports, countries with renewable resources and critical raw minerals could see new lucrative revenue streams and gain influence in a shifting international landscape.

The Paris Agreement highlights the fundamental connection between addressing climate change and "equitable access to sustainable development and the eradication of poverty" (UNFCCC, 2015). While sustainable development is at the core of the Paris Agreement, inequalities between wealthy and poor countries, as well as among individuals within countries continue to increase (Chancel et al., 2022). The impacts of inequality are starkly evident in the energy transition, where countries have unequal access to **modern energy** – both within and between countries – and varying speeds of renewable energy buildout. Inequality poses a challenge to achieving the goals of the Paris Agreement justly. Countries that have historically contributed the least to climate change are some of the most vulnerable to the impacts of climate change, and income and wealth inequalities impact the capacity of countries and individuals to mitigate emissions and adapt.

Defined as affordable, reliable, and low-emission energy (OECD and IEA, 2010).

Green hydrogen is gaining prominence as a climate change and sustainable development opportunity and pushed strongly by countries across the Global North and South. While green hydrogen is in its nascency, it offers a potentially lucrative opportunity for resource-rich countries and a decarbonisation solution for industrialised countries. For resource-rich countries in the Global South, the production of low-cost green hydrogen could support the development of **upstream**, **midstream**, and **downstream** industries, facilitate domestic decarbonisation, and, in cases of surplus, yield export revenue. Scaling green hydrogen production can directly or indirectly impact several sustainable development goals (SDGs) including SDG 6 (clean water and sanitation), SDG 7 (affordable and clean energy), SDG 8 (decent work and economic growth), and SDG 13 (climate action). For countries in the Global North, importing green hydrogen could supplement domestic production and help decarbonise hard-to-abate industries.

The upstream hydrogen supply chain refers to the production of green hydrogen using renewables. The midstream supply chain encompasses storage, conversion to derivatives, and transportation of hydrogen. Finally, the downstream hydrogen supply chain refers to the usage of hydrogen (e.g., fertiliser production or steel production).

A growing number of international initiatives target green hydrogen. Green hydrogen was included in the 2021 Glasgow Breakthrough Agenda (COP26 Presidency, 2021) and the G7 launched a Hydrogen Action Pact in 2022 (G7 Germany, 2022). Public spending on hydrogen research and development (R&D) is increasing and accounted for 5% of the global R&D budget for clean energy technologies in 2021 (Bermudez et al., 2022). The European Investment Bank (EIB) recently announced EUR 1 billion of indicative funding to support large-scale public sector hydrogen projects (EIB, 2023). And the World Bank Group created the Hydrogen for Development Partnership (H4D) to foster capacity building and knowledge sharing and increase developing countries access to concessional financing to scale hydrogen projects (World Bank, 2022). As international cooperation and hype around hydrogen continues to grow, stakeholders must also grapple with the challenges posed by green hydrogen production to ensure it fulfils its dual objectives. Considerable emphasis should be placed on ensuring hydrogen development does no harm to water, energy, or land access and provides a developmental "value added" for producers (Morgen et al., 2022).

This report intends to serve as a starting point to guide public **development finance institutions (DFIs)**, particularly multilateral development banks (MDBs), and policymakers in defining priorities related to green hydrogen. DFIs with their thought leadership, public mandate, and commitments to align their financial flows with the Paris Agreement, and close connection to the countries, have multiple entry points to support a sustainable transition, including in the context of green hydrogen. Policymakers will also play a pivotal role in defining parameters for green hydrogen production which respect to climate and sustainable development objectives.

DFIs are specialised public institutions (e.g., banks, credit unions, insurance firms, and investment companies) whose core objective is to contribute to the realisation of sustainable development goals and human rights.

The report presents green hydrogen's opportunities and obstacles within the framework of sustainable development and the mitigation goals of the Paris Agreement. It investigates under which conditions and to what extent green hydrogen can support domestic and global decarbonisation efforts while serving development objectives. The report establishes principles for investments in sustainable green hydrogen production, addressing two dimensions: first, how to ensure that investments promote positive impacts on sustainable development and avoid negative consequences, and second, how to ensure alignment with the rapid and profound decarbonisation of the energy system. The scope of the report does not cover hydrogen development in the Global North but discusses sustainability criteria for importers.

This report is the first output under this stream of research and is complemented with case studies on Namibia, India, and Colombia **(see summaries in → Section 5)**. Concrete recommendations for incorporating our considerations into existing processes of MDBs will be provided in a third deliverable in early 2024.

02

FOSSIL FUEL DEPENDENCE AND ECONOMIC IMPLICATIONS

Many developing and emerging economies rely to a large extent on fossil fuels. These same economies often face high debt distress and rising climate risks which impact their ability to reach the SDGs and transition to 1.5°C-compatible pathways. Strong dependencies on fossil fuels cause different risks. The following sections explore how exposure influences countries. The text aims mainly at describing why a transition away from fossils, as it is required for meeting the mitigation goals of the Paris Agreement, needs to be carefully understood and planned for countries reliant on fossil fuels. It should however be noted that overreliance on any single energy carrier or source, including green hydrogen, could have similar implications.

2.1 FOSSIL FUEL EXPORTERS

Fossil fuels often represent a critical source of income for producing countries. And yet, the development of fossil fuels has not always led to the enhanced well-being of the population. Countries with abundant natural resources can have poorer development and economic outcomes than countries with fewer natural resources – often referred to as the resource curse (Sachs and Warner, 1995). Over dependence on raw material exports (e.g., critical minerals or fossil fuels like oil or coal) can also concentrate rents in low value creation activities and potentially harm the economic competitiveness of higher value-added sectors – a phenomenon referred to as Dutch disease.

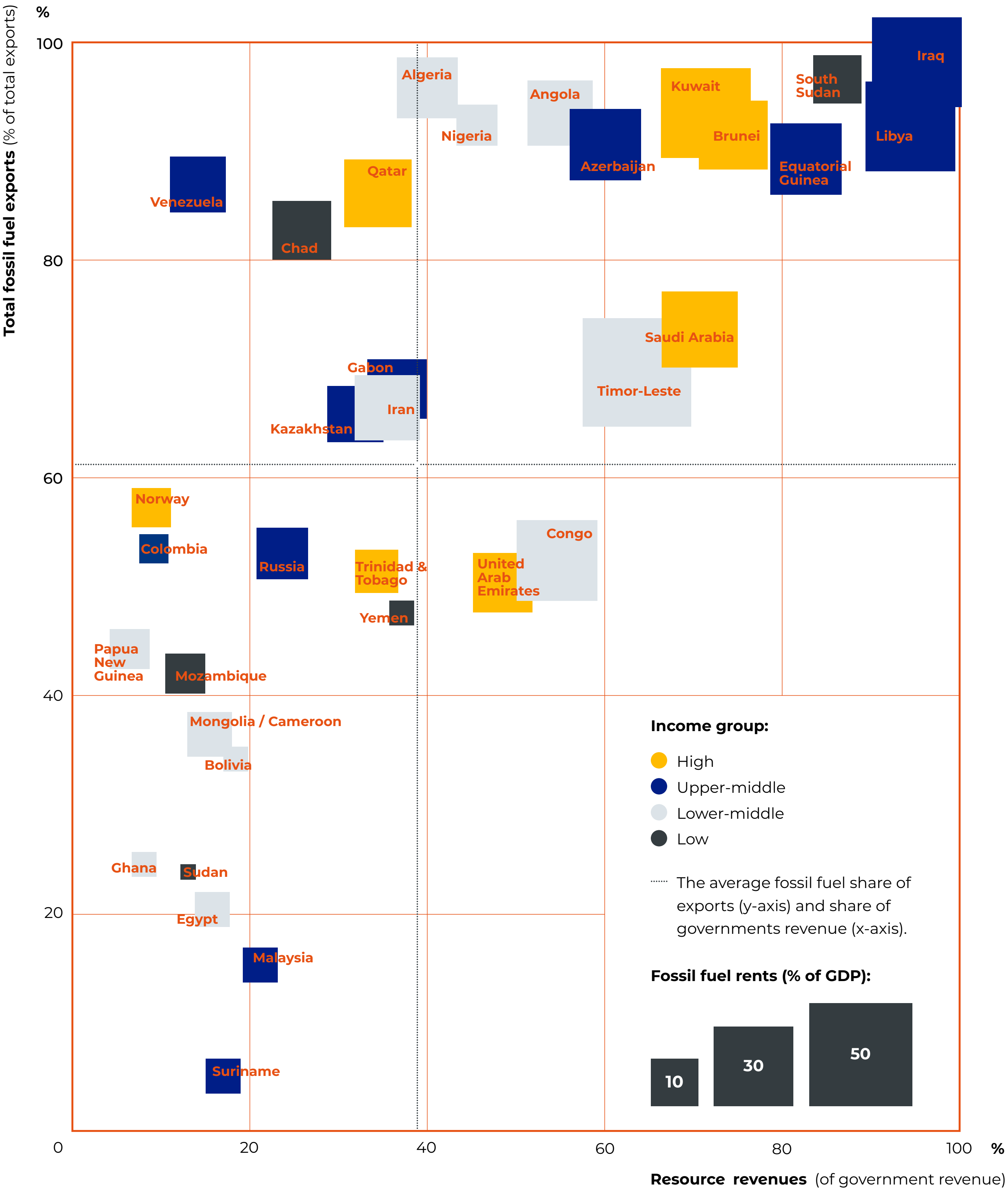
The resource curse is not inevitable and a number of academics have challenged the assumptions and methodology behind the resource curse (Easterly, 2002; Maloney, 2002; Stevens et al., 2015).

Fossil fuel dependence leaves producing countries' budgets vulnerable to international demand fluctuations and market price volatility. Jensen (2023) found that on average in fossil fuel export-dependent economies, fossil fuels account for over 60% of total exports and 39% of total government revenue **(→ Figure 1)**. The figure shows that fossil fuel dependence varies and is spread across geographies. Thirteen of the forty fossil fuel dependent countries are classified by the World Bank as “Fragile and Conflict-affected Situations”. Fossil fuel dependent economies will be exposed to fiscal and economic consequences of global decarbonisation which could exacerbate conflict and inequalities. With fossil fuel demand phasing out, dependent countries stand to lose more than 60% of oil rents between 2030-2040 under a global net zero scenario (Jensen, 2023). Exporting countries need to transition towards other economic sectors, independent of the availability of fossil fuel reserves.

Countries with abundant fossil fuel resources will need alternative sources for generating revenues in a 1.5°C compatible world and strategies in place to ensure a just transition for all. Managing the impact of transition in fossil fuel dependent developing economies with already strained public finances and low levels of per capita earnings will be challenging without substantial international support (Jensen 2021a).

2.2 RISKS FOR IMPORTERS OF FOSSIL FUELS

Countries reliant on fossil fuels imports are similarly vulnerable to global energy market price fluctuations and supply shortages, as vividly illustrated by the energy crisis following Russia's invasion of Ukraine. The sudden scarcity of Russian fossil gas and geopolitical instability not only increased energy import bills and caused fuel shortages but led to inflation increasing consumer prices for many goods (Eurostat, 2022b; IEA, 2022a). Arndt et al. (2023) found that across 19 developing



Source: Adapted from Jensen 2023a.

Figure 1

Fossil fuel dependence of fossil fuel exporters

countries, fossil fuel price increase caused by the Russian invasion was the single largest contributor to national GDP losses and that increased fuel prices resulted in higher production costs across most sectors.

Countries that rely on energy supply imports can spend substantial amounts of their budget on energy imports. In Senegal, refined petroleum and crude petroleum are the first and third largest imports, and accounted for about 16% of imports by value in 2020 (Climate Action Tracker, 2022). The same year, more than half of the EU's gross available energy was imported (Eurostat, 2022a). Reliance on fossil fuel imports negatively impacts energy security, particularly if a country is overly dependent on imports from few partners and can lead to a trade deficit.

2.3 UNEQUAL INTERNATIONAL TRADE

Future energy trade should not only support decreased dependence on fossil fuel commodities globally, but also address local development needs in a way that decreases economic disparities between developed and developing countries. Unequal trade dynamics between countries exporting raw materials and those exporting manufactured goods have remained persistent over time and exacerbated economic disparities between developed, developing and emerging economies (Weber et al., 2021). Power imbalances in trade relations result in the impact of excessive resource consumption largely felt in the Global South where extraction and low value-added segments of the value chain are located. Research indicates that unequal exchange between the Global North and South over the period 1990 to 2015 drained from the South raw materials and embodied resources equivalent to USD 242 trillion (constant 2010 USD) (Hickel et al., 2022). The appropriation of resources without capturing value locally poses a threat to sustainable development and global justice.

A transition in line with the 1.5°C limit of the Paris Agreement and SDGs should support economic diversification in producer countries and build out domestic upstream, midstream, and downstream supply chains. Through building out domestic renewable energy and green technology value chains, resource rich countries can diversify exports from raw fossil fuel materials and low-value creation products towards high-value creation products. Green hydrogen offers an opportunity for countries abundant in solar and wind resources to harness their domestic assets for the dual purpose of aiding global and domestic decarbonisation endeavours, while advancing sustainable development goals at home. However, some stakeholders have raised concerns that green hydrogen trade will further the extraction of resources from the Global South to the Global North in the form of sunlight and wind power and not lead to developmental benefits (Kalt and Lekalakala, 2023).

03

HYDROGEN PRODUCTION AND ITS ROLE IN A 1.5°C COMPATIBLE TRANSITION

This section provides technical background on hydrogen production and describes, where supply and demand centres currently are. It also summarises the outlook for green hydrogen under decarbonisation scenarios.

3.1 HYDROGEN PRODUCTION

Hydrogen is a secondary energy source and versatile fuel that can be produced from a variety of renewable or non-renewable energy sources (e.g., coal, fossil gas, oil, biomass, renewables, nuclear, and oil) and production processes (e.g., coal gasification, stream reforming, electrolysis, etc.) (IEA, 2021b). Its potential to act as a decarbonisation solution strongly depends on the fuel and method with which it is produced. The fuel is the most abundant chemical substance in the universe but because of its low volumetric energy density, high flammability, and low liquification temperature, storing and transporting hydrogen presents a challenge (IEA, 2021b).

There is no globally agreed sustainability standard for green hydrogen or its derivatives. Hydrogen is often classified with different colours based on its production process **(see → Box 1)**. However, the IEA (IEA, 2023c) recently advocated for a move away from colour classification towards assessing the emission intensity of hydrogen production. Categorisation based on production process alone does not allow for precise insights into the sustainability and climate impact of hydrogen. They argue such a shift to internationally agreed emissions standards would enhance comparability among producers, increase transparency regarding production emissions, and facilitate regulation and certification requirements necessary for global trade. Consensus could also offer investors in the green hydrogen supply chain greater clarity and bolster investment. We continue to use the colour classification throughout the report as there is currently a lack of agreed standards.

In addition to emission standards, broader sustainability criteria are needed to ensure green hydrogen production and trade contributes to decarbonisation and sustainable development aims. Sustainability criteria for green hydrogen should consider, among other things: the renewable share of the energy mix; value chain emissions of hydrogen and its derivatives; good governance and transparency in export countries; participation of local civil society; overall economic interest of exporting country; value creation at local level and energy poverty in exporting country (The German National Hydrogen Council, 2021). It is also crucial to consider sustainable sourcing and management of inputs, for example land use for renewable energy, water for electrolysis, and nitrogen for green ammonia.

Box 1

Colour classification of hydrogen by production process

Hydrogen is classified and coded with different colours based on its production process. The most common classifications are:

Green hydrogen – Green hydrogen is produced via water electrolysis[1] with exclusively renewable electricity and releases the least amount of Greenhouse Gas (GHG) emissions. Its production is facilitated by an electrolyser and requires significant renewable energy and water inputs.

Grey hydrogen – Grey hydrogen is produced from natural gas or methane through steam methane reforming[2]. Crucially, GHG emissions are not captured. Most hydrogen currently produced is fossil fuel-based and utilises this method.

Blue hydrogen – Blue hydrogen is also produced with natural gas or methane, but the process relies on carbon capture, utilisation and storage (CCUS) to trap and store CO_2 emissions. Blue hydrogen is sometimes referred to as low-emission hydrogen. But it is crucial to note blue hydrogen production from fossil gas releases upstream and midstream GHG emissions, risks contributing to methane leakage, and often does not contribute to long-term carbon sequestration as most active projects utilise captured carbon for enhanced oil recovery[3] (EOR).

Black or brown hydrogen – Black or brown hydrogen is produced from coal. Black hydrogen refers to that produced from bituminous coal while brown hydrogen refers to that produced from lignite coal. Hydrogen is produced through coal gasification[4]. Black and brown hydrogen production releases high amounts of CO_2 and is the most polluting production process. Hydrogen produced through coal gasification can utilise CCUS, but there are technical challenges in deriving high purity hydrogen and CO_2 pure enough for use or storage (IEA, 2021b).

Pink hydrogen – Pink hydrogen is produced through the electrolysis of water powered by nuclear energy. While the process is low emission, it generates nuclear waste.

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[1] Electrolysis is the process of using an electrical current to split water (H_2O) into oxygen (O) and hydrogen (H_2). The electricity for electrolysis can be supplied from renewable or nonrenewable sources. The process is zero emission and produces only hydrogen and water when renewable energy is used (EIA, 2023a)

[2] Steam methane reforming is a chemical process that involves the reaction of carbon monoxide with water vapor to produce hydrogen (EIA, 2023b).

[3] Enhanced oil recovery is the process of extracting hard to extract oil that has not been retrieved from primary or secondary recovery techniques. CO_2 and other gases are injected into reservoirs which can improve oil mobility (through increasing its viscosity) and push oil towards the production well (McGlade, 2019).

[4] Coal gasification is a thermal-chemical procedure that transforms coal into a compound known as syngas which is comprised of carbon monoxide (CO), hydrogen (H_2), carbon dioxide (CO_2), methane (CH_4), and water vapor. This method entails the controlled partial oxidation of coal using air, oxygen, steam, or carbon dioxide to generate a gaseous fuel (Midilli et al., 2021). Coal gasification is used mainly in the chemical industry to produce ammonia.

Unabated refers to the use of fossil fuel combustion without the use of carbon capture and storage technology.

3.2 HYDROGEN SUPPLY AND USE TODAY

Today, hydrogen production predominately utilises **unabated** fossil fuels. In 2021, hydrogen production from natural gas (grey hydrogen) and coal (black hydrogen) accounted for 62% and 19% of total production, respectively (IEA, 2022b). The energy intensive process emits close to 900 megatonnes (Mt) CO_2 emissions per year (IEA, 2021b). **"Low-emission hydrogen"** accounts for the smallest share of current hydrogen production (0.7%) and is mostly produced with carbon capture and storage (CCS) (so-called "blue hydrogen") (IEA, 2022b) **(→ Figure 2)**.

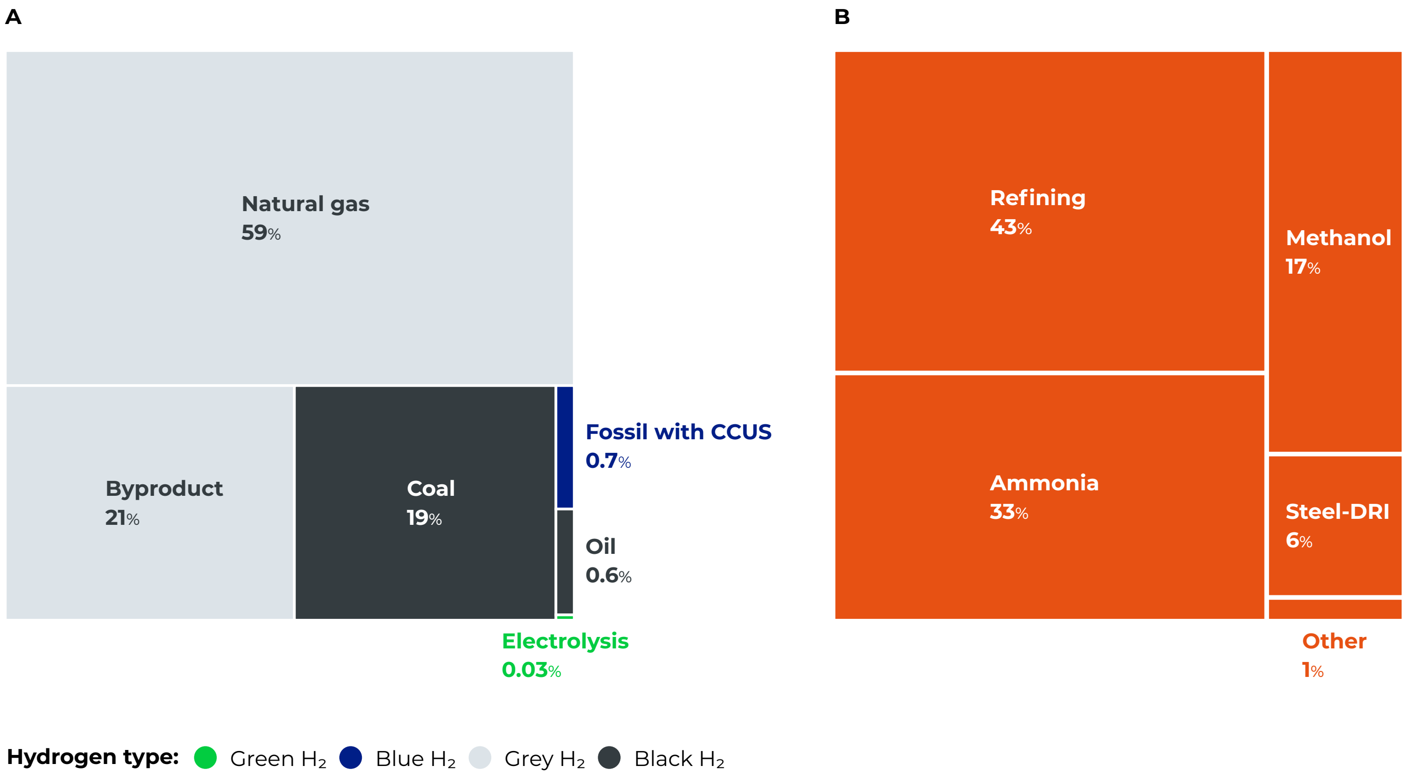
Green hydrogen today is on average more expensive than grey or blue (fossil-fuel based) hydrogen. In 2021, hydrogen produced from unabated natural gas ranged from USD 1.0-2.5/kg H_2 while hydrogen produced natural gas with CCS ranged from USD 1.5-3.0/kg H_2. Green hydrogen production ranged from USD 4.0-9.0/kg H_2 (IEA, 2022b). While hydrogen production from natural gas has been the cheapest option to date, it is highly susceptible to market volatility. Indeed, gas price fluctuations caused by Russia's invasion of Ukraine tripled the cost of grey hydrogen in 2022. Emission penalties under carbon pricing are expected to increase the future cost of unabated fossil-based hydrogen (IEA, 2021b)

The IEA uses the term low-emission hydrogen to refer to hydrogen produced from renewables (green hydrogen), nuclear (pink hydrogen), and biomass, and from fossil fuels with CCUS (IEA, 2022b).

In turn, falling renewable energy generation costs and technology improvements are estimated to make green hydrogen – particularly that powered by solar photovoltaics (PVs) – cost competitive with hydrogen produced from fossil fuels as early as 2030 (IEA, 2021b; The Hydrogen Council and McKinsey & Company, 2021b). Hydrogen production from hybrid solar PV and wind systems could fall to USD 1.5-2.0/kg H_2 by 2030 in some regions (e.g., North Africa, the Middle East, and China) (IEA, 2021b, p. 126). By 2050 it could fall below USD 1.0/kg H_2 by 2050 (IEA, 2022b).

Irrespective of the energy source or production method employed to generate hydrogen, it can be utilised for the same final applications. Traditionally hydrogen has been used in oil refining and as feedstock in industrial processes like methanol and ammonia production and as a reducing agent to produce direct reduction iron (DRI) for steelmaking. Oil and gas refining accounts for over 40% of global demand for hydrogen **(→ Figure 2)** (IEA, 2023a). The remaining demand is driven by the production of ammonia (33%), methanol (17%), and DRI (5%) (IEA, 2023a). Most hydrogen used in industry is produced with unabated fossil fuels, leading industrial hydrogen production to account for 680 Mt of CO_2 emission in 2022 (IEA, 2023a).

Green hydrogen is also increasingly seen to play a role in in non-traditional applications across industry, transport, power, and heat sectors (Liebreich, 2020). But, while the use of hydrogen is technically possible in various sectors, it is not always the most energy- or cost-efficient decarbonisation alternative and



Source: Authors based on IEA, 2021a, 2021b, 2021d.

Figure 2

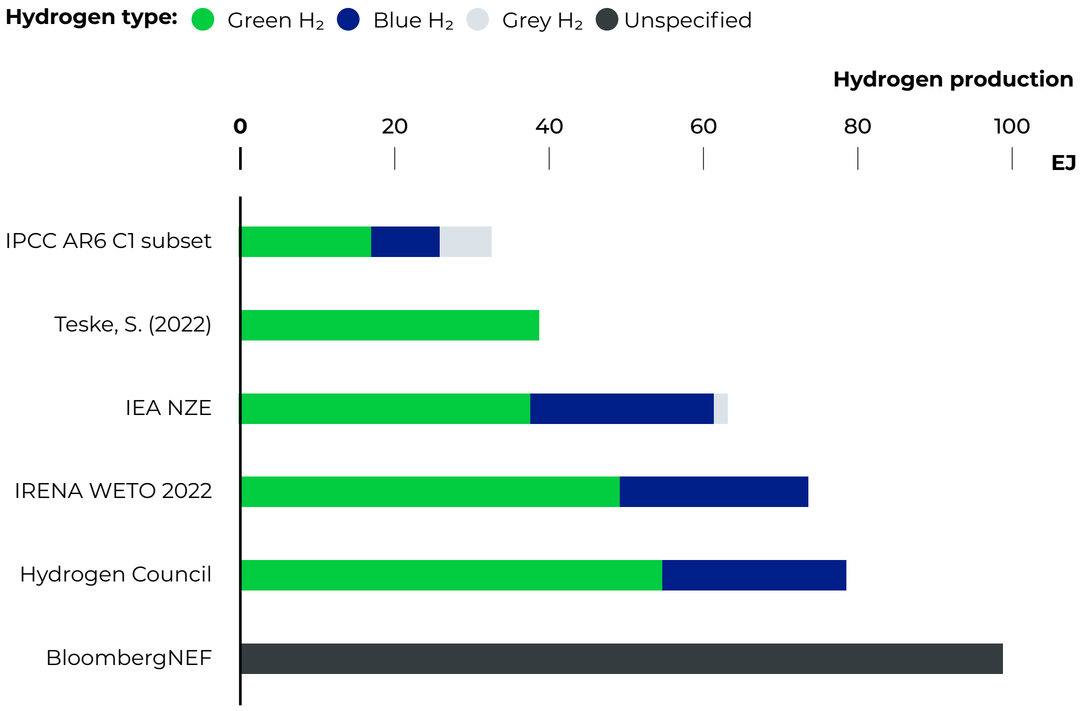
Hydrogen supply by production (A) and hydrogen demand by area (B)

production capacities are limited **(see → Section 4.2).** In Paris-aligned scenarios, green hydrogen has a targeted and limited role to play in so called no-regret applications. No-regret hydrogen applications are defined as use in sectors that are hard-to-abate where there is not a cheaper or more efficient alternative (e.g., electrification) (Andreola et al., 2021). There is a role for green hydrogen and its derivatives in decarbonising thermal energy use in industrial processes (e.g., steel production), serving as a feedstock that replaces fossil-based inputs to chemical processes (e.g., fertiliser production and petrochemical production), decarbonising transport fuel in remote locations where electrification is not possible (e.g., aviation, shipping, and heavy-duty mining), and storing electricity from renewables (IEA, 2019; de Villafranca Casas et al., 2022; Jaramillo et al., 2022).

3.3 DEMAND FOR GREEN HYDROGEN UNDER DECARBONISATION SCENARIOS

Worldwide hydrogen demand reached 95 Mt in 2022 (IEA, 2023a). The top consumers were China (29%), North America (17%), the Middle East (13%), India (9%), and Europe (8%). Estimates of future green hydrogen demand under Paris-aligned pathways vary widely from about 40 exajoule (EJ) to 100 EJ (or 333 – 833 Mt) **(→ Figure 3)** (BloombergNEF, 2020; IEA, 2021d, 2021b; IRENA, 2021, 2022b; The Hydrogen Council and McKinsey & Company, 2021a; Byers et al., 2022; Teske, 2022). Predictions vary depending on scenarios' assumptions about energy demand, technological development, market development, consumer preferences, and government support (Griffiths et al., 2021). The IEA predicts that in Paris-compatible pathways, hydrogen and hydrogen-derivatives will scale from 1% of total final consumption (TFC) today to 4% by 2030, and 13% in 2050 (IEA, 2021b).

Assuming hydrogen has an energy density of approximately 0.12 EJ per kg.



Source: Authors based on BloombergNEF, 2020; IEA, 2021d, 2021b; IRENA, 2021, 2022b; The Hydrogen Council and McKinsey & Company, 2021a; Byers et al., 2022; Teske, 2022.

Figure 3

Projected hydrogen production by 2050 in 1.5°C compatible decarbonisation scenarios

Existing climate mitigation scenarios however maintain the Global North's energy privilege and project large energy inequalities between the Global North and South into the future (Hickel and Slamersak, 2022). This means that projected hydrogen demand is based on mitigation scenarios that do not consider restricting the growth of energy consumption in the Global North. Hickel and Slamersak (2022) argue that a just transition requires energy convergence, where rich countries reduce energy use and emissions while developing countries are afforded sufficient energy for development. Such a global shift might affect the projected global demand for green hydrogen.

The application of hydrogen to new end uses is expected to rapidly scale after 2030, especially in hard-to-abate sectors where direct electrification is not a viable alternative (IEA, 2022c). The industrial sector is anticipated to remain a large consumer, but demand from oil refining is expected to decline in Paris-compatible scenarios where future oil demand decreases. Near-term demand is mostly anticipated in existing industrial centres in Europe, the United States, China, Japan, and Korea (IEA, 2023a) and lags behind for much of the Global South. In Europe, future hydrogen demand from industry for feedstock derivatives like ammonia is estimated to remain constant, while demand in the steel and chemical plastic recycling sectors rises (Andreola et al., 2021). Demand for green hydrogen and ammonia in transportation is also anticipated to increase, in particular in shipping due to **regulation** on the sulphur content in bunker fuels which incentivises decreasing heavy oil in shipping (IEA, 2019). On a global scale, the IEA's Net Zero Scenario projects a near-term hydrogen demand for grid injection – blending hydrogen into natural gas grids (IEA, 2021b). While **blending hydrogen** with gas can result in near-term emission reductions and promote hydrogen demand, it risks extending fossil fuel dependency and has minimal emission reductions .

The International Maritime Organisation (IMO) introduced new regulations on bunker fuels that limit sulphur content to no more than 0.5% in marine fuels to protect the environment and reduce sulphur oxides in the air. This is predicted to lead to increased hydrogen use in marine fuel production which can be used to comply with the sulphur regulation (Vedachalam et al., 2022).

The emissions avoided via blending depend on the cost of hydrogen and natural gas, the blended share of hydrogen, and the CO_2 intensity of the hydrogen input. If the hydrogen and gas inputs have near-zero emissions (green hydrogen and gas with CCS), a 5% blend (by volume) would reduce the emission intensity of the natural gas by 2% (IEA, 2019). Hydrogen is less energy dense than gas. Therefore, blending decreases the energy content of delivered gas, meaning the end user requires greater volumes.

3.4 TRANSPORTATION FROM PRODUCTION CENTRES TO DEMAND CENTRES

Regions with high potential for cost competitive green hydrogen production are not necessarily the places with high demand in the near-term. If green hydrogen is produced close to demand centres (e.g., industrial facilities or refineries), transportation and storage costs are minimal. However, if green hydrogen must be transported long distances to demand centres, the costs of transmission and distribution can amount to three times the production costs (IEA, 2019) and be economically unattractive compared to domestic production (Galimova et al., 2023).

The transportation of green hydrogen from production centres to demand centres entails inherent losses. Depending on its form, hydrogen can be transported via pipelines, road transport, or ships. Unique properties of hydrogen require specialised transport equipment to combat metal embrittlement and maintain pressure and cryogenic temperatures (IEA, 2019). Because of hydrogen's low energy density, it must be compressed, liquefied, or incorporated into derivatives (e.g., ammonia or liquid organic hydrogen carriers) to ease transportation. Shipping liquified hydrogen is a nascent industry – the first commercial ship was piloted between Australia and Japan in 2022 (Harding, 2019). The conversion of hydrogen for transportation to ammonia or a liquid organic hydrogen carrier and then reconversion before end-use entails additional efficiency losses (IEA, 2019) **(→ Section 4.2)**.

For shorter distances (under 1500 km), hydrogen can be transported via pipeline. Pipelines could also serve to store hydrogen which could then be utilised to balance out the grid (Hüwener and Martin, 2021). There is some potential to repurpose existing gas infrastructure for hydrogen transmission which could cut infrastructure investment costs and reduce the time needed to develop new transmission networks (IEA, 2022b). However, investment costs are still significant, and complex regulatory frameworks and technical limitations pose a challenge to repurposing gas pipelines (Jayanti, 2022). Not all fossil fuel infrastructure can be repurposed and there is a risk that investments to retrofit fossil infrastructure lock-in fossil fuel use under the guise that it is hydrogen ready.

In the future energy system, countries with competitive advantage in renewable energy resources could become sites of green industrial clusters (IRENA, 2022a). Relocation of energy intensive industries to locations where energy savings exceed additional shipping costs could support industrialisation, auxiliary supply chain development and economic development in green hydrogen producing countries.

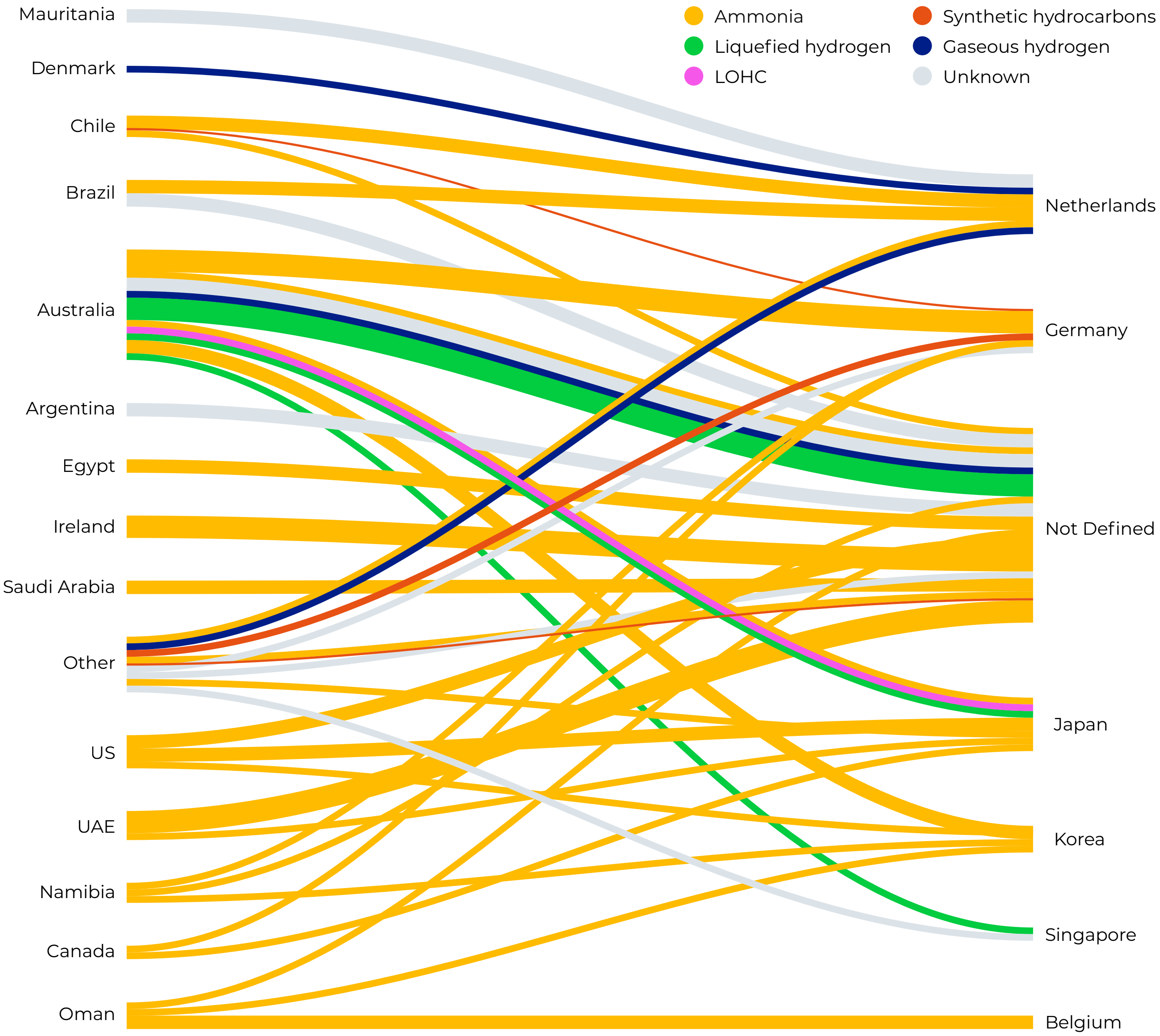
3.5 AN UNCERTAIN FUTURE FOR GREEN HYDROGEN

A growing number of stakeholders and countries are engaged in green hydrogen as an emerging decarbonisation solution. So far, over 41 countries have developed hydrogen strategies, which focus to varying degrees on producing green hydrogen domestically, increasing demand for green hydrogen, and building up partnerships with other countries to import or export green hydrogen (IEA, 2023a). Broadly, strategies set national targets for upstream and downstream infrastructure development (e.g., electrolysis capacity, retrofitting transmission networks, etc.), introduce policies that promote industrial application (e.g., public procurement quotas, mandates, or purchase subsidies), highlight anticipated future domestic demand, and encourage hydrogen clusters (i.e., co-locating production and demand centres).

Japan was the first country to formulate a national green hydrogen strategy in 2017 (METI, 2017). Other large demand centres have more recently released hydrogen strategies which often rely on building partnerships for import. The European Union's hydrogen strategy anticipates a demand of 20 Mt by 2030, half of which would be imported (European Commission, 2020). Germany's newly released National Hydrogen Strategy sets out a plan to build domestic hydrogen infrastructure, highlights envisioned sectoral usage, sets out sustainability standards, and notes hydrogen partnerships will be crucial to meet domestic demand needs (BMWK, 2023) – an import strategy is expected in late 2023.

Countries in the Global South are also publishing or developing green hydrogen strategies and roadmaps which anticipate varying degrees of near-term domestic demand and often plan to export to international markets. India sets out to be a leading producer and supplier of green hydrogen, with the objective to produce 5 Mt per year by 2030 with the potential to scale up to 10 Mt depending on the growth of export markets (Government of India, 2022). Namibia aims to produce 10-15 Mt of green hydrogen per year by 2050 despite minimal existing industrial capacity. In the near term, it plans to export and focus on building up domestic industry (Republic of Namibia, 2022). Colombia aims to build out a low carbon export economy along the hydrogen value chain and expects exports to yield more than USD 5 billion in revenue in the future (MME, 2021) **(→ Section 5)**.

While there are a growing number of hydrogen strategies, there is a risk that hydrogen targets are inflated and not reflective of the volumes of hydrogen needed to cover solely no-regret applications. A number of countries have indicated ambition to export green hydrogen but demand from international markets to off-take supply has yet to materialise at the same magnitude. While the IEA predicts high demand for green hydrogen in the future, the number of countries set to import is, so far, largely unclear or concentrated in Europe and Asia (IEA, 2022b) **(→ Figure 4)**. Questions remain around the location of production and demand centres (Galimova et al., 2023), as well as how technology advancements and policy will influence uptake. So far, most green hydrogen cooperations financed by the Global North have the objective to export the green fuel to Northern industrial demand centres.



Source: Authors based on IEA, 2023a.

Note: The graphic includes low-emission hydrogen which according to the IEA includes hydrogen derived from renewables, gas with CCUS, nuclear, and biomass.

Figure 4

Potential low-emission hydrogen trade flows

04 PRINCIPLES FOR A SUSTAINABLE, PARIS-ALIGNED GREEN HYDROGEN PRODUCTION

Green hydrogen's future role in the energy system necessitates clear sustainability criteria that steer investments towards high impact applications which are 1.5°C-compatible and support development priorities. Green hydrogen should be seen as more than just a climate mitigation tool; it represents a developmental opportunity for emerging and developing economies. A green hydrogen economy should not be at the expense of exporting countries and not exacerbate existing inequalities. Instead, new age energy and trade partnerships should present opportunities for countries with rich renewable resources to further their sustainable development priorities and decarbonise domestically.

The following sections present sustainable green hydrogen principles which emerged from the authors' research, encompassing both developmental considerations and the imperative alignment to 1.5°C-compliant energy sector transition. Such principles should be applied in conjunction with existing environmental, social, and corporate governance (ESG) criteria. Meeting sustainability criteria should be underpinned by rigorous environmental and socio-economic impact assessments to evaluate the potential consequences associated with green hydrogen production.

4.1 HIGH STANDARDS FOR DEFINING GREEN HYDROGEN

The climate impact of hydrogen depends on the source of energy utilised and the production process. For hydrogen to be considered green, it needs to be produced from renewable energy (RE). Emissions from electrolysis for green hydrogen production vary depending on the upstream and midstream emissions of electricity generation. Öko-Institut (2019) found that hydrogen produced with electrolysis only has a climate benefit when produced with over 70% renewable electricity. If hydrogen is produced using electricity from the average grid – which is often reliant on fossil fuels – its emission intensity can be around 24 kg CO_2-eq/kg H_2, similar to unabated coal (IEA, 2023c). **Only hydrogen that is supplied with 100% renewable electricity should be considered green.** For electrolysers that run off-grid this means that the electricity supply needs to come directly from renewable energy source. For electrolysers that are integrated in the electricity grid, the electricity they consume needs to be added elsewhere from renewable sources, so that the hydrogen production does not lead to additional consumption of fossil energy carriers.

The most common form, grey hydrogen, is largely replaced with and uncompetitive with green hydrogen production in 1.5°C scenarios. Additional grey hydrogen capacities should be considered “misaligned”. Blue hydrogen, where most of the CO_2 is captured and stored, can in theory produce low-carbon, yet not zero-carbon hydrogen. In practice, the technologies to sequester and store carbon are not yet economically and technically viable to reduce emissions at scale and do not result in complete emissions reduction. Relying on blue hydrogen as an instrument to support the formation of hydrogen markets, as some are suggesting, is a risky approach: CCS requires significant investments, and it is unclear whether there would be sufficient incentives to retire operations with CCS installations early and replace them with green hydrogen production. If not considered misaligned by default, blue hydrogen would require at least a very thorough check for alternatives, lock-in risks and potentially negative climate impacts. In line with previous work on Paris alignment of investments in the energy sector (Germanwatch & NewClimate Institute, 2018), we categorise nuclear-based (“pink”) hydrogen as “misaligned”.

4.2 AN EFFICIENT DECARBONISED GLOBAL ENERGY SYSTEM

Reducing GHG emissions to stay within the agreed temperature limits is a remarkable challenge, given the delays and inaction so far. This means that **all resources need to flow towards the most effective solutions, as fast as possible.**

Green hydrogen production and transportation is an energy intensive process with efficiency losses throughout production, conversion, and transmission. Efficiency losses along the supply chain, accumulate and ultimately impact the economic competitiveness and sustainability of green hydrogen. Because of its energy-intensive nature and efficiency losses, green hydrogen will not be the most energy- or cost- efficient solution in many cases (Liebreich Associates, 2021). Energy efficiency and direct electrification should be first order considerations (Lopez Legarreta et al., 2023). Adjusting agricultural practices and encouraging plant-based diets are additional measures that can limit the need for hydrogen as a feedstock for fertiliser production.

Increased electrolyser capacity, future cost reductions, and advancements in efficiency are anticipated to improve the cost competitiveness of green hydrogen against other production methods overtime (IEA, 2022b). The electrical efficiency of electrolysers varies by technology and ranges from about 56%-81% (low heating value) today, with technological improvements anticipated to lead to an improved efficiency of 70-90% in the future (IEA, 2019). To reach the required scale in hydrogen production, it needs to be economically competitive with currently used carbon-intensive technologies. And costs of green hydrogen will vary by country, meaning that not all will be competitive on an international market. Today, green hydrogen is hardly available. While future cost reductions in solar PV are anticipated to lower green **hydrogen production expenses**, limited production capacity and supply are expected to persist to the end of the decade meaning green hydrogen will likely remain a relatively expensive energy carrier. This means that its use should be limited to those cases where there are no viable alternatives.

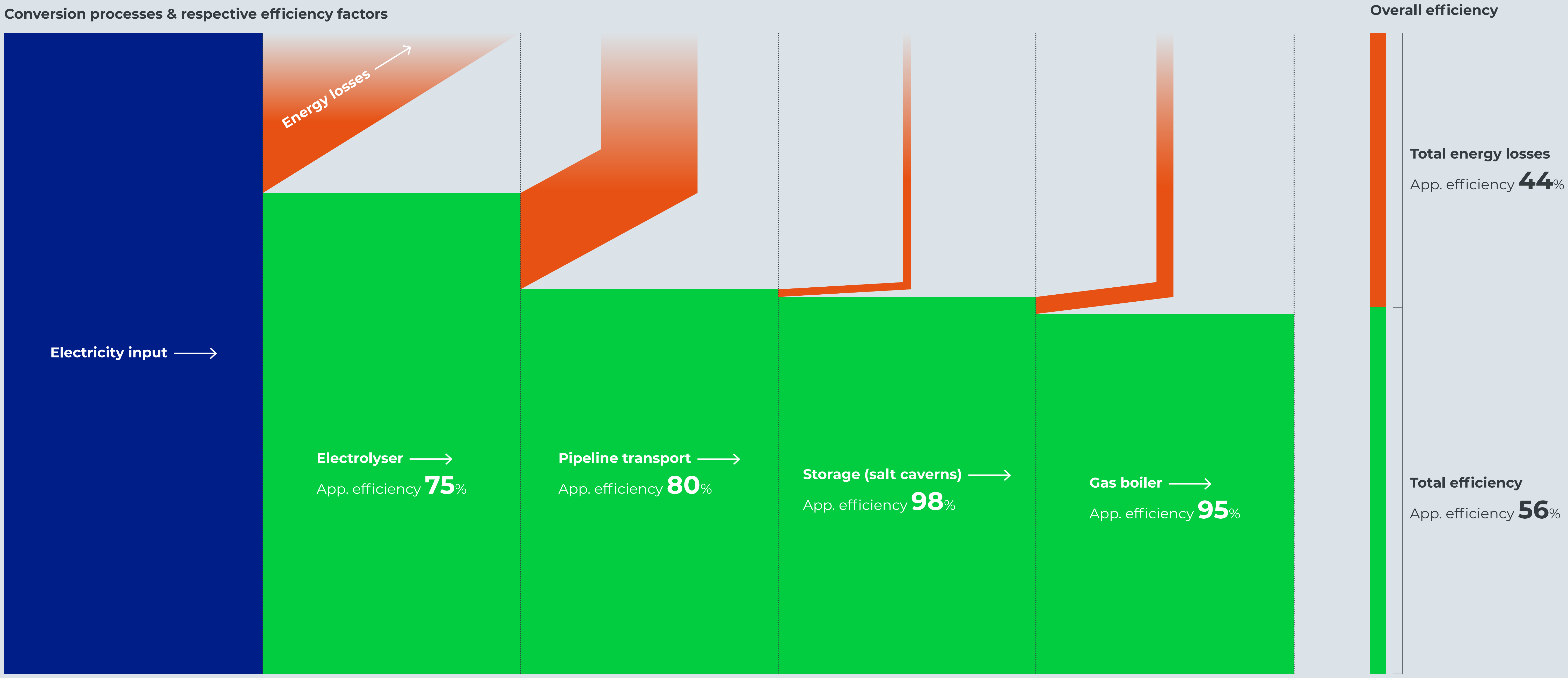
According to the IEA, in 2021 the average cost for different hydrogen production methods were: USD 1.0-2.25/kg H_2 for grey hydrogen; USD 1.5-3.0/kg H_2 for blue hydrogen; and USD 4.0-9.0/kg H_2 for green hydrogen. But the cost of hydrogen produced from solar could drop to USD 1.5/kg H_2 by 2030 and to USD 1.0/kg H_2 by 2050 (IEA, 2022b).

However, there are different end uses, currently being advocated by some, that are hardly compatible with a cost-efficient use of resources for decarbonisation and are incompatible with a 1.5°C pathway. For instance, Japan promotes co-firing ammonia derived from green hydrogen in coal-fired power plants, both domestically and across Southeast Asia.→ **Figure 5** illustrates the energy losses that would occur when using renewable energy to produce green hydrogen, which is then converted to ammonia and co-fired in coal-fired power plants. About 75% of the energy is lost along the simplified example of a supply chain, and additional energy needs for desalination of water might be required which are not included

Note: Electrolyser efficiency varies depending on electrolyser technology (i.e., Alkaline electrolyser, proton exchange membrane (PEM) electrolyser, or solid oxide electrolysis cells (SOECs) electrolyser). Efficiencies (η) range from 63-84% (IEA, 2019) and will likely increase in the future. The graphic assumes an efficiency of 75% from the electrolyser. Ammonia production uses 7-18% of total energy given as percentage of lower heating value of hydrogen (IEA, 2019). The graphic assumes an efficiency of 85% for ammonia production and a transport efficiency of shipping ammonia at 90% (Chatterjee et al., 2021). The efficiency losses of cofiring ammonia in a coal power plant depend on the age and location of the power plant. We assume a modern plant with an efficiency of 45% (IEA, 2019).

Figure 5

Example of an inefficient use of RE electricity: Energy losses in producing and co-firing ammonia in coal-fired power plants



Note: Electrolyser efficiency varies depending on electrolyser technology (Alkaline electrolyser v. PEM electrolyser v SOEC) electrolyser). Electrolyser efficiencies (η) range from 0.63-0.84. (IEA, 2019). We assume an efficiency of 75%. The transport efficiency of pipelines varies depending on distance, pipeline material, and hydrogen volume (i.e., if the hydrogen is blended or pure) (Klopčič et al., 2022). We assume an efficiency of 80% as a proxy. Storage in salt caverns has minimal losses, we assume an efficiency of 98% (IEA, 2019). Modern, highly efficient gas boilers have an efficiency of 95% (US Department of Energy, 2023).

Figure 6

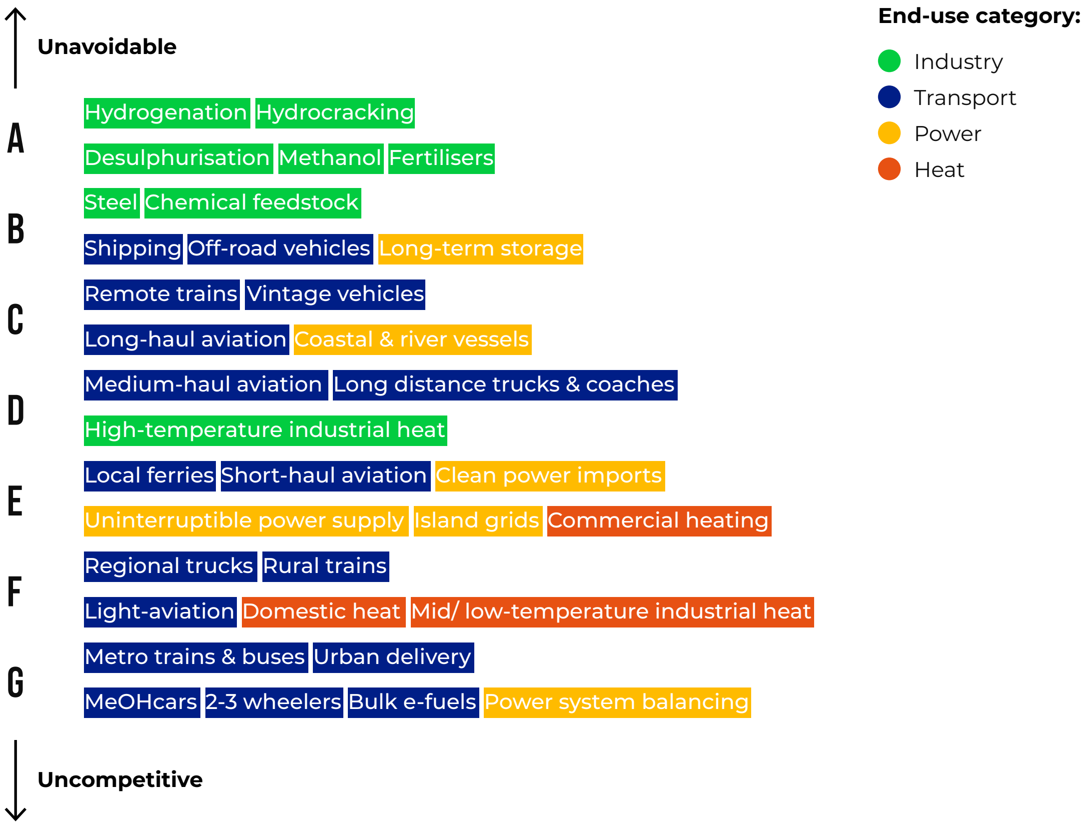
Example of an inefficient use of RE electricity: Energy losses in producing and importing green hydrogen for blending in gas boilers

in the graphic. The energy losses inherent in co-firing green ammonia with coal make the electricity output much more expensive than generating it directly with renewables. Renewable energy (RE)potentials and the option for an electricity grid connection would need to be extremely limited in a region for co-firing ammonia to become cost-competitive, assuming the process is not subsidized. And from a system perspective, a 100% hydrogen-fired gas turbine is more suited, given it can serve to cover short-term peaks in electricity demand and stabilise the grid. In 1.5°C-compatible scenarios, coal electricity phases out by 2030 in developed countries and 2040 globally (CAT, 2020) and increasingly the levelized cost of electricity (LCOE) for retrofitted co-firing coal plants is economically unviable compared with renewables (BloombergNEF, 2022). The potential of blending with or switching to green hydrogen cannot be an excuse to extend the life expectancy of fossil infrastructure.

Co-firing ammonia is only one example of a potentially counterproductive use of green hydrogen, others are e-fuels for passenger cars or blending hydrogen with fossil gas to burn in boilers for space or water heating. → **Figure 6** illustrates losses assuming a production of green hydrogen for the purpose of blending it in gas boilers. The electricity could alternatively power a heat pump, which extracts energy from the environment, thus yielding a greater amount of usable energy than what was initially invested in the system. Green hydrogen projects that are likely to fuel such inefficient end uses should be considered misaligned with the Paris Agreement, as they lead to inefficient use of scarce resources and risk locking in fossil fuel infrastructure and industries.

Producing green hydrogen for oil and gas refining should be considered misaligned or at least be approached with much caution, given that the sector needs to phase out, and that investments into fossil fuels risk becoming stranded. Future hydrogen demand for refining in industrial centres is anticipated to decrease under climate neutrality targets, for instance in the EU, demand is anticipated to be close to zero by 2040 and fully phased out by 2050 (Andreola et al., 2021). In the near term, a temporary exception could be made for the use of green hydrogen in oil and gas refining as an incentive to build up the production of green hydrogen more rapidly, which can later be shifted to future-proof use cases. However, there is risk that green hydrogen's use in refining locks in further reliance on fossil fuels and diverts supply from no regret applications. There is also risk that producers in the Global South are left with excess supply as demand from refining shrinks.

Aligned investments would be to cover green hydrogen projects that fuel demand from industrial processes that cannot be electrified, chemical processes where green hydrogen replaces grey hydrogen or its derivatives, for example fertiliser



Source: Authors based on Liebreich Associates, 2021.

Figure 7

Use cases for hydrogen in key end-use sectors

production, or aviation and shipping fuels **(→ Figure 7)**.

4.3 SUSTAINABLE AND JUST TRANSITIONS TO RENEWABLE ENERGY SUPPLY

For green hydrogen to support a globally just, sustainable energy transition, it is essential it supports the decarbonisation of all countries, and not only meets demands from the Global North. **Domestic energy needs and decarbonisation should be prioritised over exporting green hydrogen.** While renewables account for a growing share of global energy generation, in many emerging and developing countries renewables make up a small share of the energy mix today with most domestic energy demand reliant on fossil fuels or traditional biomass (IEA, 2022d).

To meet estimated global demand for green hydrogen in 2050 would require around 6,690 TWh of dedicated electricity per annum. This would equate to around 2,245 GW of onshore wind or 2,545 GW of solar PV (Collins, 2020) . The IEA estimates that by the end of 2024, global cumulative renewable capacity will reach 4,500 GW (IEA, 2023b). This shows the magnitude of dedicated electricity required.

Calculation modified from Collins (2020). Assumes a green hydrogen demand of 19 exajoules in 2050 which equates to about 139-158 Mt of green H_2 per year. Assumes 1TWh of electricity provides 20,000 tonnes of green hydrogen. Therefore, 6,690-7,900TWh of electricity are needed per year. Assumes a solar capacity factor of 30% and an onshore wind capacity factor of 34%.

Checks for Paris-alignment should consider whether the RE capacity addition dedicated to hydrogen production decreases the speed of overall energy sector decarbonisation. For example, if electrolysers are connected to the grid, they could compete with domestic energy demand in areas where RE installations are scarce. Because the current share of renewables in the grid is in most countries below where it should be for a Paris-compatible trajectory, it is crucial for producers' domestic decarbonisation that investments are provided for additional on-grid RE capacity. Progress on national energy priorities should not be hindered by the allocation of available RE to green hydrogen generation (Morgen et al., 2022). Hydrogen projects can only be considered fully aligned with the Paris Agreement, if they do not lead to an increase of fossil fuel consumption.

Electrolysers, hydrogen storage facilities and hydrogen turbines can play a role in supporting a high share of renewable electricity in the grid, if they are well integrated in the energy system. A condition for the electrolyser to not compete with energy access and put additional stress to the system is that it runs at times where demand is low, or there is excess supply from renewable energy sources. Such an integrated approach will make the classification of green hydrogen more difficult, require more coordination and decrease the full load hours of the electrolyser, potentially lowering their economic feasibility. Yet it could play an important role in transitioning power sectors of the hydrogen-producing countries.

Not all regions with high potential RE capacity have blanket modern energy access – defined as affordable, reliable, and low-emission energy. For instance, Mauritania has attracted several green energy partnerships because of its high potential for RE and green hydrogen production (bp, 2022; EIB, 2022), but access to modern energy stands at 47% nationally and only 5% in rural areas (Mauritania: Tracking SDG 7, 2023). Many developing and emerging countries still depend to a large degree on traditional biomass for cooking, heating and in some manufacturing processes. Significant investments are needed to build out local value chains for renewables, electrolysers, and transmission infrastructure to meet future demand.

Substantial RE capacities need to be installed with the electrolysers, independently of whether installations are connected to the electricity grid or not. Investments in RE capacities could facilitate the expansion of energy access for local populations. However, there is risk that developing green hydrogen in regions with high energy deficits further stretches grid capacity and reduces access for local use. Clear sustainability guidance is also needed on the system integration of electrolysers (i.e., the prioritisation of electrolysers' energy demand verses other demand sources when supply is limited). In the case that renewable installations are captive, there is a risk that the best sites could be utilised for wind and solar to produce cheap hydrogen, potentially excluding domestic users from affordable energy. Green hydrogen's energy demand should not compete with local access to energy, and in the case of captive generation, capacity should be reserved for domestic use, or a portion of revenues channelled to expanding energy access and RE transition domestically. In regions where domestic access to modern energy is not covered, rigorous checks are needed to ensure clear socio-economic benefits for local populations, including significantly advancing domestic access to energy.

4.4 INTEGRATED VALUE CHAINS FOR LOCAL VALUE CREATION

The growth of green hydrogen value chains in producer countries, spanning upstream, midstream, and downstream segments, has the potential to foster economic development, enhance local infrastructure, and promote job creation when value is harnessed within the local context. Nonetheless, it is essential to recognize that advantages extending beyond diversifying export revenues and attracting foreign direct investments are not automatic; they require deliberate consideration from the outset. **Local value creation should be integrated into producers and importers' hydrogen strategies (e.g., through local workforce requirements, investments into capacity building, local procurement mandates or quotas, etc.) and in any future international criteria for sustainable green hydrogen to avoid missed opportunities for producers.**

Establishing green hydrogen value chains carries inherent risks due to the uncertain scale of future demand and the high costs associated with required technologies. While there will be demand in hard-to-abate sectors (i.e., industry), use in other sectors is uncertain and largely dependent on government signals, technological innovation, and buildout of grid infrastructure, and might even be overestimated at least in some regions and sectors, where direct electrification is more efficient and cost-competitive. There is risk that developing and emerging countries take on substantial debt for initial investments in hydrogen infrastructure, only to find projects are not sufficiently profitable, resulting in adverse debt consequences.

To hedge this risk, an integrated value chain approach should be taken to secure domestic demand for green hydrogen (Patuleia and Waliszewska, 2023). In countries with existing industrial capacities, domestic hydrogen demand can be facilitated by setting hydrogen demand quotas to boost market uptake or setting local content requirements to support the development of upstream and downstream industry. Domestic green hydrogen use will be crucial in facilitating decarbonisation of producers' domestic hard-to-abate industries (e.g., steel production, fertiliser production, some specialised heavy-duty transport) and, together with RE, allow industrial exports to remain competitive internationally in the face of carbon pricing schemes like the European Union's Carbon Border Adjustment Mechanism (CBAM). To facilitate sustainable development and balance of trade, green hydrogen should be made available for industrial development in the Global South. Initiatives such as regional green hydrogen corridors can connect hydrogen production hubs with regional off-takers, diversify buyers, and reduce the risk of being a price taker.

In instances where green hydrogen production is a viable decarbonisation solution, investments in domestic production and related supply chains are essential for generating local benefits. Where industrial capacities are nascent, substantial investments and technical assistance can support the establishment of auxiliary industries. Strategic industrial policies are needed to support producers to seize opportunities to develop upstream, midstream, and downstream industries which benefit mitigation and development priorities. For instance, the production of green ammonia for domestic fertiliser manufacturing can support local industry and help countries overcome supply barriers that hinder food production (Fokeer et al., 2022; Malpass, 2022). Measures to support value chain development include local content requirements for parts of the value chain, pre-defined local workforce requirements, and investments in capacity building and knowledge sharing to skill the work force and build up and maintain expertise in the country (The German National Hydrogen Council, 2021; Morgen et al., 2022). Development finance institutions should develop clearly defined criteria which assess how local communities benefit from green hydrogen projects and routinely assess impact. Local stakeholders should be actively engaged in the development of a green hydrogen economy from the start to address risks and align priorities.

4.5 SAFEGUARDS FOR SUSTAINABLE LAND USE

Large scale renewable energy, electrolysers, and transmission and transportation infrastructure for hydrogen production require substantial land use, potentially competing with domestic land use. In some instances, existing infrastructure from grey hydrogen or fossil fuel production and transportation can be repurposed. In other instances, entirely new sites and infrastructure must be established. Tonelli et al. (2023) estimates that land requirements to meet 2050 hydrogen demand vary between 0.09-0.6 million km² for **solar panels** and 1.9-13.5 million km² or **wind turbines** globally , depending on the scenario for hydrogen demand. Renewable infrastructure will not be evenly distributed and will be clustered in some regions more than others.

For solar this equates to about 0.06-0.4% of the total earth land area and for wind 1.3-9% only for hydrogen production.

In building out required infrastructure, it is crucial that land rights – both formal and customary – are recognised and the United Nations (UN) principle of free, prior, and informed consent (FPIC) is abided by. There is risk that narratives seeking to utilise emerging and developing economies' vast "unused" dryland for renewable energy generation and green hydrogen hubs ignore traditional pastoral land use and perpetuate **"green grabbing"** (Waters-Bayer and Tadicha Wario, 2022). Displacement from cultural lands presents human rights concerns and competition with agricultural land use could harm local communities.

Defined as the private appropriation of land, resources, or water that is legitimised with environmental arguments (Tittor, 2016).

Safeguards are needed to minimise disruptions to local communities and environments. Environmental and socio-economic impact assessments are foundational to understanding the consequences and opportunities of green hydrogen production in each context. National hydrogen strategies and project planning should adopt a consultative and inclusive approach involving local stakeholders to ensure all voices are heard and land use risks mitigated.

4.6 SAFEGUARDING ACCESS TO WATER

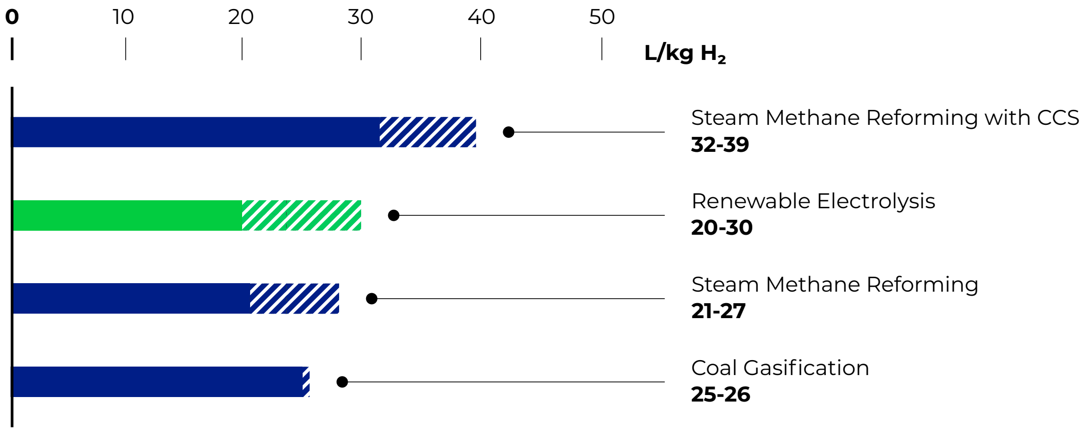
Globally, water scarcity is on the rise due to a combination of increasing water demand and diminishing water supplies exacerbated by climate change (Jones et al., 2019). Close to a third of the global population do not have safe water access – with the majority concentrated in the Asia-Pacific region and Africa (UNU-INWEH, 2023). Regions with ample solar PV capacity are well-positioned for green hydrogen production but often grapple with high water stress (Fokeer et al., 2022). This raises questions about using scarce water resources for export-oriented green hydrogen.

Based on an estimated hydrogen demand of about 74 EJ.

To meet the anticipated global hydrogen demand in 2050 with green hydrogen would require an estimated **25 billion cubic metres** (m^3) of **fresh water** per year (Blanco, 2021). The oxidation of green hydrogen releases the same amount of water input in production, however if the energy carrier is exported, embodied water is also exported (Fokeer et al., 2022). While alarm bells have been raised about green hydrogen's water consumption, its water use is estimated to be less than other hydrogen production processes at 20-30 L/kg **(→ Figure 8)** (Ramirez et al., 2023). Others suggest that replacing fossil fuels with green hydrogen would reduce the energy sector's water consumption through displacing water use in fossil fuel production (Newborough and Cooley, 2021). This does not however displace the risk that green hydrogen production in arid, but PV competitive regions could exacerbate local water scarcity and lead to conflict.

Global water consumption was 4 trillion m3 in 2014 (Ritchie and Roser, 2018). Global hydrogen's water consumption would be 0.6% of 2014 consumption.

Identifying locations with low-cost renewable energy production and water availability presents a challenge. While desalination plants can help meet freshwater demand, the desalination process produces an environmentally damaging brine byproduct which must be sustainably disposed of to avoid negative impact on marine ecosystems. In arid regions with limited desalination. capacity and local demand for green hydrogen it needs to be carefully considered whether additional



Source: Adatped from Ramirez et al., 2023.

Figure 8

Water demand of hydrogen production pathways

desalination plants should be brought online to service electrolysers' water demand, or if green hydrogen could instead be transported to the location. In either case, because of these limitations, the use of green hydrogen in arid regions will likely be significantly more expensive. Researchers are also exploring producing hydrogen with seawater and treated wastewater to avoid environmental and water stress concerns (Service, 2023).

Responsible water management and sourcing are vital for sustainable green hydrogen production. **Water consumption should not compete with local water demand for agriculture, existing industry, and households or harm livelihoods dependent on aquatic ecosystems.** Environmental and socio-economic impact assessments can offer insights into the potential consequences of utilising local surface and ground water reserves or redirecting limited desalination capacity for hydrogen production. Such assessments should play a large role in MDBs' evaluation of green hydrogen investments, especially in regions susceptible to water stress.

At a minimum, green hydrogen value chains should do no harm to local water access and marine environments. But the development of a hydrogen economy could also provide a developmental value add for producers through facilitating investments in water infrastructure (i.e., distribution networks and desalination plants) with capacity reserved for local use. When considering new water installations and investments in existing water infrastructure, policymakers and project developers should consider the potential impact of the privatisation of water infrastructure and strive to guarantee access to clean and affordable water is maintained for all members of society. There is a role for MDBs to play in de-risking and facilitating investments in public infrastructure that support expanded access to safe and affordable water.

05 GREEN HYDROGEN PRODUCTION AND CONSIDERATIONS IN SELECTED COUNTRIES

We conducted analyses on the state of green hydrogen development in three countries: Namibia, India, and Colombia. These countries were chosen due to their geographic diversity, differing progress in the energy transition, and emerging focus on green hydrogen production for domestic use and/or export. All are classified by the International Monetary Fund (IMF) as middle-income countries but still face developmental challenges which must be considered. All have high potentials for renewable energy generation and often come up as possible candidates to supply green hydrogen to international demand centres like Europe. The following section summarises key findings, but longer versions of the cases studies can be found on our website.

We found that the countries are at different stages in their development of hydrogen strategies and adjacent policy support. While all countries view green hydrogen as a developmental opportunity, they approach the development of green hydrogen fundamentally differently:

All three have different **standards** for hydrogen production. India and Namibia have both set targets for green hydrogen. While Namibia has not clarified the emissions threshold for defining green hydrogen, India specifies that production-related emissions should be lower than 2 $kgCO_2/kgH_2$. India also considers biomass-based hydrogen to be green, without setting sustainability standards for the type of biomass used in production. Colombia, on the other hand, intends to produce both green and blue hydrogen until production of the former becomes fully competitive and naturally displaces the latter's market share, thus raising risks of stranded assets and overreliance on CCUS.

The countries have different visions for future hydrogen **applications**, not all of which are efficient. India and Colombia both plan for green hydrogen to substitute current demand for grey hydrogen in existing industries, with application in oil refining projected to continue in both countries for much longer than can be considered Paris-aligned. India and Colombia are also considering a role for green hydrogen fuel cells for decarbonising transport sectors like road and railways which can be directly electrified more efficiently. Namibia's strategy for green hydrogen use is not as developed, but it notes a potential future role for green hydrogen to decarbonise its mining sector and as ammonia for fertiliser production.

All countries plan on leveraging their comparative advantage and capitalising on the green hydrogen export opportunity, but not all provide details on how they will ensure a **sustainable and just transition** within their own borders. Namibia plans to produce green hydrogen almost entirely off-grid and mainly for exports, thus limiting the opportunity to decrease electricity imports from South Africa, decarbonise its own electricity mix or expand energy access for its own population. India is considering consumption mandates to promote green hydrogen use in domestic industries and incentivises grid-connection of electrolysers by offering waivers of transmission charges. Colombia, with its predominantly hydro-based electricity generation, plans to connect electrolysers to the grid and work on a system for guarantees of origin. However, it does not specify any criteria for additionality to ensure green hydrogen production does not cannibalise renewable electricity consumption domestically.

All three countries have noted the importance of local **value creation** to accompany green hydrogen development. India is subsidising domestic electrolyser manufacturers and may set local content mandates in its green hydrogen procurement processes. Colombia emphasises local outcomes like job training, reskilling, capacity building, industrial development, and national research and innovation, but stops short of outlining a plan for the same. Namibia foresees employment opportunities from industrial development and note several components of the value chain which could be localised but does not provide further details.

Finally, all three countries face significant **environmental risks** associated with domestic green hydrogen production. It is likely that green hydrogen will exacerbate the water scarcity issues in all three, particularly because its production will be concentrated in the most arid regions where solar and wind resources are strongest. Land availability is already a challenge for expansion of renewables in India. None of the countries has specified how it plans to safeguard against the adverse environmental or social impacts of green hydrogen development. Colombia is considering streamlining permitting requirements in general, which could risk compromising environmental and social safeguards to accelerate the green hydrogen industry. Namibia plans to address environmental concerns through a community-based natural resource management approach but has not outlined specific sustainability guidelines targeted at developers.

» 06 CONCLUSIONS

This report describes the current use and prospects of green hydrogen in the context of an equitable, globally just transition towards a Paris-aligned future. It outlines principles to consider not only for MDBs, which are the focus of the larger research project as the umbrally of this work, but also other decision makers working on green hydrogen in the public sphere. Three country case studies, India, Namibia, and Colombia, accompany the global findings and provide country-specific, real-world insights.

Future energy systems will need to counter current inequalities and ensure that basic needs of all people are met sustainably. The future availability of energy will depend on a combination of factors, including the scaling of renewable technologies, distribution and storage solutions, efficiency measures, and particularly in the Global North, life-style changes.

Green hydrogen, with high transformation losses and transportation costs compared to other forms of energy, will remain an expensive and valuable good and the world will need to focus on limiting hydrogen demand through direct electrification of processes and efficiency. The traded volumes of green hydrogen will be lower than those of fossil fuels currently. Consequently, green hydrogen will not be sufficient to replace the fossil fuel industry in terms of export revenue and only a fraction of fossil infrastructure today in terms of volume will be needed for green hydrogen, even if repurposing is technically an option. As the energy carrier is still in its fledgling stages, future trade flows and domestic green hydrogen demand remain largely theoretical. This means that investments in green hydrogen today are risky, and particularly for developing and emerging countries, stranded assets could impede development goals. Yet, not investing in green hydrogen at all risks remaining locked-in to fossil fuels, which will in a 1.5°C future be disadvantageous for competitiveness and cement in dependencies on fossil fuel imports for many countries.

To meet future demand, substantial investments are needed in renewables, transmission and transportation infrastructure, and capacity building. Scaling green hydrogen poses big challenges, but also offers a chance to reform energy systems in a way that promotes decarbonisation efforts and support sustainable development. In the near-term, government support is key to develop cost-competitive hydrogen supply chains and direct its use to spaces where it is most required. International support and cooperation are necessary to ensure regions are not left behind and to set global sustainability standards needed to facilitate international trade.

Green hydrogen can contribute to economic diversification and allow the population to benefit from the transition, if done right. For the development of green hydrogen to support a truly just transition, it must prioritise the development goals of the Global South and focus on implementing green hydrogen in the areas where it is essential for decarbonising end use – and only there. The priorities for governments and development finance institutes should be:

- **Build up renewable energy infrastructure:** Energy demand is drastically increasing in developing countries, and electricity supply must be improved for reliable and affordable access to services. The production of green hydrogen requires additional renewable electricity. At the same time, the 1.5° Paris temperature target requires rapid decarbonisation of the power sector. At least 1.5 TW of renewable energy per year needs to be installed by 2030, up from 2 TW cumulatively in place today (Climate Analytics, 2023).

  To fully benefit from the uptake of renewable energy technologies, it is critical that developing countries have the possibility to participate in the supply chain of those technologies, rather than purely rely on imports of the technologies and international expertise to construct and maintain the installations. International cooperation and finance can play a crucial role in enhancing the local content share of renewable energy industries, by facilitating access to technologies and building up local supply chains. Targeted technical assistance can further assist countries in formulating and refining national strategies and policies. Defining how this can best be done on a case-by-case basis and identifying financing methods for integrating renewables into local supply chains should be a priority.

- **Integrate electrolysers and additional RE capacities in national grids where possible.** Electrolysers can technically be run at times when RE supply exceeds electricity demand, and hydrogen turbines in combination with storage can be used as a tool to balance variable renewables. Planning additional RE capacities, demand side management, electrolysers and grid connections jointly to facilitate a high share of renewables in the grid can support the energy transition in the country and enhance electrification and local energy access. The production of green hydrogen would be an additional effect. Compared to an isolated electrolyser and RE system without grid connect, the full load hours of the electrolysers would decrease, and with it the return on investment. International finance could fill this gap in income compared to a profit-optimised electrolyser for the benefit of an efficient overall system and development goals.

- **Make domestic green hydrogen available for industrial development in the Global South.** In countries where industrialisation is prioritised in development strategies, or where hard-to-abate industries already exist (e.g., steel or fertiliser production or mining with heavy-duty transport needs), the use of green hydrogen will be critical for international competitiveness. In the light of emerging carbon border adjustment mechanisms, industrial goods produced via zero-emissions processes will have a competitive advantage over high-emissive production. The availability of green hydrogen will be essential for producing countries and should be prioritised over exports. Development finance providers should work with the countries to understand potential domestic hydrogen demand and prioritise this before exports.

- **Export green hydrogen to other countries.** Where a country can produce green hydrogen that is competitive on a global market, the export of the fuel can generate income, diversify export structures and support the decarbonisation of importing countries. However, future trade of green hydrogen should avoid reproducing dependencies on energy resource rents, and both potential importers and exporters of green hydrogen should develop a realistic understanding of the possible volumes of trade, where today we observe a tendency towards overestimating possible flows.

  Importing countries will need robust policies to ensure the sustainability of green hydrogen, covering positive impacts on both the development objectives and the decarbonisation efforts of the country of origin. Countries might also strategically use exports in the near future to incentivise the development of production capacities, even at times where green hydrogen is not yet competitive domestically, with the objective to later expand the production to cover the emerging domestic demand. For potentially importing countries to support this development, this would mean equitable agreements with the exporters that allow a shift towards domestic production once needed.

The priorities above illustrate the importance of the international community to foster an inclusive, just development of green hydrogen. MDBs play a key role in supporting decarbonisation, sustainable development, and economic diversification. Public banks and financial institutions have the opportunity to assist developing and emerging countries in this transition, even if green hydrogen may not yet appear as a financially viable venture. Our future research will go into more depth and lay out approaches and tools MDBs could use to this end.

REFERENCES

A

Andreola, S., Menos-Aikateriniadis, C., Paxton, A., et al. (2021) No-regret hydrogen: Charting early steps for H2 infrastructure in Europe. Berlin. Available at: https://static.agora-energiewende.de/fileadmin/Projekte/2021/2021_02_EU_H2Grid/A-EW_203_No-regret-hydrogen_WEB.pdf

Arndt, C., Diao, X., Dorosh, P., et al. (2023) 'The Ukraine war and rising commodity prices: Implications for developing countries', Global Food Security, 36, p. 100680. doi:10.1016/j.gfs.2023.100680

B

Bermudez, J.M., Evangelopoulou, S. and Pavan, F. (2022) Hydrogen: energy systems overview. Paris. Available at: https://www.iea.org/reports/hydrogen

Blanco, H. (2021) 'Hydrogen production in 2050: how much water will 74EJ need?', Energy Post EU, 22 July. Available at: https://energypost.eu/hydrogen-production-in-2050-how-much-water-will-74ej-need/

BloombergNEF (2020) Hydrogen Economy Outlook. Key Messages. Bloomberg New Energy Finance. Available at: https://data.bloomberglp.com/professional/sites/24/BNEF-Hydrogen-Economy-Outlook-Key-Messages-30-Mar-2020.pdf (Accessed: 12 October 2022)

BloombergNEF (2022) 'Japan's Ammonia-Coal Co-Firing Strategy a Costly Approach to Decarbonization, Renewables Present More Economic Alternative', Bloomberg, 28 September. Available at: https://about.bnef.com/blog/japans-ammonia-coal-co-firing-strategy-a-costly-approach-to-decarbonization-renewables-present-more-economic-alternative/

BMWK (2023) National Hydrogen Strategy Update. Berlin. Available at: https://www.bmwk.de/Redaktion/EN/Publikationen/Energie/national-hydrogen-strategy-update.pdf?__blob=publicationFile&v=2

bp (2022) bp and Mauritania to explore green hydrogen at scale, bp press Releases. Available at: https://www.bp.com/en/global/corporate/news-and-insights/press-releases/bp-and-mauritania-to-explore-green-hydrogen-at-scale.html (Accessed: 13 June 2023)

Byers, E., Krey, V., Kriegler, E., et al. (2022) 'AR6 Scenarios Database hosted by IIASA'. International Institute for Applied Systems Analysis. doi:10.5281/zenodo.5886912

C

CAT (2020) Paris Agreement Compatible Sectoral Benchmarks: Elaborating the decarbonisation roadmap. Berlin, Germany: Climate Action Tracker (Climate Analytics, NewClimate Institute). Available at: https://climateactiontracker.org/documents/753/CAT_2020-07-10_ParisAgreementBenchmarks_FullReport.pdf (Accessed: 1 December 2022)

Chancel, L., Piketty, T., Saez, E. and Zucman, G. (2022) World Inequality Report 2022. Available at: https://wir2022.wid.world/www-site/uploads/2022/01/Summary_WorldInequalityReport2022_English.pdf

Chatterjee, S., Parsapur, R.K. and Huang, K.-W. (2021) 'Limitations of Ammonia as a Hydrogen Energy Carrier for the Transportation Sector', ACS Energy Letters, 6(12), pp. 4390–4394. doi:10.1021/acsenergylett.1c02189

Climate Action Tracker (2022) Natural Gas in Africa - why fossil fuels cannot sustainably meet the continent's growing energy demand. Available at: https://climateactiontracker.org/documents/1048/CAT_2022-05_Report_NaturalGasinAfrica.pdf

Climate Analytics (2023) 2030 targets aligned to 1.5°C - Evidence from the latest global pathways. Berlin. Available at: https://climateanalytics.org/media/2030_targets_for_1-5.pdf

Collins, L. (2020) 'A wake-up call on green hydrogen: the amount of wind and solar needed is immense', Recharge News, 20 March. Available at: https://www.rechargenews.com/transition/a-wake-up-call-on-green-hydrogen-the-amount-of-wind-and-solar-needed-is-immense/2-1-776481

COP26 Presidency (2021) COP26 World Leaders Summit- Statement on The Breakthrough

Agenda. 02.11.2021. COP26 Presidency. Available at: https://ukcop26.org/cop26-world-leaders-summit-statement-on-the-breakthrough-agenda/ (Accessed: 25 October 2022)

E

Easterly, W. (2002) 'The Elusive Quest for Growth: Economists' Adventures and Misadventures in the Tropics', Southern Economic Journal, 68(4), p. 979. doi:10.2307/1061505

EIA (2023a) 'Hydrogen Explained: Production of hydrogen'. Washington D.C: U.S. Energy Information Administration. Available at: https://www.eia.gov/energyexplained/hydrogen/production-of-hydrogen.php

EIA (2023b) 'Hydrogen Explained: Production of hydrogen'. Washington D.C: U.S. Energy Information Administration

EIB (2022) Mauritania and the EIB strengthen renewable energy and green hydrogen cooperation, EIB Newsroom. Available at: https://www.eib.org/en/press/all/2022-290-mauritania-and-the-eib-strengthen-renewable-energy-and-green-hydrogen-cooperation (Accessed: 13 June 2023)

EIB (2023) India: EIB backs green hydrogen deployment and joins India Hydrogen Alliance. Available at: https://www.eib.org/en/press/all/2023-045-eib-backs-green-hydrogen-deployment-in-india-and-joins-india-hydrogen-alliance#:~:text=Today in Mumbai Kris Peeters%2C Vice-President of the,billion%2C subject to Indian government and EIB approvals.

European Commission (2020) A hydrogen strategy for a climate-neutral Europe. Available at: https://ec.europa.eu/energy/sites/ener/files/hydrogen_strategy.pdf (Accessed: 14 April 2021)

Eurostat (2022a) Energy production and imports. Available at: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Energy_production_and_imports

Eurostat (2022b) 'Flash estimate - June 2022 Euro area annual inflation up to 8.6%'. Luxembourg. Available at: https://ec.europa.eu/eurostat/documents/2995521/14644614/2-01072022-AP-EN.pdf/72dcf5e4-56cb-5b8c-1a1f-d342666b8657#:~:text=Euro area annual inflation is,office of the European Union.

F

Fokeer, S., Sievernich, J. and Schwager, P. (2022) No Achieving a Green Hydrogen transition built on equity and consensus Strategies and challenges for a just green hydrogen transition, Industrial Analytics Platform. Available at: https://iap.unido.org/articles/achieving-green-hydrogen-transition-built-equity-and-consensus

G

G7 Germany (2022) 'G7 Leaders' Communiqué'. Available at: https://www.g7germany.de/g7-de

Galimova, T., Fasihi, M., Bogdanov, D. and Breyer, C. (2023) 'Impact of international transportation chains on cost of green e-hydrogen: Global cost of hydrogen and consequences for Germany and Finland', Applied Energy, 347, p. 121369. doi:10.1016/j.apenergy.2023.121369

Germanwatch & NewClimate Institute (2018) 'Aligning investments with the Paris Agreement temperature goal - Challenges and opportunities for Multilateral Development Banks'. Cologne/Bonn/Berlin. Available at: https://newclimate.org/wp-content/uploads/2018/09/MDB_WorkingPaper_2018-09.pdf

Government of India (2022) National Green Hydrogen Mission. Available at: https://www.india.gov.in/spotlight/national-green-hydrogen-mission

Griffiths, S., Sovacool, B.K., Kim, J., et al. (2021) 'Industrial decarbonization via hydrogen: A critical and systematic review of developments, socio-technical systems and policy options', Energy Research & Social Science, 80, p. 102208. doi:10.1016/J.ERSS.2021.102208

H

Harding, R. (2019) 'Japan launches first liquid hydrogen carrier ship', Financial Times, 10 December. Available at: https://www.ft.com/content/8ae16d5e-1bd4-11ea-97df-cc63de1d73f4

Heinemann, C. and Kasten, P. (2019) 'Die Bedeutung strombasierter Stoffe für den Klimaschutz in Deutschland'. Öko-Institut e.V. Available at: https://www.oeko.de/fileadmin/oekodoc/PtX-Hintergrundpapier.pdf

Hickel, J., Dorninger, C., Wieland, H. and Suwandi, I. (2022) 'Imperialist appropriation in the world economy: Drain from the global South through unequal exchange, 1990–2015', Global Environmental Change, 73, p. 102467. doi:10.1016/j.gloenvcha.2022.102467

Hickel, J. and Slamersak, A. (2022) 'Existing climate mitigation scenarios perpetuate colonial inequalities', The Lancet Planetary Health, 6(7), pp. e628–e631. doi:10.1016/S2542-5196(22)00092-4

Hüwener, T. and Martin, A. (2021) 'Gas pipelines for hydrogen?' Available at: https://www.iis.fraunhofer.de/en/magazin/series/series-hydrogen/hydrogen-gas-pipelines.html

I

IEA (2019) The Future of Hydrogen for G20. Seizing today's opportunities. Japan, Japan: International Energy Agency. Available at: https://iea.blob.core.windows.net/assets/9e3a3493-b9a6-4b7d-b499-7ca48e357561/The_Future_of_Hydrogen.pdf (Accessed: 17 August 2022)

IEA (2021a) Global hydrogen demand by sector in the Net Zero Scenario, 2020-2030, Charts – Data & Statistics. Available at: https://www.iea.org/data-and-statistics/charts/global-hydrogen-demand-by-sector-in-the-net-zero-scenario-2020-2030 (Accessed: 5 September 2022)

IEA (2021b) Global Hydrogen Review 2021. Paris, France: International Energy Agency. Available at: https://www.iea.org/reports/global-hydrogen-review-2021 (Accessed: 2 August 2022)

IEA (2021c) Hydrogen demand in industry, 2020, Charts – Data & Statistics. Available at: https://www.iea.org/data-and-statistics/charts/hydrogen-demand-in-industry-2020 (Accessed: 5 September 2022)

IEA (2021d) Net Zero by 2050: A Roadmap for the Global Energy Sector. Paris, France: International Energy Agency. Available at: https://www.iea.org/reports/net-zero-by-2050 (Accessed: 5 August 2023)

IEA (2022a) Global Energy Crisis: How the energy crisis started, how global energy markets are impacting our daily life, and what governments are doing about it, International Energy Agency. Available at: https://www.iea.org/topics/global-energy-crisis

IEA (2022b) Global Hydrogen Review 2022. Paris, France: International Energy Agency. Available at: https://www.iea.org/reports/global-hydrogen-review-2022 (Accessed: 19 October 2022)

IEA (2022c) Hydrogen: Energy system overview. Paris. Available at: https://www.iea.org/reports/hydrogen

IEA (2022d) World Energy Balances (2022 edition). Paris, France: International Energy Agency

IEA (2022e) World Energy Outlook- WEO2022. Paris: International Energy Agency

IEA (2023a) Global Hydrogen Review 2023. Paris, France: International Energy Agency. Available at: https://www.iea.org/reports/global-hydrogen-review-2023 (Accessed: 19 October 2023)

IEA (2023b) Renewable Energy Market Update: Outlook for 2023 and 2024 - International Energy Agency. Available at: https://iea.blob.core.windows.net/assets/63c14514-6833-4cd8-ac53-f9918c2e4cd9/RenewableEnergyMarketUpdate_June2023.pdf

IEA (2023c) Towards hydrogen definitions based on their emissions intensity. Paris. Available at: https://www.iea.org/reports/towards-hydrogen-definitions-based-on-their-emissions-intensity

IRENA (2021) World Energy Transitions Outlook - 1.5°C Pathway. Abu Dhabi, United Arab Emirates: International Renewable Energy Agency. Available at: https://www.irena.org/publications/2021/Jun/World-Energy-Transitions-Outlook (Accessed: 5 August 2022)

IRENA (2022a) Geopolitics of the energy transformation: The hydrogen factor. Abu Dhabi, United Arab Emirates: International Renewable Energy Agency. Available at: https://irena.org/publications/2022/Jan/Geopolitics-of-the-Energy-Transformation-Hydrogen (Accessed: 16 September 2022)

IRENA (2022b) World Energy Transitions Outlook 2022: 1.5°C Pathway. Abu Dhabi, United Arab Emirates: International Renewable Energy Agency. Available at: https://www.irena.org/publications/2022/Mar/World-Energy-Transitions-Outlook-2022 (Accessed: 4 August 2022)

J

Jaramillo, P., Kahn Ribeiro, S., Newman, P., et al. (2022) 'Chapter 10', in IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum,. Cambridge University Press, Cambridge, UK and New York, NY, USA. doi:10.1017/9781009157926.012

Jayanti, S.E.-P. (2022) 'Repurposing pipelines for hydrogen: Legal and policy considerations', Energy Reports, 8, pp. 815–820. doi:https://doi.org/10.1016/j.egyr.2022.11.063

Jensen, L. (2023) Global Decarbonization in Fossil Fuel Export-Dependent Economies. Nairobi. Available at: https://www.undp.org/publications/global-decarbonization-fossil-fuel-export-dependent-economies

Jones, E., Qadir, M., van Vliet, M.T.H., et al. (2019) 'The state of desalination and brine production: A global outlook', Science of The Total Environment, 657, pp. 1343–1356. doi:10.1016/j.scitotenv.2018.12.076

K

Kalt, T. and Lekalakala, M. (2023) 'The green hydrogen frontier – neocolonialism, greenwashing or just transition?' Heinrich Böll Stiftung. Available at: https://za.boell.org/en/2023/01/18/green-hydrogen-frontier-neocolonialism-greenwashing-or-just-transition

Klopčič, N., Stöhr, T., Grimmer, I., et al. (2022) 'Refurbishment of Natural Gas Pipelines towards 100% Hydrogen—A Thermodynamic-Based Analysis', Energies, 15(24). doi:10.3390/en15249370

L

Liebreich Associates (2021) The Clean Hydrogen Ladder. Available at: https://www.linkedin.com/pulse/clean-hydrogen-ladder-v40-michael-liebreich/ (Accessed: 16 August 2022)

Liebreich, M. (2020) Liebreich: Separating Hype from Hydrogen – Part Two: The Demand Side, Bloomberg New Energy Finance. Available at: https://about.bnef.com/blog/liebreich-separating-hype-from-hydrogen-part-two-the-demand-side/ (Accessed: 16 May 2023)

Lopez Legarreta, P., Kahlen, L., Reyes de la Lanza, S., et al. (2023) The role of hydrogen in dearbonisation - investment opportunities for Latin America. Cologne. Available at: https://newclimate.org/sites/default/files/2023-03/the_role_of_hydrogen_in_decarbonisation_24_02_final_0.pdf

M

Maloney, W. (2002) Innovation and Growth in Resource Rich Countries. 148

Malpass, D. (2022) A transformed fertilizer market is needed in response to the food crisis in Africa, World Bank Blogs. Available at: https://blogs.worldbank.org/voices/transformed-fertilizer-market-needed-response-food-crisis-africa

Mauritania: Tracking SDG 7 (2023) The Energy Progress Report. Available at: https://trackingsdg7.esmap.org/country/mauritania (Accessed: 13 June 2023)

McGlade, C. (2019) 'Can CO2-EOR really provide carbon-negative oil?' Paris: IEA (International Energy Agengy). Available at: https://www.iea.org/commentaries/can-co2-eor-really-provide-carbon-negative-oil

METI (2017) Basic Hydrogen Strategy. Tokyo, Japan: Ministerial Council on Renewable Energy, Hydrogen and Related Issues. Ministry of Economy, Trade and Industry

Midilli, A., Kucuk, H., Topal, M.E., et al. (2021) 'A comprehensive review on hydrogen production from coal gasification: Challenges and Opportunities', International Journal of Hydrogen Energy, 46(50), pp. 25385–25412. doi:10.1016/j.ijhydene.2021.05.088

MME (2021) Colombia's Hydrogen Roadmap. Ministerio de Minas y Energía Colombia. Available at: https://www.minenergia.gov.co/documents/5862/Colombias_Hydrogen_Roadmap_2810.pdf (Accessed: 6 October 2023)

Morgen, S., Schmidt, M., Steppe, J. and Wörlen, C. (2022) 'Fair Green Hydrogen: Chance or Chimera in Morocco, Niger and Senegal?' Berlin: Rosa Luxemburg Stiftung. Available at: https://www.rosalux.de/fileadmin/rls_uploads/pdfs/sonst_publikationen/Studie_Fair_Hydrogen.pdf

Newborough, M. and Cooley, G. (2021) 'Green hydrogen: water use implications and opportunities', Fuel Cells Bulletin [Preprint], (December). Available at: https://itm-power-assets.s3.eu-west-2.amazonaws.com/Green_Hydrogen_Water_Use_56b96f577d.pdf

O

OECD and IEA (2010) Energy Poverty: How to make modern energy access universal?, Special early excerpt of the World Energy Outlook. Available at: http://www.iea.org/IEAnews/4710/Poverty_jones.pdf

P

Patuleia, A. and Waliszewska, A. (2023) Making clean technology value chains work for EU economic comvergence: A case study on Portugal. Berlin. Available at: https://www.e3g.org/wp-content/uploads/E3G-Report-Making-clean-technology-value-chains-work-for-EU-economic-convergence.pdf

R

Ramirez, K., Weiss, T., Kirk, T. and Gamage, C. (2023) 'Hydrogen Reality Check: Distilling Green Hydrogen's Water Consumption'. Rocky Mountain Institute. Available at: https://rmi.org/hydrogen-reality-check-distilling-green-hydrogens-water-consumption/

Republic of Namibia (2022) Namibia. Green Hydrogen and Derivatives Strategy. Windhoek. Available at: https://gh2namibia.com/gh2_file_uploads/2022/11/Namibia-GH2-Strategy-Rev2.pdf

Ritchie, H. and Roser, M. (2018) Water use and stress, Our World in Data. Available at: https://ourworldindata.org/water-use-stress

S

Sachs, J. and Warner, A. (1995) Natural Resource Abundance and Economic Growth. Cambridge, MA. doi:10.3386/w5398

Service, R.F. (2023) 'Splitting seawater could provide an endless source of green hydrogen', Science [Preprint]. Science. Available at: https://www.science.org/content/article/splitting-seawater-provide-endless-source-green-hydrogen

Stevens, P., Lahn, G. and Kooroshy, J. (2015) The Resource Curse Revisited. Available at: https://www.chathamhouse.org/sites/default/files/publications/research/20150804ResourceCurseRevisitedStevensLahnKooroshyFinal.pdf

T

Teske, S. (2022) Achieving the Paris Climate Agreement Goals. Part 2: Science-based Target Setting for the Finance industry – Net-Zero Sectoral 1.5˚C Pathways for Real Economy Sectors. Cham, Switzerland: Springer. Available at: https://link.springer.com/content/pdf/10.1007/978-3-030-99177-7.pdf (Accessed: 24 August 2022)

The German National Hydrogen Council (2021) Sustainability criteria for import projects for renewable hydrogen and PtX products. Available at: https://www.wasserstoffrat.de/fileadmin/wasserstoffrat/media/Dokumente/EN/2021-10-29_NWR-Position_Paper_Sustainability_Criteria.pdf

The Hydrogen Council and McKinsey & Company (2021a) Hydrogen for Net-Zero: A critical cost-competitive energy vector. Available at: https://hydrogencouncil.com/wp-content/uploads/2021/11/Hydrogen-for-Net-Zero_Full-Report.pdf (Accessed: 20 September 2022)

The Hydrogen Council and McKinsey & Company (2021b) Hydrogen Insights: A perspective on hydrogen investment, market development and cost competitiveness. Available at: https://hydrogencouncil.com/wp-content/uploads/2021/02/Hydrogen-Insights-2021.pdf (Accessed: 7 September 2022)

Tittor, A. (2016) Green Grabbing, InterAmerican Wiki: Terms - Concepts - Critical Perspectives. Available at: https://www.uni-bielefeld.de/einrichtungen/cias/publikationen/wiki/g/green-grabbing.xml (Accessed: 27 September 2023)

Tonelli, D., Rosa, L., Gabrielli, P., et al. (2023) 'Global land and water limits to electrolytic hydrogen production using wind and solar resources', Nature Communications, 14(1), p. 5532. doi:10.1038/s41467-023-41107-x

U

UNFCCC (2015) Adoption of the Paris Agreement. FCCC/CP/2015/L.9/Rev.1. Paris, France: United Nations Framework Conventions on Climate Change. Available at: http://unfccc.int/resource/docs/2015/cop21/eng/l09r01.pdf

UNU-INWEH (2023) Global Water Security 2023 Assessment. Ontario. Available at: https://reliefweb.int/report/world/global-water-security-2023-assessment

US Department of Energy (2023) Furnaces and Boilers. Available at: https://www.energy.gov/energysaver/furnaces-and-boilers (Accessed: 21 June 2023)

V

Vedachalam, S., Baquerizo, N. and Dalai, A.K. (2022) ‘Review on impacts of low sulfur regulations on marine fuels and compliance options’, Fuel, 310, p. 122243. doi:10.1016/j.fuel.2021.122243

de Villafranca Casas, M.J., Nilsson, A., Smit, S., et al. (2022) Decarbonisation in the global steel sector: tracking the progress. Cologne and Berlin, Germany: NewClimate Institute. Available at: https://newclimate.org/sites/default/files/2022-12/steel_final.pdf (Accessed: 2 December 2022)

W

Waters-Bayer, A. and Tadicha Wario, H. (2022) Pastoralism and large-scale REnewable energy and green hydrogen projects: Potential & Threats. Available at: https://www.boell.de/sites/default/files/2022-05/Pastoralism-and-large-scale-REnewable-energy-and-green-hydrogen-projects.pdf

Weber, I.M., Semieniuk, G., Westland, T. and Liang, J. (2021) What You Exported Matters: Persistence in Productive Capabilities across Two Eras of Globalization. 299. doi:doi.org/10.7275/21780201

World Bank (2022) World Bank Group Announces International Low-Carbon Hydrogen Partnership. Available at: https://www.worldbank.org/en/news/press-release/2022/11/15/hydrogen-for-development-partnership-h4d-launch

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