The role of green hydrogen in a just, Paris-compatible transition

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Authors
Hanna Fekete, Imogen Outlaw (NewClimate)

Graphics and layout:
Polina Korneeva (NewClimate)

Reviewed by:
Anja Gebel (Germanwatch), Valerie Laxton (WRI), Laura Sabogal (E3G), Lukas Kahlen (NewClimate)

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Abbreviations

CBAM	Carbon Border Adjustment Mechanism
CCS	Carbon Capture and Storage
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
EBRD	European Bank for Reconstruction and Development
EIB	European Investment Bank
EU	European Union
GHG	Greenhouse Gas
H4D	Hydrogen for Development
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
KfW	Kreditanstalt für Wiederaufbau - German Development Bank
LNG	Liquefied natural gas
m^3	Cubic meters
MDB	Multilateral Development Bank
Mt	Megatonnes
PV	Photovoltaic
SDG	Sustainable Development Goal

1 Introduction and objectives

Global equity and sustainable development of countries is at the core of the Paris Agreement, yet inequalities between wealthy and poor countries, as well as among individuals within countries continue to increase. Inequality poses a significant challenge to achieving the goals of the agreement (Chancel et al. 2022). This inequality is very obvious in matters related to the energy transition, for example the speed of renewable energy additions or access to electricity. A Paris-compatible transition must counter this reality and ensure the equitable participation of all in a zero-emission future.

To meet the goals of the Paris Agreement, strong shifts in the energy sectors are essential. These changes entail the sharp decline of global fossil fuel production and consumption, with "no need for investment in new fossil fuel supply", according to the IEA (2021b). The global demand for fossil fuel decreases in a 1.5°C compatible pathway and fossil fuel exporting developing countries will need to find alternative sources of income. At the same time, access to modern energy still needs to be provided and enhanced in many countries to support livelihoods and economic development. In this context, building economic resilience and forming an equitable transition that positively impacts development is a core challenge that development finance institutions can support.

Green hydrogen is emerging as a possible transition solution and pushed strongly by some countries in both the Global North and South. For resource-rich countries in the Global South, green hydrogen can develop up- and down-steam industries, support domestic decarbonisation, and, in cases of excess supply, yield export revenue. This briefing seeks to provide a balanced view on the opportunities and challenges of green hydrogen in the context of sustainable development in the Global South and the mitigation goals of the Paris Agreement. The research investigates under which conditions and to what extent green hydrogen can support a transition of countries in the Global South away from fossil fuels while serving development objectives. It lays out criteria for investments in sustainable hydrogen-related projects, covering two sides: how to ensure positive impacts of green hydrogen production on the sustainable development, and how to ensure consistency with a fast and profound decarbonisation of the energy system. The scope of the paper does not cover hydrogen development in the Global North but does consider sustainability criteria importers should consider.

This document intends to serve as a starting point to guide public development finance institutions and policy makers in setting priorities for climate finance related to green hydrogen. It is the first output under this stream of research and will be complemented with various case studies and concrete suggestions for integrating our considerations in existing processes at Multilateral Development Banks (MDBs) over the next year. MDBs are the focus of the research project under which this report was developed, and through their thought leadership, a clear mandate and commitment to align their portfolios with the Paris Agreement and their close connection to the countries, MDBs have multiple entry points to support a sustainable transition, also in the context of green hydrogen.

2 Background

2.1 Dependency on fossil fuels and its implication on the economy

Many developing and emerging economies are facing debt distress and rising climate risks which impact their ability to reach the sustainable development goals and transition to a 1.5°C-compatible pathway. Many of those countries today rely to a large extent on fossil fuels. In a 1.5°C world, the production and consumption of fossils will need to eventually end. According to the IEA, no additional investment in fossil fuel production is required for a pathway towards net-zero by 2050 (IEA 2021b). This means that fossil fuel infrastructure needs to be decommissioned and alternative revenue and energy sources developed.

Strong dependencies on fossil fuels cause different risks for countries. For fossil-fuel exporting countries particularly in the Global South, a lack of diversity in exports creates a dependency on the revenues of fossil fuels and makes the countries' budgets vulnerable to international demand and market prices. A UNDP (2023a) report found that on average in fossil fuel export-dependent economies, fossils account for 14% of GDP rents annually. With fossil fuel demand phasing out, dependent countries stand to lose more than 60% in oil rents between 2030-2040 under a global net zero scenario (Jensen 2023b). Exporting countries will need to transition towards other economic sectors, independent of the availability of fossil fuel reserves. Capacities added today are at risk of becoming stranded assets.

Even if in the past, the development of fossils has not always enhanced the well-being of the population, fossil fuels represent a critical source of income for producing countries. Countries with abundant natural resources can paradoxically have poorer development and economic outcome than countries with fewer natural resources – often referred to as the resource curse (Sachs and Warner 1995)[1]. Over dependence on raw material exports can 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 (Ebrahimzadeh n.d.). Countries with abundant fossil fuel resources will need alternative sources for generating revenues in a 1.5°C compatible world.

Fossil fuel exporters are also impacted by unequal trade exchange between exporters of raw materials and manufactured goods which has remained largely persistent and exacerbated economic divergence between rich and poor countries (Weber et al. 2021). 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 risks undermining sustainable development. To avoid unequal trade and the faults of the resource curse, future energy trade should prioritise local development needs and integrate up and downstream supply chains into the producer's economy. Countries that currently depend on fossil fuels for imports are similarly vulnerable to price changes and scarcity in supply on global energy markets, as the energy crisis following Russia's illegal invasion of Ukraine illustrated vividly. 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 2022b). In Europe, high energy prices attributed to Russia's invasion of Ukraine increased food prices by 14% from 2022 to 2023 (Arce, Koester, and Nickel 2023). Production costs for energy-intensive industries were also reported to have risen by 50% in some sectors (Crispeels et al. 2022) – with price increases mostly passed on to consumers.

Many countries that rely on imports for their energy supply spend substantial amounts of their budgets 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 – as seen in the case of Germany's reliance on Russian gas.

To support sustainable development and energy security, a transition that is compatible with the Paris Agreement's limit of 1.5°C warming should support the economic diversification of countries and enable them to decrease dependencies on individual commodities. Economic and technological complexity is associated with higher future growth and more stability (Hidalgo and Hausmann 2009; Nepelski and De Prato 2020). Research also finds that a higher level of economic complexity can be a safeguard against market shocks and reduce fiscal vulnerability (Gomez-Gonzales, Uribe, and Valencia 2023; Gueneri and Yalta 2020). Shifting from exporting lower value creation products (i.e., raw fossil materials) towards

[1] 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, Lahn, and Kooroshy 2015).

renewables can support diversification if integrated into local up- and down-stream value chains and utilised domestically to produce complex but low emission products that can be exported competitively.

Green hydrogen is one avenue through which MDBs can support decarbonisation, sustainable development, and economic diversification. However, future trade of green hydrogen should avoid reproducing dependencies on energy resource rents and other negative implications associated with the resource curse. Public development finance institutions, including the MDBs, can support building out local upstream and downstream industries and support export diversification through developing local capacity to produce increasingly complex products (i.e., embodied hydrogen products like green steel) for export.

2.2 Current developments around green hydrogen

Green hydrogen is emerging as a potential solution for decarbonisation and sustainable development and industries, civil society and an increasing number of governments is engaging in the topic. So far, over 25 countries have developed hydrogen strategies, which focus to varying degrees on producing green hydrogen domestically and/or building up partnerships with other countries to import or export green hydrogen (IEA 2022c). 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. The United States' Green Hydrogen strategy anticipates a domestic demand of 10 million tonnes (Mt) in 2030, 20 Mt in 2040 and 50 Mt by 2050 (US Department of Energy 2023b). India sets out to be a leading producer and supplier of green hydrogen, with the objective to produce 5 Mt per year by 2030 (Government of India 2022). Finally, the European Union's hydrogen strategy anticipates a demand of 20 Mt by 2030, half of which would be imported (European Commission 2020). However there is a risk that hydrogen targets are inflated and not reflective of the volumes of hydrogen needed to cover solely no-regret applications or the competitiveness of hydrogen with electrification (Graf 2023).

MDBs are also engaged in developing a global green hydrogen economy. The European Bank for Reconstruction and Development (EBRD) is supporting Egypt's first green hydrogen facility which will produce green ammonia for domestic and international markets (Zgheib 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).

However, international trade of green hydrogen is not guaranteed to facilitate economic growth or sustainable development in exporting countries. Many green hydrogen cooperations financed by the Global North have emerged to build production in the Global South, mainly with the objective to export the green fuel to the North. Germany for example is fostering "hydrogen partnerships" with various developing countries and aims at importing hydrogen as part of the national hydrogen strategy. This could compete with decarbonisation efforts of the countries in the Global South (see section 5.3). Some civil society representatives have also raised concerns that green hydrogen trade will further the extraction of raw resources from the Global South to the Global North and perpetuate the trend of unequal exchange (Kalt and Lekalakala 2023). .

2.3 Hydrogen classifications and uses

There is no globally agreed definition for green hydrogen or its derivatives. Hydrogen is classified with different colours based on its production process (see Box 1). However, the IEA (2023) 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 improve transparency, facilitate regulation and certification, and support investment in hydrogen supply chains. Criteria for green hydrogen should consider the renewable share of the energy mix, as well as emissions throughout the entire value chain (The German National Hydrogen Council 2021) and sustainable sourcing and management of inputs (e.g., water for electrolysis or nitrogen for green ammonia).

Box 1: Classification of hydrogen by colour

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

Grey hydrogen – Grey hydrogen is produced from natural gas or methane through steam reforming. Crucially, greenhouse gas (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, but the process relies on carbon capture and storage (CCS) to trap and store CO_2 emissions. Blue hydrogen is sometimes referred to as low-emission hydrogen, but its production still depends on fossil fuels, which release upstream and midstream GHG emissions and relies on technology not yet available a scale.

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.

Green hydrogen – Green hydrogen is produced via water electrolysis with exclusively renewable electricity and releases no GHG emissions. Its production is facilitated by an electrolyser and requires significant renewable energy and water inputs.

3 The role of green hydrogen in a 1.5°C compatible transition

Deep sectoral transformations are needed across all sectors globally to move towards net zero GHG emissions and align with the Paris Agreement (Kuramochi et al. 2018). Fossil fuels must be phased out and zero-emission alternatives scaled to facilitate decarbonisation. Direct electrification, energy efficiency and, particularly in the Global North, avoiding overconsumption will play a significant role in decreasing GHG emissions.

Where those measures are insufficient to fully decarbonise a sector, green hydrogen enters the stage. While the use of hydrogen is technically possible in various sectors, it is not always the most energy- or cost-efficient decarbonisation alternative and production capacities are very limited (see section 4.5). Green hydrogen thus has a targeted and limited role to play in Paris-aligned scenarios. Green hydrogen and its derivatives can decarbonise thermal energy use in industrial processes, serve as a feedstock that replaces fossil-based inputs to chemical processes (e.g., fertiliser production, petrochemical production), decarbonise transport fuel in remote locations where electrification is not possible (e.g., aviation, shipping, and heavy-duty mining), and store electricity from renewables (IEA 2019; Jaramillo et al. 2022; de Villafranca Casas et al. 2022).

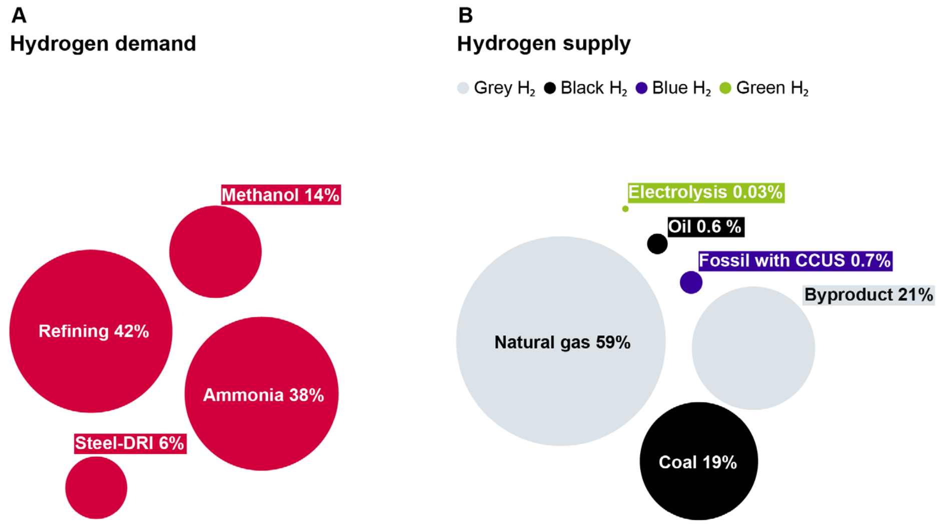
Globally, green hydrogen production, trade and use are still in its infancy, and all parts of its value chain need to be scaled. This poses big challenges, but also offers a chance to reform energy systems in a way that they promote a just transition and support sustainable development.

3.1 Hydrogen production

Today, hydrogen production predominately utilises unabated fossil fuels[2]. In 2021, hydrogen production from natural gas and coal accounted for 62% and 19% of total production, respectively (IEA 2022c). The energy intensive process emits close to 900 Mt CO_2 emissions per year (IEA 2021a). “Low-carbon hydrogen”[3] accounts for the smallest share of current hydrogen production (0.7%) and is mostly produced with CCS (so-called “blue hydrogen”) (IEA 2022c) (Figure 1).

Worldwide hydrogen demand reached 94 million tonnes (Mt) in 2021. The top consumers were China (28 Mt), the United States (12 Mt), the Middle East (12 Mt), Europe (8 Mt), and India (8 Mt) (IEA 2022c). Hydrogen demand today is largely concentrated in the oil refining and chemical sectors (Figure 1). Oil and gas refining accounts for a third of global demand for hydrogen (IEA 2019). Other demand is driven by the production of ammonia, methanol, and direct reduction iron (Lopez Legarreta et al. 2023).

[2] Unabated refers to the use of fossil fuel combustion without the use of carbon capture and storage technology.
[3] Low-carbon hydrogen refers to green and blue hydrogen (with CCS).



Source: Authors based on (IEA, 2021c, 2021b, 2021d)

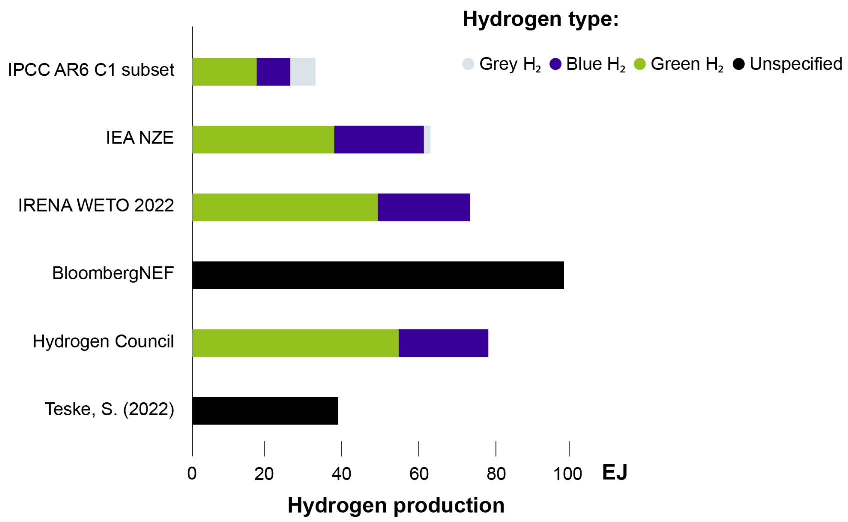
Figure 1: Hydrogen demand by area (A) and supply by production (B) technology in 2020 (Lopez Legarreta et al. 2023)

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

In turn, falling renewable energy generation costs and technology improvements will make green hydrogen – particularly that powered by solar PVs – cost competitive with hydrogen produced from fossil fuels in the future under certain conditions (IEA 2021a; The Hydrogen Council and McKinsey & Company 2021). Hydrogen production from hybrid solar PV and wind systems could fall to 1.5 to 2 USD/kg H_2 by 2030 in some regions (e.g., North Africa, the Middle East, and China) (IEA 2021a, 126). By 2050 it could be produced for below 1.0 USD/kg H_2 by 2050 (IEA 2022c).

3.2 Future demand for green hydrogen

Estimates of future green hydrogen demand under Paris-aligned pathways ranges from about 40 exajoule (EJ) to 100 EJ (Figure 2) (Lopez Legarreta et al. 2023). Estimates 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 2021a). Existing climate mitigation scenarios 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 2022a). 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 (2022b) 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 as well and shift demand centres.



Sources: Authors based on (BloombergNEF, 2020; IEA, 2021f, 2021c; IRENA, 2021c, 2022h; The Hydrogen Council and McKinsey & Company, 2021a; Byers et al., 2022; Teske, 2022)

Figure 2: Projected hydrogen production by 2050 in 1.5°C compatible decarbonisation scenarios (Lopez Legarreta et al. 2023)

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 2022d). 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. In Europe, future 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)[4]. The IEA's Net Zero Scenario also projects a near-term hydrogen demand for grid injection – blending hydrogen into natural gas grids (IEA 2021a). 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 (IEA 2019)[5].

3.3 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 (See graphic). 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 the costs of transmission and distribution can amount to three times the production costs (IEA 2019).

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 ship. Unique

[4] 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 2022).

[5] The emissions avoided via blending depend on the cost of hydrogen and natural gas, the blended share of hydrogen, and the CO2 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.

properties of hydrogen require specialised transport equipment to combat metal embrittlement and maintain pressure and cryogenic temperatures (IEA 2019). Hydrogen has a low energy density and 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) (compare section 4.5).

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 2022c). 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 repurpose fossil infrastructure lock-in fossil fuel use under the guise that it is hydrogen ready.

3.4 Support needs and international cooperation on green hydrogen

In the near-term, government support is key to develop cost-competitive hydrogen supply chains. Governments in the Global North and South have adopted hydrogen strategies that aim to develop green and low-carbon hydrogen economies through for instance, setting national targets for up and downstream infrastructure development (e.g., electrolysis capacity, retrofitting transmission networks, etc.), introducing policies that promote industrial applications (e.g., public procurement quotas, mandates, or purchase subsidies), and encouraging hydrogen clusters (i.e., co-locating production and demand centres). In 2021, public funding for hydrogen research and development (R&D) equated to 5% of the total R&D budget for clean energy technologies (Bermudez, Evangelopoulou, and Pavan 2022). Both the United States' Inflation Reduction Act (IRA) and the European Green Deal Industrial Plan offer substantial support for green hydrogen generation (European Commission 2023; U.S. Department of Energy 2022). Germany also launched a financing platform for green hydrogen infrastructure development in developing and emerging economies (KFW 2023).

Multilateral cooperation is key to set international standards and foster the energy transition, including green hydrogen where needed. As green hydrogen requires substantial investments and its future is to some extent uncertain, international support is needed to facilitate the development of hydrogen economies in developing countries to ensure regions are not left behind. International cooperation on a green hydrogen economy is growing with the 2021 Glasgow Breakthrough Agenda including hydrogen as a focus area (COP26 Presidency 2021) and the G7 launching a Hydrogen Action Pact in 2022 (G7 Germany 2022).

Green hydrogen is nascent but offers a potentially lucrative trade opportunity for some resource rich countries. International trade of green hydrogen also provides a solution for industrialised countries with high hydrogen demand but limited production potential. A global green hydrogen economy can help address the challenges of the global energy transition but the conditions under which green hydrogen is efficient and sustainable should be scrutinised (See more in Chapter 3). Research criticises for example that unequal exchange, where prices for resources that are extracted from the Global South are kept low through "power imbalances in the global political economy", leads to a drain of the Global South and the impacts of using excess resources in the Global North are mostly felt in the Global South (Hickel et al. 2022).

4 Criteria for a sustainable, Paris-aligned green hydrogen production

The shift from fossil fuel production towards zero-emission alternatives (i.e., green hydrogen) has geopolitical implications for the energy system. Green hydrogen will play a role in the future energy system but to deliver on mitigation and development priorities, clearly defined sustainability criteria are needed to avoid reproducing inequalities and guide investments towards high impact applications that are 1.5°C compatible (Heinemann and Mendelevitch 2021).

Green hydrogen may present an opportunity for resource-rich developing countries to benefit from new age energy and trade partnerships. Historically, trade partnerships were marred by unequal exchange and the appropriation of resources and labour by colonial powers which stunted (Hickel et al. 2022) – and continue to stunt – development in the global South. A future hydrogen economy should not be at the expense of exporting countries and should not hinder the sustainable development or decarbonisation pathways of producers.

The green hydrogen value chain directly or indirectly impacts 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). Framing the climate emergency in terms of its impact on sustainable development, rather than focusing on climate mitigation alone, can highlight the developmental priorities of particularly low-income countries (Sathaye et al. 2007). Future international trade of green hydrogen should place considerable emphasis 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).

The following sections cover criteria for sustainable hydrogen projects both from a development perspective as well as regarding the need to transition the energy sector in line with 1.5°C.

4.1 Access to water and land

Green hydrogen production requires access to large supplies of high-quality water for the electrolysis.. 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). Identifying locations with low-cost renewable energy production and water availability presents a challenge.

Regions with significant capacity for solar PVs have a competitive advantage for green hydrogen production, but these regions also face high levels of water stress (Fokeer, Sievernich, and Schwager 2022), raising questions about the appropriateness of utilising scarce water resources for export oriented green hydrogen. In arid regions with access to seawater, desalination plants can be utilised to meet freshwater demand. However, the desalination process produces an environmentally damaging brine biproduct which must be sustainably disposed of to avoid negative impact on marine ecosystems. Researchers are exploring producing hydrogen with seawater to avoid environmental and water stress concerns (Service 2023).

Electrolysers consumes on average 0.27 litres of fresh water per kWh of hydrogen (IEA 2019). To meet the estimated global hydrogen demand in 2050 with green hydrogen would require 25 billion cubic metres (bcm)[6] of fresh water per year[7] (Blanco 2021). Newborough and Cooley (2021) note that

[6] Based on an estimated hydrogen demand of about 74 EJ.

[7] Global water consumption was 4 trillion m^3 in 2014 (Ritchie and Roser 2018). Global hydrogen's water consumption would be 0.6% of 2014 consumption.

replacing fossil fuels with green hydrogen would globally reduce water consumption in the energy sector. However, increased water use from electrolysers in hydrogen-producing regions could exacerbate local water scarcity and lead to conflict. When green hydrogen is used, it produces energy and releases water back into the atmosphere. Fokeer, et. al (2022) argue that to retain water resources locally, there is a strong case to utilise green hydrogen domestically to produce green goods.

Responsible water management and procurement is crucial for sustainable green hydrogen. Water consumption for electrolysis 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 provide insight into the potential harm of utilising local surface and ground water reserves or diverting limited desalination capacity for hydrogen production. In arid regions with limited desalination capacity and local demand for green hydrogen that cannot be covered through other zero-carbon energy carriers, it needs to be carefully considered whether additional desalination plants should be brought online to service electrolysers' water demand, or green hydrogen could 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.

At a minimum, green hydrogen value chains should do no harm to local water access and marine environments. But importers can also go further and ensure that the development of a hydrogen economy guarantees producing countries developmental benefits (Morgen et al. 2022). Targeted investments in water infrastructure (i.e., distribution networks and desalination plants) for green hydrogen production with additional capacity for local use can provide positive spill over benefits and expand freshwater access for water scarce producers. Development finance institutions could make this a condition for green hydrogen production projects in regions where access to water is not granted.

4.2 High standards for defining green hydrogen

As described earlier, hydrogen, as a secondary energy resource, is produced from renewable or non-renewable primary energy sources. Its climate impact 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). The Öko-Institut (2019) found that hydrogen produced with electrolysis only has a climate benefit when produced with over 70% green electricity. To fully decarbonise the energy sector, a close to 100% share of renewable electricity would be required. Only hydrogen that is supplied with 100% renewable electricity should be considered green.

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". Grey hydrogen is currently the most common form of hydrogen production and in 1.5°C scenarios is largely replaced by green hydrogen production (see chapter 3.1). This means that additional grey hydrogen capacities can also 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 lack economic and technical viability to reduce emissions at scale. 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.

4.3 Sustainable and just transitions to renewable energy supply

For a Paris-compatible pathway, the power sector needs to largely decarbonise, well before 2050, with renewable energy playing the largest role by far. However, in most countries, renewables make up a small share of the energy mix today, which means domestic energy demand is reliant on fossil fuels. To meet future demand for green hydrogen, RE capacity would need to reach over 10,000 gigawatts (GW) per year by 2050 for green hydrogen production alone[8](IRENA 2022), and total global renewable capacity needs to increase by 60% to align with the IEA Net Zero by 2050 Scenario (IEA 2022e). Significant investments are needed to build out local value chains for renewables, electrolysers, and transmission infrastructure to meet future demand.

Globally, the use of fossil fuels needs to decrease drastically, which means that hydrogen projects can only be considered fully aligned with the Paris Agreement, if they do not lead to an increase of fossil fuel consumption (see previous section). 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.

The check for Paris-alignment should consider whether the capacity addition dedicated to the hydrogen production decreases the speed of providing access to electricity and the overall decarbonisation of the electricity sector, for example if areas for RE installation are scarce. Progress on national energy priorities should not be hindered by the allocation of available RE to green hydrogen generation (Morgen et al. 2022). Sufficient RE capacities would need to be installed with the electrolysers, independently of whether the installation is connected to the electricity grid or not.

Regions with high solar and wind potential have a comparative advantage in low-cost green hydrogen production (IEA 2022c). However, 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 countries still depend to a large degree on traditional biomass for cooking, heating and in some manufacturing processes. Traditional biomass for cooking is inefficient, unsustainable, and linked to premature deaths (IEA 2022a). Access to modern forms of energy is key for improved health, education opportunities, and gender equality. To meet the Sustainable Development Goal 7 on Affordable and Clean Energy, traditional biomass usage needs to electrify or be replaced with modern bioenergy that is sustainably sourced (ibid).

There is risk that developing green hydrogen in regions with high energy deficits further stretches grid capacity and reduces access for local use. Or that the best sites are utilised for wind and solar to produce the cheapest hydrogen, potentially excluding domestic users from affordable energy. There is also risk that land use required for the hydrogen supply chain displaces local populations (formal and informal) or competes with agricultural land use (Fokeer, Sievernich, and Schwager 2022). Green hydrogen's energy demand should not compete with local access to energy. Domestic use of green hydrogen should also be prioritised to avoid delaying decarbonisation or access to energy for local populations. Green hydrogen should not be promoted in regions where domestic access to modern energy is not covered, unless projects identify clear socio-economic benefits including significantly advancing domestic access to energy or food production.

4.4 Local value creation

Upstream and downstream components of green hydrogen value chains can support economic development, build out local infrastructure, and contribute to job creation in producer countries when value is captured at the local level. However, benefits past diversifying export revenues and increasing foreign direct investments are not a given and must be actively considered from the start. Local value creation should be integrated into producers and importers' hydrogen strategies and in any future

[8] Total wind and solar capacity in 2021 was 1,612 (IRENA 2022)

international criteria for sustainable green hydrogen to avoid missed opportunities and trade imbalances for the producing country.

Developing a green hydrogen value chain is risky as the scale of future demand is not guaranteed and technologies required for it are very expensive still. While there will be demand in hard-to-abate sectors where industries embark on a decarbonisation pathway, use in other sectors is uncertain and largely dependent on government signals and technological innovation, 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 countries borrow money for high initial investments for hydrogen infrastructure but that projects are not sufficiently profitable, leading to negative debt impacts

To hedge this risk, an integrated value chain approach should be taken to secure domestic demand for green hydrogen (Patuleia and Waliszewska 2023). Domestic demand can be facilitated by setting demand targets which boost market uptake and support downstream green hydrogen value chains. Domestic green hydrogen use will be crucial in facilitating decarbonisation of domestic hard-to-abate industries (e.g., steel production, fertiliser production, some specialised heavy-duty transport (mining) and, together with RE, allow industrial exports to remain competitive internationally in the face of carbon pricing schemes like the European Union's CBAM. Risk can be further decreased by diversifying the importer base through regional green hydrogen corridors.

Investments to support the development of domestic green hydrogen supply chains are crucial to capture socio-economic benefits for local communities and move countries towards decarbonisation. Traditionally, raw commodity exports offer low value creation options compared to their processed alternatives often concentrated in wealthier importing states. Strategic industrial policies are needed to support producers to seize opportunities to develop downstream green hydrogen value chains which are higher value and 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, Sievernich, and Schwager 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 (Morgen et al. 2022; The German National Hydrogen Council 2021).

Investors and importers should develop clearly defined criteria which assess how local communities benefit from green hydrogen projects and routinely assess impact. Impact assessments should cover among other things domestic infrastructure developments, job creation, increased access to basic resources (i.e., modern energy and water), environmental impact, and land use (Morgen et al. 2022). Local stakeholders (at the local, regional, and national level) should be actively engaged in the development of a green hydrogen economy from the start to address risks and align priorities.

4.5 A cost-efficient decarbonised global energy system

Green hydrogen production and transportation is an energy intensive process with efficiency losses along the supply chain. Efficiency losses from production, conversion, and transmission, 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. Energy efficiency and direct electrification should be first order considerations (Lopez Legarreta et al. 2023). Adjusting agricultural practices and, particularly in developed countries, encouraging sufficiency are additional measures that can limit the need for hydrogen.

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. The replacement of coal-fired power plants with renewable energy, a switch to electric vehicles and heat pumps, as well as replacing coal blast furnaces with hydrogen-based production routes for steel are among the most effective measures to reduce emissions via renewable electricity technologies (Agora Energiewende 2023).

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 2022c). The electrical efficiency (% LHV) of electrolysers varies by technology and ranges from about 56%-81% 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 (see section 3.3). Today, green hydrogen is hardly available, and it will remain a relatively expensive energy carrier in the future. This means that its use should be limited to those cases where there are no viable alternatives.

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. Figure 3 illustrates the losses that would occur for example when using green hydrogen to produce ammonia for the purpose of co-firing it in coal-fired power plants, a technology promoted by Japan domestically and across Southeast Asia. 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 in this graphic. This will make the electricity output much more expensive than generating it directly with renewables. RE potentials and the option for an electricity grid connection would need to be extremely limited in a region for cofiring 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). The potential of blending with or switching to green hydrogen cannot be an excuse to extend the life expectancy of fossil infrastructure.

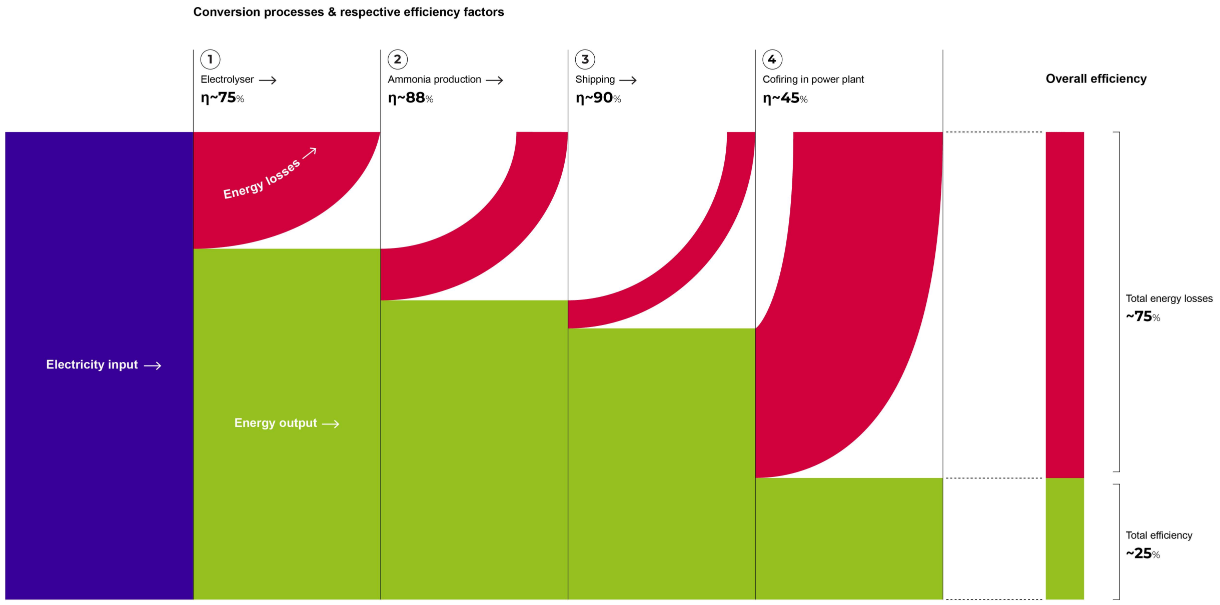


Figure 3: Example of an inefficient use of RE electricity: Energy losses in producing and co-firing ammonia in coal-fired power plants.

Note: Electrolyser efficiency varies depending on electrolyser technology (i.e., Alkaline electrolyser, proton exchange (PEM) electrolyser, or solid oxide electrolysis cells (SOECs) electrolyser). Efficiencies range from 63-84% (IEA 2019) and will likely increase in the future. The graphic assumes an efficiency of 75%. 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 88% for ammonia production and a transport efficiency of shipping ammonia at 90% (Chatterjee, Parsapur, and Huang 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).

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 4 illustrates losses assuming a production of green hydrogen for the purpose of blending it in gas boilers. The electricity could alternatively be used to run a heat pump, which extracts energy from the ambience, thus resulting in even more usable energy than was put into the process. 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.

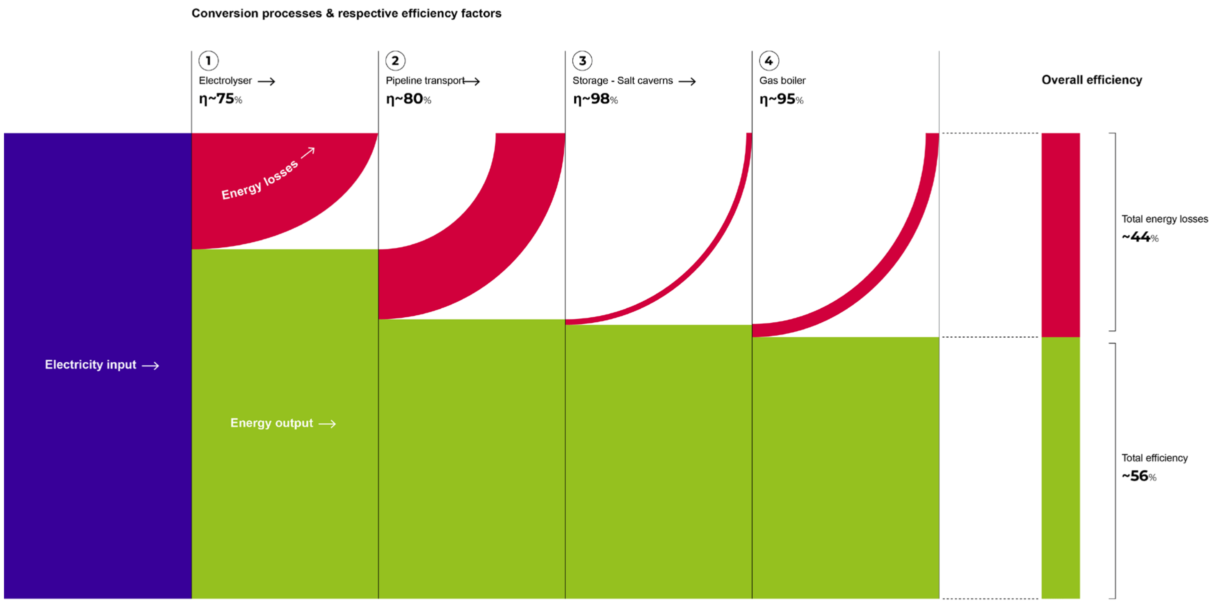


Figure 4: Example of an inefficient use of RE electricity: Energy losses in producing and importing green hydrogen for blending in gas boilers.

Notes: Electrolyser efficiency varies depending on electrolyser technology (Alkaline electrolyser v. proton exchange (PEM) electrolyser v solid oxide electrolysis cells (SOECs) electrolyser). Electrolyser efficiencies 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 75% 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 2023a).

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 directing investments into it risks additional stranded assets. An exception could be a situation where the temporary use of green hydrogen in oil and gas refining is an incentive to more rapidly build up the production of green hydrogen, which can later be shifted to future-proof use cases. A report on hydrogen use in the EU assumes that the demand from refining for hydrogen is close to zero by 2040 and fully phased out by 2050 under the climate neutrality target (Andreola et al. 2021).

Likely aligned would be 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 production, or aviation and shipping fuels (see also Figure 12 in Lopez Legarreta *et al.*, 2023).

5 Conclusions

Green hydrogen will remain an expensive form of energy and the world will need to focus on limiting demand through electrification, efficiency and, particularly in the Global North reducing overconsumption. Even in the long term, the traded volumes of green hydrogen will be lower than those of fossil fuels currently. Green hydrogen will not be sufficient to replace the fossil fuel industry in terms of export revenue volumes. The energy carrier is still in its fledgling stage and future trade flows and domestic green hydrogen needs are uncertain to a large degree. This means that investments in green hydrogen today are risky, and particularly for developing countries, stranded assets can be a threat to development objectives.

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.

Green hydrogen can contribute to a diversified economy 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 will be necessary to prioritise development goals in the Global South and push green hydrogen in the areas where it is needed to decarbonise end use – and only there. The priorities for governments and development finance institutes should be:

- **Build up renewable energy infrastructure as a no-regret measure**: 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°C limit requires a fast decarbonisation of the power sector. At least 1.5 TW per year need 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 help increase the local content for renewable energy, through enabling access to technologies and building up local supply chains. Defining how this can best done on a case-by-case basis, and how the integration in local supply chains could be financed 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, 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.** Where the continuation or raise of industries such as for example steel or fertiliser production or mining with heavy-duty transport needs are part of countries' development strategies, 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 those 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 the importing countries. Importing countries will need strong policies to ensure the sustainability of green hydrogen, covering a positive impact on the development objectives and the decarbonisation 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. Equitable agreements with importing countries are important to allow a shift towards domestic production once needed. Countries could use for example channels like the Just Energy Transition Partnerships to negotiate such agreements.

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 this process, and have the opportunity to enable developing countries in this transition even if green hydrogen is "not a business case" yet. Our future research will go into more depth and lay out approaches and tools MDBs could use to this end.

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NewClimate – Institute for Climate Policy and Global Sustainability gGmbH

Cologne Office
Waidmarkt 11a
50676 Cologne, Germany

Berlin Office
Schönhauser Allee 10-11
10119 Berlin, Germany

Phone: +49 221 999 83 300
Email: info@newclimate.org
Website: www.newclimate.org