IDOS German Institute of Development and Sustainability

IDOS DISCUSSION PAPER **9/2023**

Green Hydrogen: Implications for International Cooperation

With Special Reference to South Africa

Andreas Stamm

Tilman Altenburg

Rita Strohmaier

Ece Oyan

Katharina Thoms

Green hydrogen: Implications for international cooperation

With special reference to South Africa

Andreas Stamm, Tilman Altenburg, Rita Strohmaier, Ece Oyan
and Katharina Thoms

Bonn 2023

Dr Andreas Stamm is a senior researcher in the "Transformation of Economic and Social Systems" programme at the German Institute of Development and Sustainability (IDOS).

Email: andreas.stamm@idos-research.de

Dr Tilman Altenburg is head of the "Transformation of Economic and Social Systems" programme at the German Institute of Development and Sustainability (IDOS).

Email: tilman.altenburg@idos-research.de

Dr Rita Strohmaier is a senior researcher in the "Transformation of Economic and Social Systems" programme at the German Institute of Development and Sustainability (IDOS).

Email: rita.strohmaier@idos-research.de

Ece Oyan is a researcher in the "Transformation of Economic and Social Systems" programme at the German Institute of Development and Sustainability (IDOS).

Katharina Thoms is a research associate at the Institute for Technology and Innovation Management at RWTH Aachen University.

Published with financial support from the Federal Ministry of Education and Research (Bundesministerium für Bildung und Forschung, BMBF)

Suggested citation:
Stamm, A., Altenburg, T., Strohmaier, R., Oyan, E., & Thoms, K. (2023). *Green hydrogen: Implications for international cooperation. With special reference to South Africa* (IDOS Discussion Paper 9/2023). Bonn: German Institute of Development and Sustainability (IDOS). https://doi.org/10.23661/idp9.2023

IDOS Discussion Paper / German Institute of Development and Sustainability (IDOS) gGmbH
ISSN 2751-4439 (Print)
ISSN 2751-4447 (Online)
ISBN 978-3-96021-210-2 (Print)
DOI: https://doi.org/10.23661/idp9.2023

Tulpenfeld 6, 53113 Bonn
Email: publications@idos-research.de
https://www.idos-research.de

Printed on eco-friendly, certified paper.

MEMBER OF Johannes-Rau-Forschungsgemeinschaft

Acknowledgements

This discussion paper was made possible through funding from the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH on behalf of the German Federal Ministry for Economic Cooperation and Development (BMZ) and from the German Federal Ministry of Education and Research (BMBF) through the project “Global Hydrogen Potential Atlas” (HYPAT). The authors are grateful to Vidushi Dembi and Anna Stamatogiannakis for their significant contributions to this report; and to Muhammed Patel, Thabo Chauke, Gaylor Montmasson-Clair, Simon Roberts, Antonio Andreoni, Florian Güldner and Yan Chen for their valuable comments on it. The responsibility for errors remains with the authors.

Abstract

Green hydrogen – produced with renewable energy – is indispensable for the decarbonisation of economies, especially concerning “hard-to-abate” activities such as the production of steel, cement and fertilisers as well as maritime transport and aviation. The demand for green hydrogen is therefore booming. Currently, green hydrogen is far more expensive than fossil fuel-based alternatives, but major initiatives are underway to develop a global green hydrogen market and bring costs down. Green hydrogen is expected to become cost-competitive in the mid-2030s.

Given their endowment with solar and wind energy, many countries in the Global South are well-positioned to produce low-cost green hydrogen and are therefore attracting investments. Whether and to what extent these investments will create value and employment for – and improve environmental conditions in – the host economies depends on policies. This discussion paper analyses the potential industrial development spillovers of green hydrogen production, distinguishing seven clusters of upstream and downstream industries that might receive a stimulus from green hydrogen. Yet, it also underlines that there is no automatism. Unless accompanied by industrial and innovation policies, and unless there are explicit provisions for using revenues for a Just Transition, hydrogen investments may lead to the formation of socially exclusive enclaves.

The paper consists of two parts. Part A provides basic information on the emerging green hydrogen market and its technological ramifications, the opportunities for countries with abundant resources for renewable energy, how national policies can maximise the effects in terms of sustainable national development and how this can be supported by international cooperation. Part B delves into the specific case of South Africa, which is one of the countries that has an advanced hydrogen roadmap and hosts several German and international development projects. The country case shows how a national hydrogen strategy can be tailored to specific country conditions and how international cooperation can support its design and implementation.

Keywords: Green hydrogen, energy transition, industrial development, industrial policy, South Africa, Just Transition, technological learning, international cooperation

Contents

Figures

Tables

Abbreviations

AEM	anion exchange membrane
BMBF	Federal Ministry of Education and Research
BMZ	German Ministry for Economic Cooperation and Development
CBAM	Carbon Border Adjustment Mechanism
CCS	carbon capture and storage
CCU	carbon capture and use
CH4	methane
CO	carbon monoxide
CO2	carbon dioxide
COP	Conference of the Parties
DRI	direct reduced iron
DSI	Department of Science and Innovation
EAF	electric arc furnace
EPC	engineering, procurement and construction
EU	European Union
FCEV	fuel-cell electric vehicle
FDI	foreign direct investment
GHG	greenhouse gas
GIZ	German Agency for International Cooperation / Deutsche Gesellschaft für Internationale Zusammenarbeit
H2	hydrogen
HySA	Hydrogen South Africa
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
KfW	German Credit Institute for Reconstruction
km	kilometre
LH2	liquefied hydrogen
LOHC	liquid organic hydrogen carrier
MENA	Middle East and North Africa
MJ	megajoule
Mt	million tonnes
MW	megawatt
NDC	Nationally Determined Contribution
PEM	polymer electrolyte membrane
PGM	platinum-group metal
PtX	Power-to-X
PV	photovoltaic
R&D	research and development

SAF	sustainable aviation fuel
SASOL	South African Synthetic Oil Limited
SEZ	special economic zone
SOEC	solid oxide electrolysers
TRL	technology readiness level
TVET	technical and vocational education and training
TWh	terawatt-hour
UNFCCC	United Nations Framework Convention on Climate Change

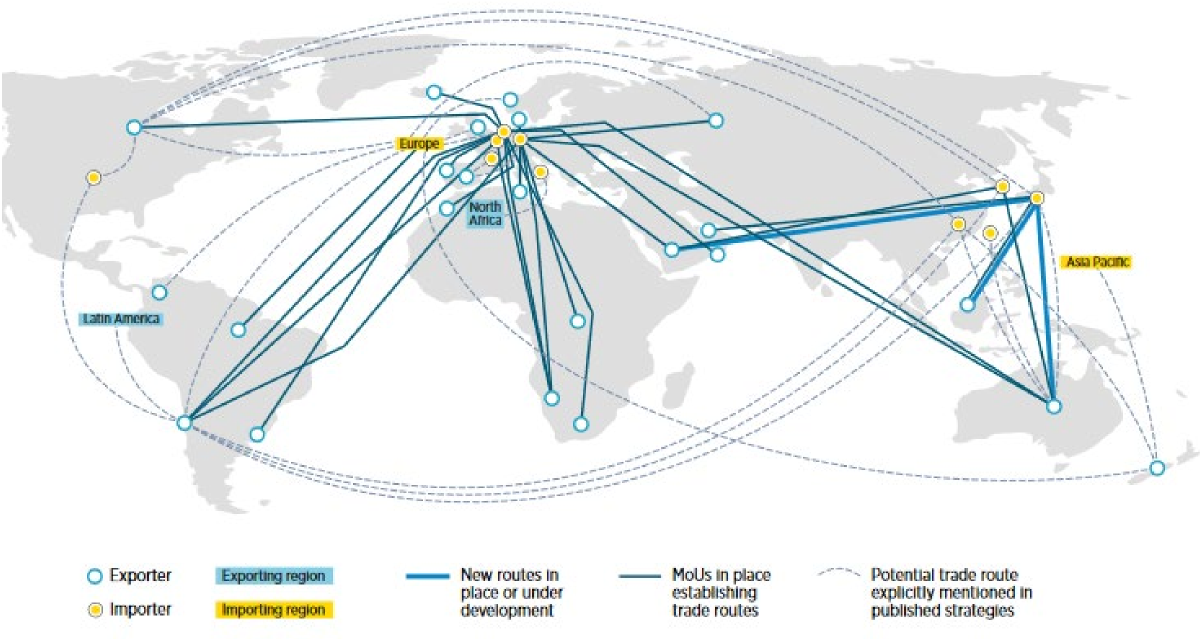
Introduction

Green hydrogen features prominently in policy plans of both old industrialised and developing countries. It is an essential part of the decarbonisation of the global economy, especially for the so-called hard-to-abate industries, such as iron and steel, chemicals and cement, as well as for long-distance transport. Demand for green hydrogen is therefore set to increase enormously, with supply lagging far behind for at least the next two decades.

This projected demand provides vast opportunities for all those countries with good renewable energy endowments – many of which are in sub-Saharan Africa, the Middle East and North Africa (MENA) region, Latin America and South Asia. These countries can produce green hydrogen to decarbonise hard-to-abate sectors in their own economies, they can tap into the rapidly growing world market for hydrogen, and they can create competitive advantages and attract international investments in energy-intensive industries that are under particular pressure to reduce their carbon footprints. Hence, they can embark on a variety of green hydrogen strategies with promising economic co-benefits. At the same time, there are risks involved: risks of failed investments, given the uncertainties of a newly developing technology; environmental risks; and socio-political risks related to capital-intensive, large-scale investments that may develop into enclaves with minimal local linkages and encourage rent-seeking, which in turn may trigger political resistance.

Multiple international agreements have been signed between potential import and export countries (Figure 1).

Figure 1: An expanding network of hydrogen trade routes, plans and agreements



Source: International Renewable Energy Agency (IRENA, 2022, p. 12)

In the case of Germany, international cooperation is now heavily focussing on green hydrogen. Multiple hydrogen partnerships have been established with potential export countries, especially countries and regions with excellent solar and wind resources as well as available, underutilised land. This includes the Gulf region, Northern Africa, South Africa and Namibia, Chile and India, among others. Their main objective is, on the German side, to accelerate investments in export projects to secure imports into Germany. This discussion paper approaches the topic from a different perspective (one that is also echoed in the hydrogen strategy of Germany's Ministry for Economic Cooperation and Development, BMZ): that of developing countries with favourable conditions for renewable energy generation. How can these countries harness the increasing green hydrogen demand for sustainable national development, accumulate new capabilities, make their industries fit for a low-carbon future, create additional employment as well as tax and foreign exchange earnings while minimising the risks? How can green hydrogen thus contribute to a Just Transition? The paper also explores how development cooperation can support such a transition.

The paper consists of two parts. **Part A** provides basic information on the emerging green hydrogen market, the opportunities for countries with abundant resources for renewable energy and how development cooperation can help countries exploit the opportunities in support of sustainable national development. **Part B** delves into the specific case of South Africa, which is one of the countries that has an advanced hydrogen roadmap and hosts several German and international development projects. The country case shows how specific country conditions lead to tailored hydrogen strategies and, in the same vein, discusses the specific contribution of a bilateral cooperation programme.

PART A: The green hydrogen economy – opportunities and challenges

Part A consists of six sections. Section 1 clarifies the role of green hydrogen in the transition to low-carbon economies. Section 2 explains the various ways of producing hydrogen with different carbon footprints. Section 3 deals with the economic sectors demanding green hydrogen, while Section 4 outlines routes that green hydrogen producing countries can take to maximise development co-benefits and decarbonise their own economies. Section 5 highlights some uncertainties of the newly emerging market and how those create risks for potential exporters. Section 6 concludes the general part of the paper by drawing conclusions for development cooperation.

1 The need for green hydrogen

The term "hydrogen economy" was first coined in the 1970s by the chemist John Bockris (Brandon & Kurban, 2017) and was already linked at that time to non-fossil energy sources (solar and nuclear). While several industrialised countries, most notably Japan, have shown strong interest in the development of hydrogen technologies in the years since, it was the steadily declining costs of solar and wind energy that turned green hydrogen from a hypothetical decarbonisation option to a recently hyped one: For some hard-to-abate industries – such as iron and steel, chemicals and cement, as well as for long-distance passenger and heavy cargo transport – it is the only means of decarbonisation. Thus, it is an essential part of the net-zero puzzle. It is estimated that by 2050, 4-11 per cent of the world's energy demand will run on hydrogen, with the energy carrier being more important for Europe than China (Riemer et al., 2022).

Hydrogen already constitutes an important input in countries with a strong industrial sector. In 2020, global hydrogen demand amounted to 90 million tonnes (Mt), 80 per cent of which was linked to ammonia production and oil refining. The remaining part was used in combination with other gases for methanol production and direct reduced iron (DRI) for steel production (International Energy Agency [IEA], 2021a). The European Union (EU) currently uses approximately 9.7 Mt of hydrogen annually (Kakoulaki et al., 2021), or 330 terawatt-hours (TWh) (European Union [EU], 2020, p. 6). The German National Hydrogen Strategy speaks of 55 TWh of hydrogen produced and processed in the country, which implies that Germany accounts for around 16 per cent of all hydrogen currently handled within the EU – the largest share among member states.

To achieve the net-zero target, not only will the hydrogen produced today have to be replaced by low-carbon hydrogen; but the global hydrogen demand is expected to increase considerably, given its enormous potential for decarbonising industrial processes and transport. The benchmark of 110 TWh mentioned in the German National Hydrogen Strategy for 2030 translates into 3.3 Mt, twice as much as is currently used. For the same year, the EU plans to process 10 Mt of green hydrogen (European Commission, 2023).[1] In 2050, demand in Germany is expected to reach 380 TWh – a sevenfold increase compared to current levels – whereas estimates for the EU project 2,700 TWh of green hydrogen to be used (German Advisory Council on the Environment [SRU], 2021).

Given the expected demand, 35 countries have published or are currently preparing a national hydrogen strategy, with many more countries undertaking measures in this regard (World Energy Council – Germany [WEC], 2022). Twenty-nine parties of the United Nations Framework

1 The EU aims to increase annual production of green hydrogen to 10 million tonnes by 2030.

Convention on Climate Change (UNFCCC) mention hydrogen as a contributing factor to climate change mitigation and energy transition in their Nationally Determined Contributions (NDCs) (Climate Watch, 2023). Although many of these strategies have been drafted on the level of nation states, it is clear that the green hydrogen transition will require comprehensive international coordination. Some of the big future consumers lack the renewable energy potential to satisfy demand domestically. This is especially the case for Europe, Japan and Korea, whereas other prospective big consumers – such as China, the United States, Canada and Australia – will likely not be dependent on imports (Wappler et al., 2022).

2 The variety of hydrogen colours and where Europe positions itself on the colour spectrum

Large quantities of low-carbon hydrogen are needed to decarbonise hard-to-abate economic activities around the world. The challenge is to increase its use as an energy carrier and feedstock in the respective industries and transport sectors and to produce it in the most climate friendly way possible. Not all hydrogen is the same. Corresponding to the way it is produced, different types, or “colours”, are distinguished, with very different carbon footprints (see Figure 2).

Today, the bulk of hydrogen is produced from fossil fuels, representing 6 per cent of natural gas use and 2 per cent of coal consumption and accounting for 830 Mt carbon dioxide (CO2), which is equivalent to 2 per cent of global annual CO2 emissions in 2021 (IEA, 2019a). Steam methane reforming is the predominant process for hydrogen production and employed in 95 per cent of EU hydrogen production. Fossil fuels such as natural gas and petroleum or coal are usually used as feedstock. Under pressure and high temperatures, the hydrocarbons contained in the energy sources are converted into methane (CH4), carbon monoxide (CO) and CO2. These substances are then catalysed to form hydrogen. Given its high carbon intensity, this type of hydrogen is commonly referred to as “grey” hydrogen. A much smaller amount of current hydrogen production – so-called brown or black hydrogen – is based on the gasification of bituminous (black) and lignite (brown) coal, which is an even more polluting process.

Yet, hydrogen can also be produced sustainably by either using renewable energy or other low-carbon sources or by capturing the greenhouse gas (GHG) emissions generated in the production and use of fossil fuels. For green hydrogen, renewable energy – mostly solar and wind but also hydropower and geothermal energy – is used for decomposing water into oxygen and hydrogen via electrolysis. The most important low-carbon alternative is “blue” hydrogen, which is generated from the steam reduction of natural gas, whereby natural gas is split into hydrogen and CO2, and the latter is stored (carbon capture and storage, CCS) or used (carbon capture and use, CCU) for industries. However, blue hydrogen has its own risks. Environmentally, CCS must ensure that there is no leakage of GHGs, and doubts remain due to the by-product emissions. Schippert, Runge, Farhang-Damghani and Grimm (2022, p. 8) analyse in detail the GHG emissions along the blue hydrogen supply chain. Natural gas production and transport are the main steps in the chain related to methane and other emissions. Thus, for countries aiming at using blue hydrogen, they recommend switching the import product from natural gas to hydrogen, as this significantly reduces overall GHG emissions.

Whether blue or green hydrogen is the most cost-competitive option for low-carbon hydrogen generation depends on the prices of natural gas – as the feedstock for blue hydrogen – and on technological innovations in both pathways. Aurora Energy Research (2023) calculates the levelised costs of renewable hydrogen in 2030 produced in Germany to be between EUR 3.90 and 5.00/kg H2. Hydrogen imported via ship from Morocco would cost between EUR 4.58/kg H2 (transported as liquefied hydrogen, LH2) and EUR 4.72/kg H2 (transported as ammonia). Imports from Morocco via pipeline would cost EUR 3.72/kg H2 (Aurora Energy Research, 2023).

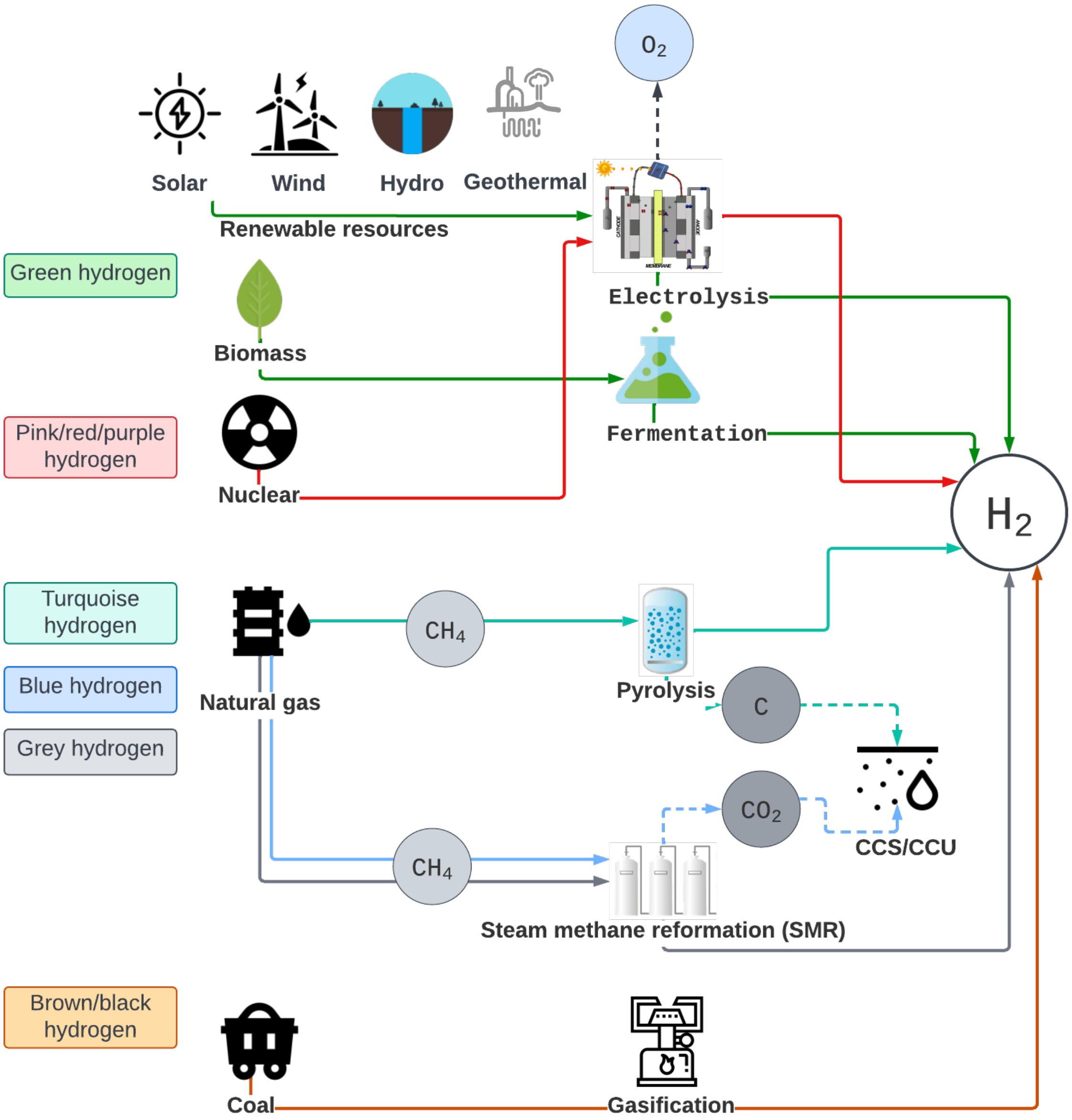
Oni, Anaya, Giwa, Di Lullo and Kumar (2022) calculated the costs of blue hydrogen based on different parameters (technologies, plant size and ambitions of carbon sequestration). They conclude prices between USD 1.22 and 2.55/kg. This implies that currently blue hydrogen is significantly cheaper than green hydrogen. This is likely to change in the coming years. First, the willingness of Europe to achieve independence from Russia with regard to gas imports will make the feedstock for blue hydrogen a permanently scarce commodity. Technological innovations are the other drivers of a shift in the relative competitiveness of both processes. Currently, a lot is being invested into research and development (R&D) for green hydrogen, as various world regions try to gain an edge in this technology of the future. In June 2021, the US Department of Energy launched the “Hydrogen Shot” initiative, aiming at reducing the cost of clean hydrogen to USD 1 per 1 kilogram in 1 decade (“1 1 1”) (Energy Efficiency & Renewable Energy, s.a.). The Norwegian electrolyser manufacturer NEL wants to achieve production costs of USD 1.5/kg already by the year 2025.

An entirely CO2-free process to produce hydrogen based on natural gas is methane pyrolysis: The thermal decomposition of methane only produces carbon as a by-product of (in this case, “turquoise”) hydrogen. Turquoise hydrogen is often seen as another potential bridge technology in the transition from fossil fuels to renewable energies. There is, however, still a long way to go to consider it a commercially viable option. Schneider, Bajohr, Graf and Kolb (2020) analyse the various processes required for the pyrolysis process and see them at technology readiness levels (TRLs) of only three to five. In addition, the political wish to lower the amount of natural gas imports to central Europe may work against the further development of this technology.

Carbon-free hydrogen can also be generated from nuclear energy. Some governments consider this – variously named “pink” or “red” – hydrogen as sustainable. Given the safety concerns of nuclear energy generation, the risks of nuclear arms proliferation and the unresolved challenges regarding the final deposit of nuclear waste, this is highly contested.

Last but not least, another green option is to produce hydrogen from biomass through anaerobic digestion (or “dark fermentation”). In this process, microorganisms digest biomass and organic waste and thereby release hydrogen. Advantages of the technology are the utilisation of organic waste (which is abundantly available and would anyway need treatment) and higher energy-efficiency in comparison to water electrolysis. However, although dark fermentation is well-established for producing methane from biomass, it has not been deployed for hydrogen production on a large commercial scale and is envisaged only by a few countries so far – notably those with a strong bioenergy sector, such as Brazil.

Figure 2: The hydrogen colour spectrum



Source: Authors

Green hydrogen is the first-best solution for curbing emissions from hard-to-abate sectors. Yet, it will be difficult to deploy renewable energy generation and electrolyser capacity fast enough to meet the ambitious decarbonisation targets. If that is the case, other varieties of low-carbon hydrogen, notably blue hydrogen, might be considered as bridge technologies to allow for a faster transition towards hydrogen-powered industrial processes and modes of transport:

> The goal of supplying Europe with sustainable, green hydrogen is undisputed. However, to reach this goal as fast as possible, blue hydrogen could help providing sufficient quantities of the gas in order to build up supply chains in the scaling phase of the hydrogen economy faster. Transport chains and applications could run on blue hydrogen in a transition phase to build up a market for the commodity and then gradually switch to green hydrogen. (Schippert et al., 2022, p. 2)

Internationally, there is no consensus on which varieties of hydrogen qualify for decarbonisation roadmaps. Countries have different factor endowments and legacy energy systems, reflecting political decisions of the past. This leads to different political interests. France, for instance, with a nuclear power fleet covering nearly 70 per cent of its national electricity supply, considers nuclear energy a viable option to produce hydrogen, whereas others strictly oppose this position. Norway generates 44 per cent of its total energy supply with hydropower (IEA, 2022a) while being the third-largest exporter of natural gas in the world. Germany has bet on renewable energy sources since around 2000, and wind, solar and bioenergy comprised 32.5 per cent of all electricity production in the country in 2018. These path-dependencies are correspondingly reflected in national hydrogen strategies: The German national hydrogen strategy is a “green hydrogen” strategy in the strict sense, whereas France envisages the existence of a “low-carbon energy mix supported by a large nuclear fleet”. Norway defines clean hydrogen as hydrogen produced either by using renewable energies or steam reforming processes involving natural gas or other fossil fuels combined with CCS (Norwegian Ministry of Petroleum and Energy/Norwegian Ministry of Climate and Environment, 2020, p. 6). In its hydrogen strategy of 2020, it aims at achieving the same market conditions for blue hydrogen as for green hydrogen in Europe. Hence, no country will wish to lose its competitive advantage in the energy sector through too narrow a definition of “desirable” hydrogen. On the level of the EU, the hydrogen strategy from 2020 gives priority to the production and use of green hydrogen, mainly from wind and solar power. However, it also states that other low-carbon hydrogen may be needed during a transition phase in order to quickly reduce emissions from existing fossil hydrogen production and to support the simultaneous development of renewable hydrogen technology (EU, 2020, p. 5).

The EU CertifHy initiative was set up as a certification scheme to reach a common understanding on desirable forms of hydrogen production. It specifies an upper limit of 36.4 g CO2eq/MJ (equivalent/megajoules) for the carbon footprint of hydrogen produced from renewable energy (green hydrogen) or other low-carbon sources (pink, blue or turquoise hydrogen). The EU CertifHy upper limit represents a CO2eq reduction of 60 per cent relative to the 91 g CO2eq/MJ specified for hydrogen produced from steam methane reforming (grey hydrogen) (CertifHy Consortium, 2021). Hence, blue hydrogen – produced from fossil fuels coupled with CCS – will qualify, in most cases.

The current energy crisis may support those interested in a less ambitious definition of low-carbon hydrogen. For instance, Germany signed a contract with Abu Dhabi in March 2022 to ensure first deliveries of blue hydrogen. For countries assessing opportunities to export low-carbon hydrogen to Germany and Europe, this implies that they can develop export options based on their specific energy matrix as long as they meet the EU CertifHy criterion of an upper limit of 36.4 g CO2eq/MJ. In the long run, this might shift towards stricter low-carbon criteria, once the market ramp-up has significantly advanced and higher quantities of strictly green hydrogen are available.

3 The use of green hydrogen for decarbonisation

Green hydrogen is an energy carrier that can be used either directly for heat generation as well as for non-energy purposes (e.g. as a feedstock for steel or basic chemical production); or indirectly, via the conversion of green hydrogen into derivatives such as ammonia, methanol, methane and synthetic fuels. Furthermore, hydrogen can be exploited as a means for storing renewable electricity.

Despite its broad applicability, green hydrogen will likely not be used in all sectors of the economy; forecasts suggest a global hydrogen share of 4-11 per cent of the final energy demand by 2050 (Riemer et al., 2022). On the sector level, transport is projected to have the largest share of hydrogen in total energy demand (globally between 10 and 19 per cent); however, there are still many uncertainties regarding the specific application areas. For industries such as cement and chemical as well as iron and steel, hydrogen constitutes the only decarbonisation option. For heating buildings, hydrogen is projected to amount to less than 2 per cent of the final energy demand in this sector (see Riemer et al. (2022) for a detailed analysis across sectors). In the following, we summarise where green hydrogen contributes to decarbonisation and where it does not, due to the availability of better alternatives.

3.1 Where green hydrogen contributes to decarbonisation

3.1.1 Applications in industry

Hydrogen already plays an integral part in many industrial applications: as a feedstock for ammonia synthesis (55 per cent of hydrogen demand), for hydrocracking and hydrodesulphurisation in refineries (25 per cent), and methanol production (10 per cent) (Quarton et al., 2020; Riemer et al., 2022). Here, grey hydrogen will eventually be replaced by green hydrogen. On the other hand, green hydrogen opens up new application opportunities: for generating high-temperature heat or as a reactant in new production processes, such as the DRI route in steel production. How rapidly green hydrogen will be deployed depends on its cost effectiveness vis-à-vis established fossil-energy-based alternatives and legacy infrastructures as well as on policies. In the following, we give a more detailed overview of the decarbonisation potential in the main industries.

3.1.1.1 Iron and steel industry

The iron and steel industry is responsible for about 2.6 billion tonnes of CO2 emissions, which is around 9 per cent of global annual emissions (World Steel Association, 2021), due to the large quantities of coal used in current production technologies. More than 70 per cent of global steel production takes place in Asia, with China accounting for about half of worldwide production (World Steel Association, 2023), followed by India, the United States and Japan. With 40.1 Mt produced in 2021 (World Steel Association, 2023), Germany is the seventh-largest steel producer in the world and the largest in the EU. Given that the demand for steel is projected to rise, decarbonising the industry is paramount for achieving climate neutrality.

Steel can mainly be produced via two processes: the blast furnace–basic oxygen furnace route (accounting for about 70 per cent of steel production), and the electric arc furnace (EAF) route (about 28 per cent of steel production) (Ahmed, 2018; Hornby & Brooks, 2021). The main difference is in the raw materials used – blast furnaces require iron ore, whereas steel scrap or DRI is used in EAFs. In both processes, green hydrogen can be used as a reactant in DRI. Although it is the most developed non-carbon technology for DRI to date, it requires cost-intensive retrofitting of the steel plants. It is estimated that hydrogen-based direct reduction would increase the price of a ton of steel by about one-third (Kurrer, 2020). Furthermore, the ramp-up of the technology would need a significant expansion of renewable energy production. It takes 50 to 55 kWh to produce 1 kg of hydrogen, and 50 kg of hydrogen to produce 1 ton of steel. This would mean that for Germany to fully decarbonise its annual production of 40 Mt of steel, about 100 TWh of renewable energy are required. This represents a 20 per cent increase in total demand for electricity in Germany.

3.1.1.2 Cement industry

In 2019, the global cement industry was responsible for 2.3 billion tonnes of CO2 emissions, which accounted for 7 per cent of global CO2 emissions (Hasanbeigi, 2021). By far the biggest cement producer is China, with an estimated 2.5 billion tonnes produced in 2021, equalling more than half of global production. India comes second, with 330 million tons produced in 2021. Due to the broad availability of the main materials (e.g. limestone), cement can be produced at a reasonable price in almost every country; however, it is not cost-effective to transport over long distances (El-Sayed, Faheim, Salman, & Saleh, 2021), leading to a rather fragmented global market.

The main input in the production of cement is clinker. The amount of clinker used is directly related to the carbon footprint of the cement, as it emits both direct emissions via fuel combustion for process heat and process emissions due to limestone decomposition (IEA, 2021b). Thus, any decarbonisation strategy for the cement industry should target both direct and process emissions. The substitution of fossil fuels for carbon-neutral alternatives such as green hydrogen would cut direct emissions, corresponding to 35 per cent of the total CO2 emissions from the cement industry (SRU, 2021). Regarding process emissions, the addition of materials such as gypsum, blast furnace slag, fly ash and pozzolana decreases the clinker amount in cement, indirectly saving CO2 emissions. However, for the full elimination of process emissions, CCS technologies are a prerequisite. Cement thus remains one of the most challenging industries to completely decarbonise.

3.1.1.3 Chemical industry

The chemical sector is the largest industrial consumer of fossil fuels, using them equally for feedstock production and process energy. It ranks third in terms of direct CO2 emissions, contributing 925 Mt of CO2 globally in 2021 (IEA, 2022b). About half of the industry's emissions come from the production of ammonia, followed by high-value chemicals such as ethylene, propylene, benzene and methanol (IEA, 2021c). The production of these basic chemicals represents two-thirds of the sector's total energy consumption.

Ammonia. Seventy per cent of the ammonia produced worldwide is used for the production of synthetic nitrogen fertilisers such as urea, ammonia salts and ammonia solutions (IEA, 2021c). It is also used in the production of plastics, explosives and synthetic fibres. Ammonia is produced from hydrogen and nitrogen in the so-called Haber-Bosch process. Due to the use of grey hydrogen as a feedstock, ammonia production is currently highly carbon-intensive, accounting for about 2 per cent of total final energy consumption (IEA, 2021c).

Decarbonisation efforts mainly focus on making existing production methods more energy-efficient and reusing CO2 emitted during the course of hydrogen production for the production of urea (IEA, 2022b).[2] As hydrogen represents a key feedstock for ammonia, a main action point is to either overcome the necessity of hydrogen as a feedstock for ammonia production entirely or decarbonise the process step of hydrogen production itself. There are new technologies on the horizon to overcome the need for additional separate hydrogen production processes, such as the electro-catalytic nitrogen reduction reaction, biological nitrogen fixation or chemical looping processes. However, these processes are at a low TRL, and it is unclear if and when they will reach maturity (Lv et al., 2021; Royal Society, 2020). By substituting fossil hydrogen in ammonia production with green hydrogen in the future, significant CO2 emissions can be avoided. This production process currently operates at a TRL of five to nine (Royal Society, 2020). Its main economic and technical barriers strongly overlap with those of green hydrogen technologies: the costs and availability of electricity, electrolysers as well as plant capacity. There are, however, fertiliser companies that have green ammonia projects in their relatively short pipeline. A study by Rystad Energy (Oslo) shows that Fertiberia S.A. from Spain and the Norwegian fertiliser producer Yara are among the most ambitious green hydrogen offtakers, measured by the number of hydrogen purchase agreements signed (Klevstrand, 2023).

Due to the characteristics of green ammonia, such as density and storage temperature, it will likely not only decarbonise the fertiliser industry, but also be used as a transport medium for green hydrogen and a substitute for fossil fuels in, for example, heavy-duty transport and electricity. Only

2 This makes carbon capture use and storage a particularly competitive option for substantial emission reductions from ammonia production. According to the 2050 Sustainable Development Scenario by the IEA, 200 Mt of CO2 – of which 83 per cent are process emissions – can be captured, out of which 65 per cent can be used for urea production and 35 per cent are permanently stored (IEA, 2021c).

recently, an agreement was made between Canada and the United States to supply Germany with green ammonia as a substitute for natural gas in the future (Olk & Scholz, 2022).

High-value chemicals. High-value chemicals, including ethylene, propylene and benzene, are important raw materials for plastics and fuel production. At present, they are produced through crude oil refining. Switching the process to renewable synthesis would reduce CO2 emissions significantly (Miller, Armstrong, & Styring, 2022). One such route is “greening” the relevant feedstock, that is, syngas – a mixture of carbon dioxide, carbon monoxide and hydrogen – by coupling green hydrogen with CCU technology. Alternative decarbonisation pathways for high-value chemicals include the use of bio-resources to produce “bioplastics” (IEA, 2022b).

Methanol. Methanol is a versatile raw material included in plastics, paints and construction materials, but it can also be used as a liquid fuel for road transport, ships, fuel cells, boilers and cook stoves (Methanol Institute, 2023). E-methanol, produced from CO2 and green hydrogen, emits only a small fraction of CO2 and nitrogen oxide compared to fossil fuels. Together with ammonia, it is the most promising decarbonisation option for the shipping industry. Industrial-scale e-methanol plants are currently under construction in Denmark (Siemens Energy, 2022) and Norway (IEA, 2022c).

Box 1: Green hydrogen for fertiliser production

Seventy per cent of global ammonia production is used for the production of synthetic nitrogen fertilisers (IEA, 2021c). The biggest exporters of nitrogen fertilisers are currently Russia (12.1 per cent), China (12.1 per cent) and Oman (7.2 per cent). Their leading positions on the global market are largely due to their endowments with fossil fuels for hydrogen production (International Trade Centre [ITC], 2021). Recently, the prices for fertilisers have been fluctuating heavily, putting significant pressure on global food systems: Following a rise of about 80 per cent on average in 2021, prices increased about another 30 per cent starting in 2022 before reaching a peak in April 2022 (Baffes & Koh, 2022; Bourne, 2022). Since then, prices have declined but are still much higher compared to the beginning of the decade. The price spike can be mainly attributed to the Russian invasion of Ukraine, resulting in shortages of supply from Russia, Belarus and Ukraine. Rising prices for natural gas in Europe and coal in China have led to production cutbacks of ammonia, and thus further increased fertiliser input prices. Furthermore, China has implemented barriers and bans for the export of fertilisers to ensure the local supply (Baffes & Koh, 2022).

The current situation severely affects the Global South: Latin America and sub-Saharan Africa are the regions where agriculture sectors are particularly vulnerable to fertiliser supply disruptions. For instance, Brazil – one of the leading exporters of soybeans, corn, beef, chicken and pork (Bourne, 2022) – imports 85 per cent of its fertiliser consumption, mainly from Russia.

Green hydrogen can help in reducing a country’s dependence on current nitrogen fertiliser exporters. In Brazil, there are currently four ammonia projects in the pipeline, while Chile, also a large exporter of agricultural products, has reported eleven projects. Most of them are still at the level of feasibility studies. An ambitious project is currently being implemented in Spain: Together with the fertiliser producer Fertiberia S.A., the utility company Iberdrola S.A. has launched the Green H2F Puertollano I project in Spain. On an already existing production unit, a green ammonia pilot project is being formed with solar panels with a capacity of 100 megawatts (MW), a battery unit and a hydrogen buffer. The aim is to use solar electricity and water to produce green hydrogen through electrolysis (20 MW), which will feed into the production of low-carbon ammonia, and later nitrogen fertilisers (Iberdrola, 2022; IRENA, 2021). Fertiberia also has ambitious plans for producing low-carbon fertiliser in the northern Swedish region of Luleå-Boden. The project, announced in 2021, includes 600 MW of electrolysers and a green ammonia plant that produces 1,500 tons per day and an annual production of more than 500,000 t of low-carbon fertilisers and industrial products (Sharpe, 2021). The locational advantage of northern Scandinavia is the availability of renewable electricity at very low costs, which are only a fraction of the costs in other parts of Europe and many developing countries.

Source: Authors

3.1.2 Hydrogen and synfuels in the transport sector

Road and rail transport. Fuel-cell electric vehicles (FCEVs) might reach similar "sun-to-wheel" efficiency levels as battery-electric vehicles (BEVs) if they are powered with green hydrogen imported from countries with abundant solar energy (Riemer et al., 2022). This would make FCEVs attractive for long-distance rail and heavy freight transport (Wietschel et al., 2021). Although electric drives are already well-established in the rail-bound transport sector, hydrogen could potentially be used for new track sections or when the electrification of existing railroad lines is too costly. Similarly, in cargo transport, hydrogen might in the future outcompete batteries, as from a certain capacity onwards the energy density of hydrogen is higher than for batteries, and the refuelling times are shorter (Riemer et al., 2022).

Maritime shipping and aviation. For maritime transport and aviation, hydrogen represents the only decarbonisation option: Aviation and shipping cause 5 per cent of global GHG emissions. With these sectors having ambitious emission-reduction targets by 2050 in place,[3] hydrogen actually constitutes a game changer. Liquid hydrogen or derivatives such as ammonia and methanol will drive fuel cells or internal combustion engines (SRU, 2021). For aviation, fuel cells can be used for distances up to 1,600 kilometres (km), whereas the combustion of synthetic aviation fuel such as e-kerosene is foreseen for longer distances (Riemer et al., 2022). In maritime shipping, green ammonia will likely be the first fuel option (IRENA, 2021). In January 2022, Kriti Future, the world's first ammonia-fuel-ready vessel, was delivered in New York. The 274-metre-long tanker is currently fuelled with heavy oil but meets the requirements to run on green ammonia in the future (Marine Insight, 2022).

3.2 Where green hydrogen should not play a key role

Electricity generation for the grid and for heating buildings. Any conversion process along the hydrogen value chain implies a significant loss of energy: The electrolysis process – splitting water into hydrogen and oxygen – causes a loss of 20-30 per cent of energy, depending on the technology applied. For long-distance transport, hydrogen has to be liquefied by bringing it down to very low temperatures (-253 °C). This cooling process requires about 30-40 per cent of the hydrogen energy value (Chatterjee, Parsapur, & Huang, 2021). Alternatively, hydrogen can be converted, for example synthesised to ammonia, which requires further energy. If final consumption requires hydrogen in its pure form, ammonia (or other derivatives) has to be re-converted, which, in the case of "ammonia cracking", not only implies additional energy input, but also a process-related loss of hydrogen (Chatterjee et al., 2021). This means that as long as renewable energy supply is scarce, conversion and re-conversion processes should be avoided wherever possible. Thus, in most cases, it is not economically feasible nor environmentally efficient to combust green hydrogen for energy generation. The expansion of the heat district network and the use of heat pumps are preferred options for heating buildings.

Electrification and use for low- and medium-grade heat in industry. The best decarbonisation option for many manufacturing and service sectors is the direct supply of renewable electricity to drive machineries and devices – from sewing machines in the textile industry, robots in car manufacturing to data processing and storage equipment in industrial administration and services. Electrification is also the best alternative for the production of low- and medium-grade heat via boilers or other devices. An additional opportunity for decarbonising industrial processes can be the use of bioenergy for producing heat, for instance in the food

3 The International Air Transport Association is aiming for net zero emissions by 2050 (International Air Transport Association, 2021), while the International Maritime Organization has set a target of reducing annual GHG emissions by 50 per cent from 2008 levels (International Maritime Organization, 2018).

processing and paper industries, where organic by-products and waste can be used as a low-carbon energy source.

Electrification of passenger vehicles. In road transport, hydrogen can be used in FCEVs or as power-to-gas in internal combustion engines. However, especially in passenger road transport, battery electric vehicles using lithium-ion batteries and biogenic fuels are the dominant incumbent technology (Riemer et al., 2022) – in contrast to heavy freight transport (see above). Although FCEVs have some positive features, such as shorter refuelling times and longer overall lifetimes of fuel cells, battery electric passenger vehicles achieve well-to-wheel efficiencies that are twice as much as those of FCEVs and four times as much as those of internal combustion engines, with these differences again resulting from energy losses during conversion processes (SRU, 2021).

4 Economic pathways and potentials for value creation, employment and technological learning

4.1 Green hydrogen as an opportunity for developing countries

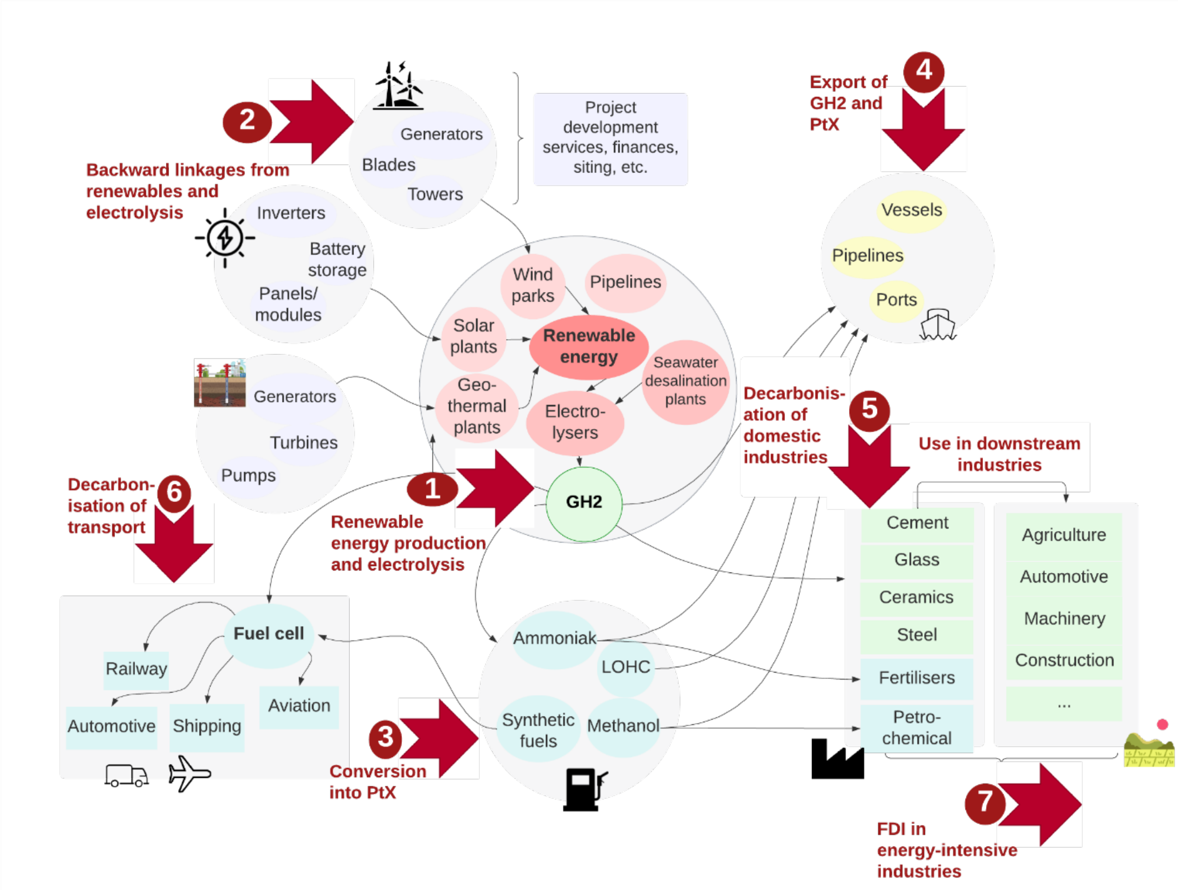
Many developing countries are blessed with abundant renewable energy resources, in particular solar and wind, and are therefore attractive for investments in green hydrogen. Large parts of Africa, the Gulf region, India and South America are well-endowed with renewable energy sources. As a continent, Africa has the largest amount of renewable energy resources, in particular solar, but also hydropower (Ethiopia), geothermal (East Africa) and wind power (Horn of Africa and coastal areas). The potential of onshore renewable energy generation is projected to be 1,000 times larger than the expected demand in 2040; thus, this allows the continent to become a net exporter of renewable energy, thereby enabling green jobs and value creation (German Credit Institute for Reconstruction, German Agency for International Cooperation, & International Renewable Energy Agency [KfW, GIZ, & IRENA], 2020).

As of March 2023, 29 parties to the UNFCCC mention hydrogen in their NDCs, 24 of which are countries from developing regions (Climate Watch, 2023). Many of these countries have already drafted their national hydrogen strategies or have hydrogen roadmaps in place (WEC, 2022). Among the countries with the highest potential for renewable energy generation, Chile is leading with regard to the number of low-carbon hydrogen projects (28), followed by Egypt (17), the United Arab Emirates (14), Brazil (12) and Oman (11). With nine projects in the pipeline, South Africa is the frontrunner in sub-Saharan Africa (IEA, 2021d).

4.2 Pathways to value creation, employment and technological learning

Rolling out renewable energy projects and converting electricity into green hydrogen and derivatives opens up manifold opportunities for industrial development. Value added and employment can be greatly increased and domestic technological capabilities enhanced if countries exploit their comparative advantages in renewable energy endowment to produce green hydrogen. These development effects can be multiplied if countries deliberately invest in industrial forward and backward linkages (Altenburg, Wenck, Fokeer, & Albaladejo, 2022). In the following, we provide an overview of potential industrial linkages that can be developed in a green hydrogen economy, distinguishing seven clusters of activities (Figure 3).

Figure 3: Industrial linkages of the green hydrogen economy



Source: Authors

First, renewable energy generation and electrolysis. The indispensable first step is investments in renewable energies (solar and wind farms, geothermal and hydroelectric projects, depending on resource endowments), in electric grids and electrolysers. As most potential producer countries are water-scarce, desalination plants are typically part of the core activities. Both water and hydrogen require pipelines and tanks with different properties. All of these activities are relatively capital-intensive and require considerable scales of production, which makes it difficult for newcomers to enter these markets. In most developing countries, the core activities will therefore be dominated by foreign investments and imported technology. However, the employment effects can be considerable, especially during construction phases. Technologically more advanced countries can of course develop indigenous capabilities and capture value locally, both in services (construction, project development, wind siting, wheeling services) and manufacturing (e.g. steel tubes). The same holds for electrolysers, for which various technologies are currently being developed in parallel – all with different technological entry barriers and potentials for industrial linkages (Box 2).

Box 2: Types of electrolysers for green hydrogen production

The chemical and technical basics of electrolysis have been known since around 1800. Electrolysis has been used for a variety of purposes, such as the electrometallurgy of aluminium, lithium, sodium, potassium, magnesium, calcium, the production of chlorine and sodium hydroxide, or for purifying copper. For the production of hydrogen, four types of electrolysers are available, each entailing specific advantages and disadvantages and displaying different levels of technology readiness. There is no single electrolyser technology that performs better across all dimensions. Alkaline electrolysers and polymer electrolyte membrane (PEM) electrolysers are already commercial, whereas anion exchange membrane (AEM) and solid oxide electrolysers (SOEC) are at lab scale.

1. Alkaline electrolysers

Alkaline electrolysers have a simple stack and system design and are relatively easy to manufacture. Classic and sturdy alkaline designs are known to behave very reliably, reaching lifetimes above 30 years. However, alkaline water electrolysis operates more efficiently on a low current density, with low hydrogen production rates. Moreover, the pressure between the anode and cathode sides needs to remain balanced to keep the hydrogen or oxygen generated by the electrolysis from penetrating the diaphragm to the other side, resulting in a risk of explosion.

2. Polymer electrolyte membrane (PEM) electrolysers

PEM electrolysers use a thin perfluorosulfonic acid membrane and electrodes with advanced architecture that allow for achieving higher efficiencies (i.e. less resistance). However, using precious metals as electrocatalysts (to provide long-term stability and optimal electron conductivity and cell efficiency) leads to high costs. Additionally, PEM electrolysers are sensitive to water impurities and can suffer from calcination. The reliability and lifetime characteristics of large-scale, MW PEM stacks still need to be validated.

3. Anion exchange membranes (AEMs)

The potential of AEMs lies in the combination of a less harsh environment from alkaline electrolysers with the simplicity and efficiency of a PEM electrolyser. It allows for the use of non-noble catalysts, titanium-free components, and – as with PEM electrolysers – operation under differential pressure levels. Until now, however, AEM membranes have had chemical and mechanical stability problems, leading to unstable lifetime profiles. Moreover, performance is not yet as good as expected, mostly due to low AEM conductivity, poor electrode architectures and slow catalyst kinetics.

4. Solid oxide electrolysers (SOEC)

Operation at high temperatures enables the use of relatively cheap nickel electrodes, reductions in electricity demands, the potential for reversibility (operating as a fuel cell and electrolyser), and the co-electrolysis of CO2 and water to produce syngas. However, high temperatures also result in the fast deterioration of catalytic performance, making the long-term operation of SOEC a challenge. SOEC are today only deployed at the kW-scale, although some recent demonstration projects have already reached 1 MW.

Source: Authors

Second, backward linkages from renewables and electrolysis. All the core industries mentioned above involve backward linkages, which may or may not accrue locally. Solar photovoltaics (PVs) require solar cells and modules as well as steel frames; wind parks require towers, blades and gear boxes; geothermal projects require turbines, pumps, condensers, cooling towers, valves, heat exchangers, etc. Energy projects generally require cables and energy storage devices. Electrolysers require electrodes and electrolyte materials, membranes and stacks. Countries can thus try to capture value in these upstream industries, investing in technological capabilities as well as demand-side incentives such as local content requirements. Some of the inputs are easier to produce locally (steel structures, wind towers, pumps, cables), whereas others are highly technology-intensive and in most cases need to be imported, for example PV cells (IEA, 2022d), wind turbine components and blades (Global Wind Energy Council, 2022).

Third, conversion into PtX. As shown earlier, the transport and storage of hydrogen is costly, as it needs to be stored at either extremely high pressures or extremely low temperatures. The commercially viable alternative is to convert hydrogen into a derivative that is easier to store and transport, such as ammonia, methane, methanol or synthetic liquid hydrocarbons, such as diesel, gasoline and kerosene. The choice of derivative depends on end-uses (e.g. ammonia for fertiliser production and synthetic kerosene as aviation fuel) and transport requirements. All forms of conversion are again capital-intensive and require experience in plant engineering.

Fourth, export of green hydrogen and PtX. The abundance of renewable energy sources puts many developing countries in an advantageous position for exporting hydrogen and derivatives. The demand for hydrogen imports is enormous, especially in Europe, Korea and Japan. As of now, Germany alone has concluded 22 hydrogen partnerships, most of which with developing countries (WEC, 2022). Whereas Japan and Korea focus on Oceania, South America and North Africa in their search for partners, Germany has signed deals with countries in sub-Saharan Africa (Namibia and Nigeria) and the MENA region (Morocco, Tunisia, Saudi Arabia, Egypt and the United Arab Emirates).

Exporting hydrogen and derivatives provides opportunities to increase foreign exchange earnings and tax revenues. Through exports, countries can tap into international energy markets and – given the enormous projected hydrogen demands of the world economy (see for instance Gas for Climate et al., 2021; Hydrogen Council, 2021) – thereby trigger investments in all the core activities, far beyond what would be needed to decarbonise local industry and transport. At the same time, most potential export countries will strongly depend on imports of industrial equipment, which may considerably reduce net export revenues. Likewise, tax exemptions are often granted to investors (which are typically permitted to operate in special economic zones), thereby reducing the host country's tax benefits.

Exporting countries will differ in terms of transport modes, which in turn impacts the choice of technologies and the potential for local economic spillovers. Countries located near major import markets can export hydrogen via pipelines, whereas maritime shipping is the only – and more costly – option for producers located beyond a "pipeline distance" of around 3,000 km (Joint Research Centre, 2021). Transport increases the levelised costs of hydrogen by at least a factor of two (Roland Berger, 2021; Wietschel et al., 2021). For example, Northern Africa can be connected to Europe via pipelines, whereas hydrogen from sub-Saharan Africa and South America must be either liquefied (LH2) or converted into ammonia or liquid organic hydrogen carrier (LOHC),[4] which adds to the costs and makes these locations relatively less attractive. There are, however, new transport options under development, which may lead to disruptive innovations and cost reductions.

Exporting countries need to invest in ports, pipelines and storage capacities. And depending on the chemical form and aggregate state used for international transport, required investments include facilities for ammonia synthesis, the generation of LOHC or the deep-freezing of hydrogen. Again, these investments are generally capital- and scale-intensive. Employment creation in the construction phase can be expected to be substantial, yet the potential for forward and backward linkages and technological learning is fairly limited. A strong export focus may therefore lead to the formation of foreign investment enclaves with only very limited opportunities for domestic learning and the upgrading of firms. Such enclaves in natural resource extraction are often associated with a "resource curse" (Auty, 1993) in terms of disincentives for other tradable sectors, rent-seeking and inequality (Mien & Goujon, 2022).

4 It is not decided which of these modes will dominate the market, whether different markets will have different modes (e.g. Japan and Korea ammonia, Europe LOHC) or whether the modes will co-exist.

Fifth, decarbonisation of domestic industries. Many local industries and transport activities can be – and have to be – reengineered for the use of green hydrogen. This includes the iron and steel, cement and chemical industries as well as long-distance passenger and heavy cargo transport (see Section 3.2). Incentives for the use of green hydrogen in these hard-to-abate sectors – either as feedstock or as an energy source – stem from national decarbonisation targets or from international pressure exerted by trading partners. The latter include both trade regulations (such as the envisaged EU Carbon Border Adjustment Mechanism, CBAM) and corporate standards imposed by lead firms in global value chains.

Using hydrogen for the decarbonisation of national industries is, of course, more relevant in economies with well-developed heavy industries, such as in India (iron and steel, glass), South Africa (coal liquefaction, steel) and Chile and Colombia (petrochemical), especially if they are exporting to the Global North. It is also important for all countries with major mining industries, such as South Africa, Chile, Mauretania, Namibia, Botswana and Mongolia, as these industries are highly energy-intensive and mostly export to international markets with higher decarbonisation standards. Green hydrogen has a vast potential for decarbonising mining, drilling and transport. Overall, decarbonisation makes products globally competitive in a net-zero world.

Sixth, decarbonisation of transport. In many low- and lower-middle-income countries, transport contributes much more than industry to GHG emissions. Moreover, outdated diesel trucks and buses release particulate matter and are responsible for urban air pollution. Thus, electrifying transport is an important approach to climate protection, clean air and public health. For light vehicles, battery-electric drives will most likely be the technology of the future, whereas for long-range buses and heavy-duty cargo transport FCEVs and also possibly the combustion of hydrogen in internal combustion engines offer techno-economic advantages. The shift from diesel-powered to low- or zero-emission vehicles requires the adaptation of existing bus and truck industries. Many – especially larger, emerging – economies have developed domestic industries that produce buses and trucks with diesel engines. Shifting to electric engines and fuel cells is costly, and the technologies for lithium batteries and fuel cells are not locally available. Most developing countries are therefore currently dependent on imported low-carbon transport technologies (e.g. battery-electric buses, trucks, urban rail systems). To align decarbonisation with local value creation, country strategies are needed to identify promising pathways and policies:

- For countries with large markets and relatively diversified industries, developing local industrial capabilities in low-carbon transport technology is an option. China promoted electric buses earlier than the rest of the world and now dominates the global market, taking market share away from the dominant “Northern” bus multinationals (Altenburg, Corrocher, & Malerba, 2022). Brazil is trying to develop e-bus technology in joint ventures with the leading Chinese bus makers. China and India are using local content requirements, procurement and research policies to build capabilities in urban rail technologies (Asimeng & Altenburg, 2022).

- There may be promising niche technologies. Chile and South Africa are developing fuel-cell mining haul trucks. South Africa is well-positioned to exploit its endowment with platinum-group metals (PGMs) and know-how in catalytic converter industries to produce membranes and other inputs for fuel cells and electrolysers (see Part B below).

- Another solution, which is also within reach for smaller countries, is to retrofit traditional vehicles, for example diesel buses, with low-carbon engines and drivetrains, be it battery-electric, fuel cells or direct combustion. This could create a significant number of jobs and leave at least parts of the transition-induced value addition in the host countries.

- Another promising opportunity is to produce and export sustainable aviation fuel (SAF) produced from green hydrogen in combination with an organic carbon source such as dedicated energy crops or agricultural residues. This creates a link between the energy and agriculture sectors and thereby can be very employment-intensive (WWF, 2019). Countries with excellent green hydrogen conditions can not only export SAF but also strengthen international air traffic hubs in their countries.

Seventh, attraction of foreign direct investment (FDI) in energy-intensive industries. Many industries, especially in the Global North, have ambitious plans for decarbonising their entire global value chains within the next two decades. Emissions trading and environmental taxes create strong incentives for decarbonisation. In countries with limited supplies of renewable energy and green hydrogen, this creates an incentive to source energy-intensive parts and components from countries with abundant supplies of low-carbon energy sources. Industries producing for example aluminium or carbon-fibre parts, green steel or energy-intensive chemicals may therefore relocate to, or source from, countries with an abundant, low-cost renewable energy supply. So far, there is only anecdotal evidence of such “renewables pull” (Samadi, Lechtenbömer, Viebahn, & Fischer, 2021) – for example, carmakers sourcing low-carbon aluminium from Saudi Arabia and Norway, where production is based on solar and hydropower, respectively. As pressure increases to decarbonise material consumption, carbon prices rise and renewable energy and green hydrogen capacity ramp up, such relocations of energy-intensive processes are expected to increase significantly, thereby providing an additional opportunity for value creation.

4.3 From factor-cost advantages to human-made competitive advantages

All these options are not mutually exclusive and may be exploited in parallel. Yet, they arguably differ considerably with regard to their development impact. Large-scale export projects, for example, may improve the balance of payment, yet they are less likely to spur domestic industrial capabilities compared to industry decarbonisation projects that help industries to adapt to low-carbon standards in export markets or R&D investments in new green hydrogen technologies. Assessing the development effects is therefore essential. In this respect, differentiating between factor-cost advantages and human-made competitive advantages is helpful.

Factor-cost advantages here include especially natural energy endowments and other locational factors that are given regardless of societal effort.

- Natural energy endowments include mainly the natural preconditions for renewable energy generation (solar irradiation, wind speed). These are the main determinants of low-cost hydrogen production. Natural energy endowments with fossil energy sources, in contrast, may deter the green hydrogen transition due to economic and political lock-ins (Unruh, 2000). However, the latter may also open new pathways. Firstly, oil- and gas-exporting countries often have industrial capabilities in producing and operating refineries and other chemical plants as well as pipelines and storage facilities, which are easily transferrable to green hydrogen investments. Moreover, traditional exporters of natural gas may produce blue hydrogen, which will likely be in demand as a bridging technology to green hydrogen.

- Other locational factors affecting hydrogen opportunities include the relative distance to import markets. Countries in pipeline distance to major markets are in an advantageous position compared to countries that need to ship hydrogen and derivatives over large distances. The availability of freshwater resources reduces the costs compared to countries that need to desalinate seawater. Also, other natural resources that feed into the hydrogen economy (e.g. platinum metals for fuel cells and organic resources for synfuels) may favour certain industrial pathways. Some geostrategic assets, such as the Suez and Panama canals, may offer opportunities for developing specific hydrogen and derivatives storage and other services, while also potentially co-locating downstream industries. The existence of underground storage opportunities for carbon sequestration is a major advantage if blue hydrogen is produced (Van de Graaf, Overland, Scholten, & Westphal, 2020).

Human-made advantages include economic diversification and technological capabilities as well as the quality of political institutions.

- Regarding economic diversification and technological capabilities, the more diverse and complex economies are, the more they can recombine capabilities to develop new competitive advantages (Hidalgo & Hausmann, 2009). Countries with a diversified economy can, on the one hand, build on local capabilities to create backward linkages from the hydrogen core activities and, on the other hand, feed green hydrogen into existing downstream industries, thereby preparing them for the emerging low-carbon world economy. Moreover, diversified economies tend to have existing infrastructure (ports, rails, pipelines, etc.) and advanced technological capabilities embedded in firms and research institutions. As an example, the existence of established air traffic hubs (such as in Qatar, Dubai, Abu Dhabi and Addis Ababa) offers opportunities to co-locate the production of synthetic aviation fuels.

- The quality of political institutions comprises a range of governance aspects. Political stability is a pre-condition for steering direct investment funds into the development and expansion of clean energy technologies. Institutional capabilities are important to ensure coordination and cooperation within and between various ministries, agencies and the private sector; to design supportive industrial policies in cooperation with the private sector but without being captured by lobby groups (“embedded autonomy”) (Evans, 1995); and to develop and enforce proper standards, among other reasons. Last, but not least, political institutions are decisive for ensuring transparency, accountability and the alignment of industrial policies with societal objectives. Economies based on natural resource rents often have established, socially exclusive political settlements, whereby rents are captured by small elites. Such legacy implies a risk of establishing hydrogen enclaves with very limited benefits for the societies at large.

The history of industrial development suggests that countries usually fare better if they move beyond existing factor-cost advantages and invest in advanced, human-made capabilities (Neary, 2003). This is because greater diversification and economic complexity increase the number of new economic opportunities via the recombination of existing assets and capabilities, thereby accelerating dynamic knowledge spillovers (Hidalgo & Hausmann, 2009; Hidalgo et al., 2018). For countries with factor-cost advantages in green hydrogen, it is thus essential to avoid the formation of enclaves and to instead invest in domestic linkages, technological learning and supporting institutions.

5 Uncertainties regarding the vision of a global hydrogen economy

What is historically unique about the global transition to a green hydrogen scenario is that it starts at nearly “zero” (hardly any green hydrogen is currently produced, transported and consumed) but projects a very steep expansion curve. In order to assess the viability of these ambitious targets, three questions are of high relevance and briefly explained below.

5.1 Can the projected fast and steep scaling-up of renewable energy generation be achieved in countries with very good natural conditions?

In order to safeguard the energy transition in the producing countries and not divert renewable power from other purposes, the German hydrogen strategy provides for a strict additionality criterion, that is, dedicated renewable energy generation for green hydrogen. Scaling up the expansion of renewable energy plants often faces considerable legal and regulatory barriers. Moreover, property owners and local communities might oppose projects for various reasons. This adds transaction costs for project developers in terms of the time and money needed to obtain agreements, get approvals and acquire financing, etc. Getting permission for a new wind farm project currently takes about six to nine years in Europe. In addition, developing countries sometimes lack a central body that coordinates all the activities of the energy sector. Last but not least, the local manufacturing of renewable energy components, such as PV panels and wind turbines, is quite constrained. China's rapid expansion in the renewable energy sector – from 328 GW in 2014 to 895 GW in 2020, dwarfing the capacities of the EU, the United States and Australia combined – would not have been possible without rigid planning and centrally managed execution of projects, let alone their competitive advantage in manufacturing renewable energy systems.

In comparison, Africa had about 56 GW of renewable energy capacity installed in 2021 (vs. 28 GW in 2011), largely hydropower. The following quantities of electricity generation are forecasted (KfW, GIZ, & IRENA, 2020). Table 1 shows the status of the energy mix today and two different scenarios about the expansion of renewable energies and the remaining fossil fuels from 2019 to 2050. The differences are partly due to the fact that the REmap data from the International Renewable Energy Agency (IRENA) do not include Northern Africa and, thus, cannot directly be compared to the International Energy Agency (IEA) scenario.

Table 1: Renewable energy expansion in Africa: Scenarios

Technology	2019	Scenario	2030	2040
Wind	5.7 GW	Africa Case IEA	51 GW	94 GW
		REmap IRENA[1]	33 GW	131 GW
Solar PV	7.2 GW	Africa Case IEA	124 GW	316 GW
		REmap IRENA	79 GW	255 GW
Hydropower	35.7 GW	Africa Case IEA	77 GW	117 GW
		REmap IRENA	55 GW	95 GW
Electricity demand/generation[2]	804 TWh	Africa Case IEA	1,662 TWh/year	2,740 TWh/year
		REmap IRENA	687 TWh/ year	1,815 TWh/year
Remaining fossil[3]	180.8 GW	Africa Case IEA	272 GW	328 GW
		REmap IRENA	45 GW	51 GW

Notes: 1 Data do not include Northern Africa; 2 Data include Northern Africa; 3 Including nuclear energy

Sources: For 2019: IRENA (2021) and Energy Information Administration (2020); for 2030 and 2040: KfW, GIZ and IRENA (2020)

These differences also translate into different scenarios regarding overall capacities for the generation of renewable electricity.The Ouarzazate solar complex in Morocco is currently the world's largest renewable energy power plant and is located in one of the world's best locations for solar energy. With 570 MW of installed capacity, it generates between 1.3 and 1.5 TWh of electricity annually, according to unconfirmed data. This could generate (assuming 25 per cent energy loss in electrolysis) about 1 TWh of green hydrogen.

According to the German National Hydrogen Strategy, 76 TWh of green hydrogen would have to be imported to Germany as early as 2030 in the medium scenario. If even only 25 per cent of this is to come from Africa, 20 Ouarzazate-type plants would have to be built exclusively for the (partial) green hydrogen supply of Germany, and half of the total energy quantities forecast for wind would have to be used for this.

It must also be factored in that the vast majority of the renewable energy capacity added should/will be used for purposes other than hydrogen generation, such as supplying electricity to 770 million people worldwide not yet connected to the grid (IEA, 2022d), direct electrification of mobility and manufacturing processes, heat pumps for space heating, etc.

5.2 Can the global electrolysing capacities be scaled up as fast as the current hydrogen strategies assume?

One further bottleneck in the ramp-up of the hydrogen economy is the expansion of electrolysis capacity. The targets announced in the national strategies so far would imply going from 0.2 GW today to well over 100 GW in 2030. To meet the target of 5 TW of installed capacity in 2050, added manufacturing capacity would even need to be 10 to 60 GW per year by 2030 and 70 to 360 GW per year by 2040 (IRENA, 2020). These ambitions contrast sharply with reality: Global electrolyser manufacturing capacity in 2018 was about 135 MW per year and the World Bank estimates that today 2.1 GW is added annually (World Bank, 2020). There is little experience with building the type of large-dimension electrolysers necessary for such a "quantum leap". China, which currently provides one-third of the global electrolyser manufacturing capacity, has ambitious goals regarding a domestic hydrogen economy and gives preference to national decarbonisation targets (Li, Steinlein, Kuneman, & Eckardt, 2022). Thus, it will likely only supply a limited number of electrolysers to third countries for the time being. This, in turn, could mean that the global green hydrogen economy will unfold with less dynamism than has been projected. On the other hand, this could afford a relatively large space for other advanced developing countries to manufacture their own electrolysers and/or deliver components and systems to clients in their respective regions.

Furthermore, electrolysers require a variety of mineral resources for their production. The main inputs to alkaline electrolysers are rather uncritical substances, in terms of both availability and costs. However, PEM electrolysers depend very much on two critical resources: platinum and iridium. Iridium is an especially rare mineral, and currently only 7 tons are produced each year – the bulk of this is produced as a by-product of platinum extraction in one single country (South Africa). South Africa currently produces 92 per cent of all platinum and 70 per cent of all iridium on the planet (Minke, Suermann, Bensmann, & Hanke-Rauschenbach, 2021, p. 23582). Global iridium production would support the manufacture of 30-75 GW of PEM electrolyser capacity over the next decade (IRENA, 2020, p. 68) – probably not enough for the implementation of countries' ambitious targets. It will be important to reduce the iridium loading of PEM electrolysers through innovation or by recycling the metal to avoid bottlenecks.

5.3 Can the required huge amounts of hydrogen and derivatives be transported in an economical, safe and clean way, given the long distances between potential exporting and importing countries?

Green hydrogen offers prospects for a new global energy geography. It is clear that Europe, Japan and Korea will be large green hydrogen importers, as national production capacities are relatively low in relation to the quantities required in industry and mobility, whereas the United States and China are expected to serve their domestic economies. As mentioned before, countries in the Global South have huge export potential, as their endowments of renewable energy sources allow them to produce more green hydrogen than they need for the decarbonisation of their economies. However, it is currently unclear how fast large-scale exports of green hydrogen (either liquefied or in the form of ammonia or LOHC) can take off. Resolving the large distances between production sites and end-users at a reasonable cost and under strong technical and environmental standards is key to the success of the green economy (Roland Berger, 2021).

The first-best option that is both technically and economically feasible is the transport of hydrogen via existing pipelines, in the best case retrofitted national gas pipelines. Not all of the technicalities concerning the pipeline transport of hydrogen have been solved yet (e.g. how to avoid embrittlement and how to increase the amount of hydrogen to be blended with natural gas). Building new pipelines, especially for hydrogen, is economically feasible for distances of up to 3,000 km, but the investment costs are high (EUR 2.5 and 4 million per km). The time needed for the planning and construction of a dedicated hydrogen pipeline would depend on various factors, not least bureaucratic efficiency and acceptance by the affected population. For most developing countries, however, the pipeline option is out of geographical reach, at least for the regions with the greatest demand: Europe, Japan and Korea. Sea vessels are the only realistic option for getting large amounts of hydrogen from production sites in the Global South to the end-users in the Global North. There are major technical and economic challenges that might impede the roll-out of a truly global hydrogen economy until at least 2030. From a technical viewpoint, due to its very low-energy density, hydrogen cannot be transported in a gaseous state (this would take up too much space) and needs to be liquefied (LH2). Apart from the energy-intensity of this process, the transport of LH2 has not yet reached technological maturity: Currently one single ship exists worldwide (as a prototype) that is able to transport LH2, and it has a very small loading capacity. The most favoured solution for transporting hydrogen is in the form of ammonia, which in the best case can simultaneously be used as a sustainable maritime fuel. As with LH2, the required number of ships necessary to cater to the needs of Germany alone are not available today, nor will be in the near future. Finally, hydrogen can also be transported in the form of LOHCs, whereby hydrogen is chemically bound to a carrier material and released at the point of destination. However, the number of landings – and thus ships – would be higher than in the case of ammonia. For all three options, transport and the re-/conversion of/into hydrogen raise the landed costs of hydrogen significantly, more than doubling the cost of production (Roland Berger, 2021).

6 German development cooperation to support green hydrogen

Development cooperation is increasingly recognising the green hydrogen potential in partner countries. Germany is one of the trendsetters in this regard. Major activities have been initiated in the last three years. Most importantly, Germany has set up several large funds for green hydrogen, partly to develop the international hydrogen market and secure German imports, and partly to support value added in partner countries:

- H2Global is an auction-based mechanism for the procurement of green hydrogen or its derivatives based on the Contracts for Difference approach: The German government provides grants to cover the difference between supply prices abroad and demand prices in Europe. The aim is to create enabling conditions for hydrogen projects;
- the PtX (Power-to-X) Growth Fund intends to accelerate the global market ramp-up and infrastructure for green hydrogen through grants for hydrogen export projects;
- the PtX Development Fund provides grants for developing and emerging economies to help build local value chains around green hydrogen.

Here we focus on official development assistance, that is, the activities under BMZ. BMZ drafted a concept paper on green hydrogen that strikes a balance between local decarbonisation, local value creation and exploiting export opportunities. It singles out four major fields of activity:

1. supporting comprehensive strategies and roadmaps, including regulatory framework reforms;
2. enhancing local market creation and value added;
3. fostering the hydrogen export economy; and
4. promoting private (foreign) investment through improving the investment climate, matchmaking and initial funding.

Moreover, it defines criteria to ensure that only “developmental” uses of hydrogen are supported, that is, those that create neither incentives for fossil fuel usage, nor land use conflicts or aggravate water scarcity or energy poverty at the household level.

In fact, strategy-supporting technical cooperation is underway in several partner countries. German development cooperation has built particular quality features over the years. In many partner countries, it is deeply embedded in local institutions, often through long-standing partnerships. Multi-level programmes are a specific strength, whereby programmes combine policy advice at the macro level with institutional capacity-building at the meso level and specific interventions at the micro level to test innovative practices, which in turn help inform the higher policy levels. Such schemes are particularly appropriate for complex new systemic challenges such as the energy system transformation. Given the uncertainties involved in this transformation, especially those related to green hydrogen, development cooperation must be conceptualised as a joint learning process with sufficient flexibility in the programme design.

Support for national hydrogen strategies should be continued and further strengthened, with a focus on the following principles:

- Domestic value creation, industrial linkages, technological learning and permanent employment. This is more likely to be achieved when green hydrogen is produced for local uses. Exports of hydrogen and derivatives may also have substantive spillovers, for example when inputs are sourced locally, but such projects are often associated with conditions that do not encourage local linkages. The BMZ concept paper acknowledges the suggested priority, yet this is not aligned with other ministries' interest in promoting large-scale projects, with the main aim of securing green hydrogen supply for industries in Germany. Moreover, there seems to be a mismatch between BMZ's strategy (advocating local value creation) and de facto resource allocation (prioritising German and European investments in large-scale projects).

- A gradual and sequenced entry into the green hydrogen economy, prioritising renewable energy roll-out and grid quality over ambitious downstream projects in electrolysers, ammonia, pipelines and the like. Renewable energy and grid investments are "no-regret" options, as they are crucial for local energy transitions and serve local industries and households while also improving conditions for hydrogen-related industrial development. The hydrogen strategies of Costa Rica – and partly also Chile and South Africa, for example – focus on the gradual implementation of small to medium-sized projects of hydrogen production and local offtake. This enables learning-by-doing, especially when accompanied by R&D investments and international knowledge transfer. Other national strategies are tilted in favour of exports, FDI and large-scale hydrogen projects (Namibia, Morocco; also e.g. the Northern Cape region in South Africa). When supporting such large-scale export projects, a strong emphasis needs to be put on avoiding the creation of enclaves with their respective political and socio-economic risks.

- Expectation management: The current global hype about green hydrogen should not obfuscate the manifold risks involved. Many factors (Section 5) may delay the industrial transformation, which then involves substantive investment risks. Failed projects, even when internationally financed, may come at a cost for the producing country, for example land dedicated to utility-scale PV facilities cannot be used for alternative purposes. Moreover, failed green hydrogen projects might lead to political frustration and a backlash against other decarbonisation projects. Such effects were observed after the failure of the Desertec project, which had been promoted since around 2004 and included far-reaching plans to produce renewable energy in the MENA region and to cover large parts of the region's electricity needs, as well as Europe's (15-25 per cent).

In the following, we focus on six areas that deserve special attention when further expanding the portfolio of German hydrogen development cooperation. As the discussion on eligible partner countries is ongoing, we suggest focussing on those countries that are: strongly committed to green hydrogen, as manifested in the existence of ambitious roadmaps; transparent in the handling of large-scale investment projects; committed to using hydrogen for national decarbonisation; and willing to do so with an explicit focus on social co-benefits. Morocco, Chile, Brazil, India, South Africa and Namibia would be among the most suitable partners.

6.1 Capacity-building for hydrogen technology foresight and industrial policy

A variety of technological and socio-economic pathways are opening up for countries endowed with abundant sources of renewable energy (Section 4.2). Some of these may spark inclusive forms of industrial development and technological learning. This is good news, especially for countries in sub-Saharan Africa, the MENA region and Latin America that have typically suffered from "premature deindustrialization" (Rodrik 2015), given the increasing dominance of East Asia, Europe and North America in global value chains. Yet, hydrogen investments also entail manifold risks for sustainable development. They may create capital-intensive techno-economic enclaves with very limited permanent employment and hardly any linkage and learning effects on the local economy. Such enclave situations might encourage rent-seeking and trigger political resistance. Some pathways may lock in fossil fuel and especially natural gas production and consumption (blue hydrogen). Moreover, there are local environmental risks related, for example, to water consumption and desalination.

Two sets of capabilities are therefore essential for countries willing to exploit the benefits of the emerging hydrogen economy while keeping risks to a minimum – and they should be supported by international cooperation. First, *technology foresight capabilities* (Stamm, 2023) are important to gain a deep understanding of the opportunities and risks involved in hydrogen investments. This is easier said than done in an industry that is just starting to unfold, and it is therefore fraught with enormous uncertainties about technological pathways, market structures and prices. Institutions are needed to scan "the horizon for emerging changes, analysing megatrends and developing multiple scenarios, to reveal and discuss useful ideas about the future" (Cordonnier & Saygin, 2022).

Second, *industrial policy capabilities* (Altenburg & Lütkenhorst, 2015) that enable countries to select promising technologies and market opportunities assess how to combine the attraction of FDI with investments into own capabilities, and develop strategies for technological learning and linkage-building. Again, this is demanding, given the enormous information asymmetries between governments and the corporations that own the technology (Arrow, 1962). Strategies need to be developed in close collaboration with the private sector, while at the same time negotiating conditions for technology transfer for local value added.

Of the countries with significant green hydrogen potential in the Global South, only a few have the required advanced and differentiated institutions, and even those that do (e.g. Brazil, South Africa) need to scale up their hydrogen-related expertise. Development cooperation should therefore support both capabilities – technology foresight and industrial policy design. This can be done with an immediate effect by commissioning specialised studies on technologies, regulatory frameworks, market forecasts and the like. In the long term, however, partner countries should be enabled to develop this expertise locally. This can be done via capacity-building through the German Agency for International Cooperation (GIZ) and/or policy-based lending (German Credit Institute for Reconstruction, KfW), an instrument providing concessional funding to enable sector reforms. BMZ may want to consider a "technology foresight and industrial policy advisory facility".

6.2 Technical and vocational education and training

All the emerging technological options related to the hydrogen economy require skills development. German development cooperation has long specialised in technical and vocational education and training (TVET). Depending on the situations in the partner countries, existing TVET institutions can be adapted to the needs of an emerging green hydrogen economy, or the creation of dedicated training centres can be supported. German development cooperation should try to work with international companies in the renewable energy and hydrogen field to design future-proof TVET programmes. Examples are engineering, procurement and construction (EPC) companies – or project developers, which are often in the driver's seat when renewable energy and hydrogen projects are implemented. Making the right investments in education and training critically depends on the quality of technology foresight (see Section 6.1).

6.3 Sharing the gains of hydrogen investments: The "Just Transition" dimension

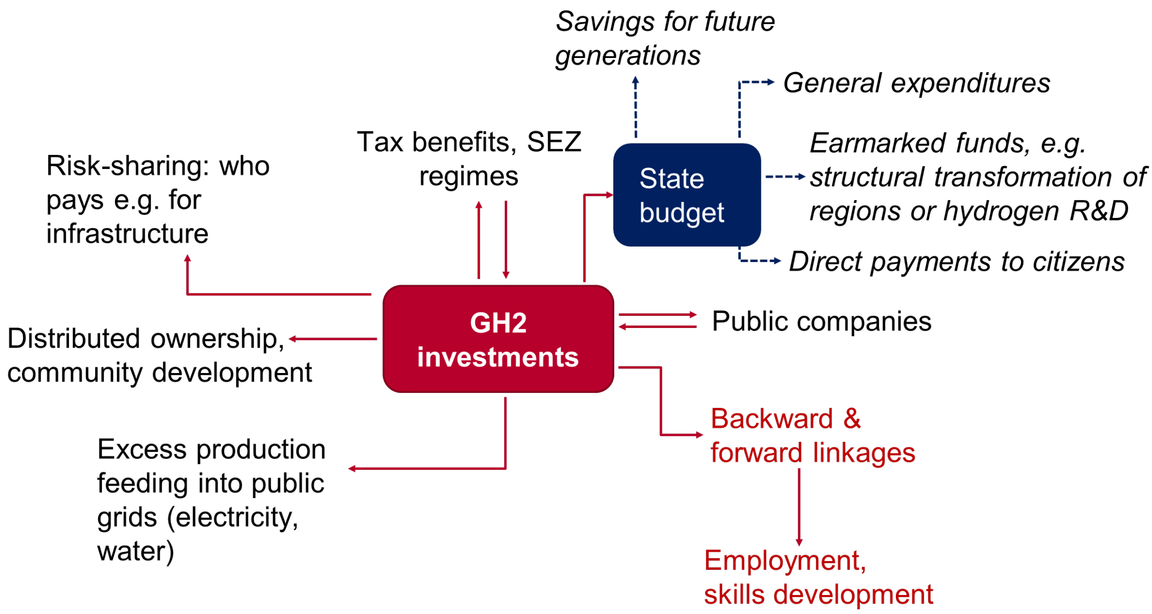
The capital- and technology-intensive character of hydrogen investments – from energy parks to electrolysers, ammonia plants, ports and pipelines – makes it difficult to create massive direct employment and community-level benefits. It tends to be driven by large foreign (and in some cases national) companies, especially in export projects. This conflicts with the expressed political interest in a *Just Transition* that is fair and equitable, leaving no one behind (Federal Ministry for Economic Cooperation and Development, s.a.). The unintended secondary effects of capital-intensive, large-scale hydrogen projects – conflicts for land, water and electricity, Dutch disease effects, rent-seeking and corruption, windfall gains for real estate investors, etc. – may further deepen existing inequalities. Employment creation (quite substantive in the construction phase) and local economic linkages (e.g. supplier development programmes, local content requirements) can spread the gains more broadly, but opportunities for local linkages are limited due to the capital- and technology-intensive nature of the technologies (SystemIQ, 2022).

Development cooperation should therefore explore, test and garner political support for other ways of sharing the gains of hydrogen investments. Figure 4 synthesises some modes of benefit-sharing. In addition to the forward and backward linkages from hydrogen industries that are at the centre of this discussion paper (highlighted in red in Figure 4), the following channels should be considered to ensure a *Just* Transition:

- Using some fiscal revenues for direct payments to citizens. Interesting models include the Alaska Permanent Fund Dividend Scheme, which pays an annual dividend to all Alaskan residents from earnings of mineral royalties; and Mongolia's resource-to-cash payment programme, which distributes coal-mining revenues as cash transfer to all citizens;
- Earmarking some fiscal revenues for broad-based or pro-poor spending (education, skills, supporting the structural transformation of regions, especially those negatively affected by low-carbon transitions, etc.);
- Support of citizen participation schemes for energy projects such as energy cooperatives and other forms of "distributed ownership" as well as community development investments, possibly as conditionality for investors;
- Conditionality for investors to produce access capacity that is fed into local infrastructure (e.g. electricity and desalinated seawater made available to local communities);
- Saving revenues for future generations and/or long-term public investments (e.g. Norwegian Oil Fund);
- Avoiding excessive tax expenditures, repatriation of profits and public infrastructure investments that benefit the investor more than the general public;
- Ensuring that the risks of major infrastructure investments (which may become obsolete if an investment fails) are fairly distributed between private and public investors.

Just Transition measures are essential not only for considerations of justice – many of the emerging hydrogen economies are characterised by extreme income inequality (South Africa, Namibia, Brazil, Chile, Gulf region) – but also for increasing public acceptance for hydrogen investments and avoid political conflicts. Development cooperation should therefore place much more emphasis on benefit-sharing, especially when supporting export-oriented, enclave-type investments.

Figure 4: Options for sharing the gains of hydrogen investments



Source: Authors

6.4 Science and technology cooperation

Many knowledge gaps still exist in hydrogen-related technologies; some technologies that are essential for reaping the full benefits of green hydrogen are not yet commercially viable, others may already have been deployed but enormous efficiency gains through improved technologies are expected in the near future. This includes, among others, energy storage technologies; carbon capture, use and storage; less energy-intensive desalination of seawater for electrolysis; more cost-efficient modes of transport for hydrogen; and appropriate tanker vessels for hydrogen trade, as well as SAFs. Knowledge gaps also exist with regard to reducing environmental impacts, such as transport without carbon leakage and the sustainable disposal of brine – the outcome of seawater desalination. Germany has a diversified set of technology institutes, such as its various technical universities and the specialised Fraunhofer and Helmholtz institutions, that explore such solutions. Dedicated research and technology cooperation programmes with hydrogen partner countries, especially under the Federal Ministry of Education and Research (BMBF), would accelerate the search for economically viable and sustainable technologies. This suggests the close alignment of BMZ and BMBF funding schemes.

Considering the strategic role of green hydrogen for a rapid international decarbonisation, removing the remaining technological uncertainties can be conceptualised as a global public good, and some of the R&D can therefore be performed at the multilateral level. A global research institute for green hydrogen could be established as an international collaborative effort with the mission of overcoming the major hurdles to the launching of a green hydrogen economy. It could be modelled after other international research missions dealing with global challenges, such as the CGIAR Centres for Agricultural Research or the Global CCS Institute in Australia.

6.5 Norms, standards and regulations

The use of hydrogen requires manifold standards for the required infrastructure, such as pipelines, hydrogen refuelling systems and tanker vessels, to ensure the safety and interoperability of systems. Such standards are being developed internationally, yet all countries need to have procedures in place to test and verify the fulfilment of these standards. Moreover, the hydrogen economy requires the regulatory reform of energy systems. This may include:

- new regulations for the energy sector in general, such as for the unbundling of electricity generation, transmission and retailing or the improvement of wheeling frameworks;
- overall environmental fiscal reform, including carbon pricing, energy taxes and fossil fuel subsidy reforms to tilt the balance in favour of low-carbon alternatives;
- specific renewable energy regulations, such as feed-in tariffs, tax allowances and technology-specific local content requirements;
- health and safety regulations for the safe production, handling and use of green hydrogen and its derivatives;
- internationally credible certification of hydrogen to meet the requirements of off-takers using internationally recognised methodologies (Altmann et al., 2022; Schnurr, 2023).

All of these enabling frameworks need to be developed and involve different line ministries, regulatory authorities, standards, testing and certification bodies. International cooperation can help develop these frameworks.

6.6 Multilateral programmes and South-South cooperation

Multilateral programmes should complement bilateral cooperation. There is a dire need for international agreements on hydrogen standards. This implies agreed safety, environmental and purely technical standards. Given the diverging views on the pros and cons of different hydrogen "colours" (Section 2), a consensus is needed about long- and medium-term (bridging technologies) decarbonisation requirements, especially when international organisations offer concessional finance. International organisations such as the IEA and IRENA provide platforms for such collaboration. Multilaterally funded research programmes could accelerate the development of critical bottleneck technologies for the hydrogen transition.

Likewise, South-South cooperation can be stimulated among countries interested in the hydrogen economy, either through direct partnerships or through regional institutions such as the Africa Green Hydrogen Alliance. GIZ can facilitate such cooperation based on its long-standing partnerships in many potential green hydrogen exporting countries as well as in regional institutions.

PART B: The hydrogen economy in South Africa

7 South Africa's dual challenge: Energy-sector crises plus decarbonisation

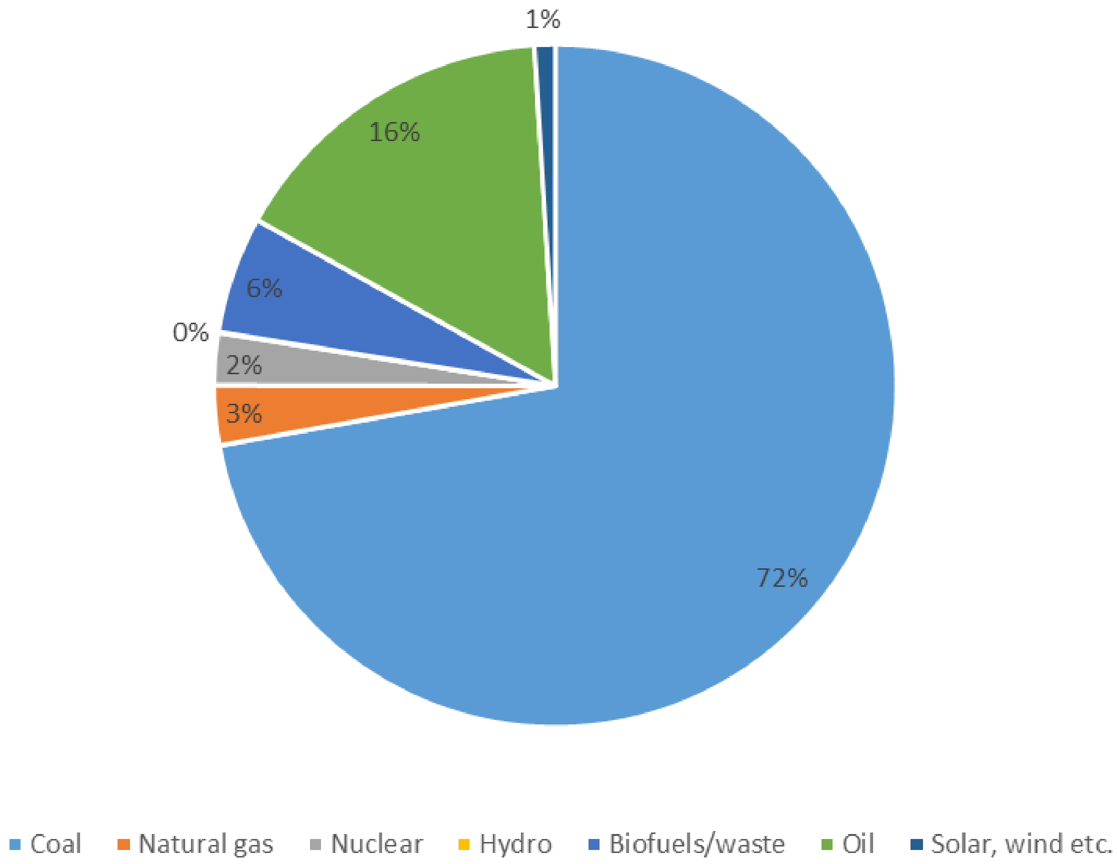
South Africa is facing a difficult dual challenge. On the one hand, it is currently going through its worst energy crisis in recent history. Outdated equipment, a lack of maintenance and corruption within state-owned utility Eskom has led to high levels of electricity supply insecurity. For 2022, the non-availability of electricity due to "load shedding" is expected to accumulate to 3.5 TWh. In February 2023, President Cyril Ramaphosa declared a "state of disaster" over the national energy crisis (VOA, 2023). Even with rolling blackouts and load shedding mostly being planned and announced, the losses for the population and the business sector are severe, and growth rates are expected to plummet to only 0.3 per cent in 2023 (VOA, 2023). On the other hand, the country urgently needs to decarbonise. As with many other parts of the African continent, South Africa is suffering from the effects of climate change. Since 1990, the national average temperature has increased at a rate of more than twice that of global temperature, which is resulting in more frequent droughts and extreme weather events. Although it is difficult to attribute specific events to global warming, the increase in the frequency and severity of adverse climate events, such as the extended droughts in the Western Cape region (second half of the 2010s) and the flooding in the Eastern Cape (January 2022) and KwaZulu-Natal (April 2022), have brought to the fore the deleterious impacts of climate change. At the same time, South Africa is, in contrast to most other countries in the Global South, a big carbon emitter. With around 7.5 tons, the per capita emissions of the country are far above the global average, exceeding even the average of the EU (6.4 tons; IEA, 2019b).

The most important factor contributing to the relatively high carbon footprint of South Africa is the structure of South Africa's energy matrix. South Africa has the fifth largest recoverable coal reserves in the world. Investments into beneficiating coal resources began during the apartheid era as the country was facing international trade sanctions, which triggered efforts to develop coal-based electricity and coal-based petrochemical production. Coal is an abundant and relatively cheap local energy carrier and is used for electricity generation in 15 – mostly old, technologically outdated and inefficient – power stations operated by Eskom. Today, 72 per cent of South Africa's net energy demand is met by using coal. In addition, South Africa exports high amounts of coal, mainly to India and Pakistan, and increasingly to China. Oil is the second-largest item on South Africa's energy matrix and has a high import dependency. Solar power and wind contribute only 1 per cent to the energy matrix (Figure 5).

Coal is not only used for electricity generation. The second-largest South African company, South African Synthetic Oil Limited (Sasol), uses coal to produce liquid fuels and chemical feedstocks that flow into numerous downstream chemical value chains for fertiliser, explosives and plastics. Sasol is a technological leader in Fischer-Tropsch technology and coal liquefaction, and today it is a multinational company with branches and subsidiaries in 22 countries (SASOL, s.a.). Coal liquefaction is a highly CO2-intensive industrial process. Sasol's Secunda facility is the largest single-facility GHG emitter worldwide (Sguazzin, 2020).

To resolve the energy crisis, South Africa would need to connect 5 GW of renewable energy to the grid annually to allow the utility Eskom to do the proper repair and maintenance work and substitute outdated power plants for which repair is no longer an option (Swilling, 2022). For comparison: The entire installed capacity of all renewables in South Africa was 5.7 GW in 2021. Adding 5 GW is the equivalent of 2,000 modern 2.5 MW windmills put into operation every year. This is just for national demand, without considering the renewable energy investment needed for exploiting green hydrogen opportunities.

Figure 5: South Africa's energy matrix (2019)



Source: IEA (2019b); authors

In the last few years, observers have noted a real shift in the South African government's attitude towards renewable energy and green hydrogen. In July 2022, the president announced a series of measures to deal with the crisis, including a removal of the exemption cap of 10 MW for renewable energy projects for which approval was required. Hence, private developers can invest in renewable energy for self-generation at whatever scale they wish to. Likewise, ambitious plan and policy reforms were announced to promote green hydrogen. Still, the challenge remains not only to leverage the needed investments, but also to do so in a way that is socially just and widely supported by the general public.

8 The need for a *Just* Energy Transition

South Africa ratified the Paris Agreement in 2016 and is thus committed to the global climate protection goals. In 2021, in preparation for the Conference of the Parties (COP) 26, South Africa updated its NDC, committing to GHG reduction targets for the years 2025 and 2030. These ambitions are framed within the concept of a "Just Transition", implying that decarbonising South Africa's energy (electricity) sector has to be aligned with the country's social needs.

South Africa's biggest challenge in terms of social equity and justice is a very high unemployment rate, especially among the young generation. In the first quarter of 2022, 63.9 per cent of people between the ages of 15 and 24 years were unemployed. The figure dropped to a still staggering 42.1 per cent for those aged between 25 and 34 years. At the same time, the official unemployment rate was 34.5 per cent (Statistics South Africa [stats sa], 2022). What makes the social and political situation particularly fragile is the fact that, in terms of wealth distribution, the country is the most unequal in the world, with a Gini Index value of 0.63 and without improvements over the past decades. This goes hand in hand with a continuing racial inequality: Statistics South Africa (stats sa, 2020) recognises a "*heavily racialised and gender-biased"* labour market, with white and male people having better access to jobs and earning significantly more than females belonging to the black African groups, despite nearly 20 years of affirmative action under the Broad-Based Black Economic Empowerment programme.

The Just Energy Transition will therefore need to strike a difficult balance between decarbonisation and ensuring that vulnerable stakeholders are shielded from rising costs, unemployment and other negative impacts, and that they are left better off after the transition. There are additional political economy considerations – vulnerable stakeholders with political clout such as unionised mine workers, power station workers and coal truckers will actively block the transition with all means, including protests and blocking highways, in order to underline their claims. There are strong political voices in South Africa, not only among coal workers but also in the African National Congress and the general public, that see renewable energy and the move to independent power producers as a political project favouring foreign investors and white local elites at the expense of national energy sovereignty based on coal and nuclear energy. Support for vulnerable stakeholders, arrangements to guarantee just revenue-sharing of the energy transition as well as a political dialogue that secures buy-in are therefore essential to ensure a smooth and widely supported transition.

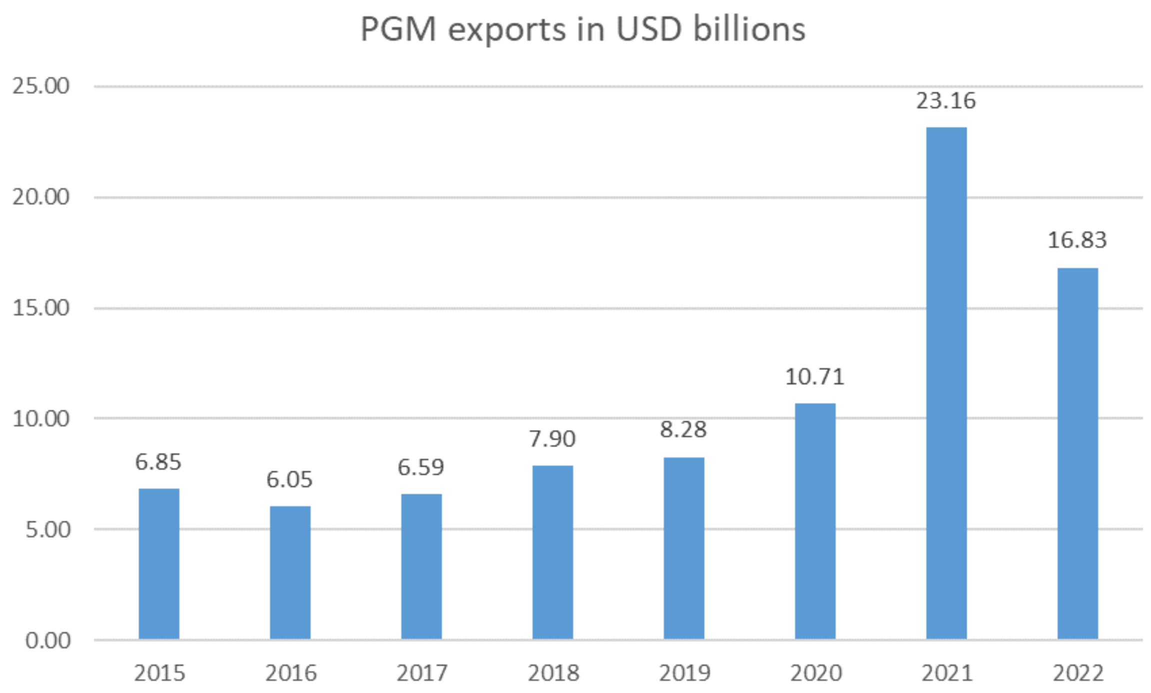
The justice dimension of the energy transformation has two main facets: to mitigate the negative economic – and especially employment – effects of phasing out of coal mining and the renewal of an industrial complex that is strongly dependent on coal; and to increase the social contributions of the emerging renewable energy and hydrogen economy.

Phasing out coal mining is a major challenge, as it threatens the jobs of nearly 150,000 workers in the coal value chain, most of which are employed in mining, where workers are well-organised in trade unions. Organised labour in the coal localities are averse to a transition away from coal, despite labour unions (at the national level) being one of the earliest advocates of a Just Transition in South Africa and the importance of recognising the impact of fossil-intensive production on the environment and communities (COSATU, 2011). Moreover, this phasing out will have effects on the trade balance. Over the past 10 years, export incomes from coal were around USD 5 billion annually (ITC, 2023a). These incomes will, over the coming decades, diminish or disappear, directly dependent on the speed with which global coal demand is reduced.

The second element of the Just Energy Transition is to increase and broaden the benefits of the emerging clean energy sector for society at large. Renewable energy projects are labour-intensive during the construction phase, but much less so during operation (see e.g. Dell'Anna (2021), or Simas and Pacca (2014) for the case of wind power). Whether and how fast clean energies can (over)compensate for the contraction in coal-based industries depends on ripple effects in the economy, that is, to what extent South Africa will be able to develop the enormous potential for forward and backward linkages, as discussed in Part A.

In the mining industry, the net effects may not be negative, as declines in coal mining may be offset by increased demand in PGM mining. In 2019, more than 500,000 employees were registered in the mining sector, thereof 39 per cent in PGM mining, 21 per cent in coal, 20 per cent in gold and 5 per cent in iron ore. The remaining 15 per cent worked in other minerals, lime works and stone quarrying (stats sa, 2021). Coal mining jobs have already seen a considerable decline, from nearly 140,000 in the 1980s (Hanto et al., 2021, p. 74). PGM mining might offset a significant number of job losses, as PGMs have recently seen increasing demand (Figure 6). This trend is likely to continue, as the energy transition requires huge investments in fuel cells and electrolysers, which today require large quantities of PGMs. At the same time, innovations are reducing the quantity of PGMs used in these industries, and demand for catalytic converters – currently a major PGM market – is expected to shrink as carmakers shift to electric vehicles. These developments make it difficult to forecast long-term PGM demand.

Figure 6: Exports of PGM metals from South Africa (2015-2021)



Source: ITC (2023b); authors

Moreover, it is not just an issue of net effects. Both types of mining are centred in partly different regions (mainly North West province for PGMs and Mpumalanga province mainly for coal and only some PGM mining) and require different skills (underground PGM vs. open cast coal mining). Structural change and compensation policies are therefore definitely needed to make the transition just and acceptable.

9 South Africa's potential for renewable energy and green hydrogen

South Africa offers exceptional initial conditions for green hydrogen. First and foremost, South Africa has very good climatic conditions (year-round) for the generation of renewable energies based on solar irradiation as well as wind. This enables low-cost hydrogen production. Also, South Africa has 1.2 million km² of land area, of which only 9 per cent is protected, which is low compared to other potential green hydrogen producing countries such as Namibia (19 per cent), Costa Rica (28 per cent) and Morocco (31 per cent). This reduces the potential trade-offs with other environmental goals (Thomann et al., 2022). Land, however, is a contentious issue in the country, with previously disadvantaged groups calling for a more equitable distribution of land resources. Establishing renewable energy projects on community lands involves cumbersome negotiations, with the effects that renewable energy projects are overwhelmingly planned and installed on land owned by mining companies or (often white) landowners, and the respective land rents are captured by the rich. As a corollary, renewable energy is perceived by many South Africans as a white-dominated, socially exclusive sector.

Another important downside is the scarcity of freshwater resources. Water security is a big issue in South Africa. Although the desalination of seawater is an option, it also has environmental costs in terms of energy requirements and the ecosystem effects of the disposal of brine into the sea. Moreover, failed desalination projects have cost South African municipalities substantial amounts (Patel, 2018). Politically, it is highly problematic to install desalination projects for green hydrogen in water-stressed areas unless those project make potable water available for the surrounding municipalities.

Overall, renewable energy and green hydrogen thus offer great opportunities for the country, but the social, economic and environmental effects of the transformation are highly contingent upon the policy design. This assessment (and the pressure of the energy crisis) recently led South Africa's government to step up its efforts in support of renewables and green hydrogen, develop a series of comprehensive new strategies, fast-track project regulatory approvals and offer tax incentives.

10 South Africa's hydrogen ambitions

South Africa's decisive support for green hydrogen is reflected in very recent and detailed development plans and regional projects. In February 2022, South Africa's Department of Science and Innovation (DSI) published a detailed Hydrogen Society Roadmap for South Africa 2021 (Department of Science and Innovation [DSI], 2022). The document serves as "a national coordinating framework to facilitate the integration of hydrogen-related technologies in various sectors of the South African economy". In addition to investments in the green power sector (renewables and a special emphasis on grid modernisation and extension), the strategy highlights the decarbonisation of heavy-duty transport and energy-intensive industries (cement, steel, mining, refineries) as major objectives. Hydrogen and hydrogen fuel-cell technologies are highlighted as specific industries in which South Africa might become an international "Centre of Excellence" in manufacturing. In terms of export opportunities, the goal is to "position South Africa as a global player in the green hydrogen and green ammonia markets". The strategy identifies four "catalytic projects":

- the Platinum Valley Initiative (or South African Hydrogen Valley)
- the CoalCO2-X Project
- Boegoebaai Special Economic Zone (SEZ)
- the Sustainable Aviation Fuels (SAF) project

Notably, the strategy includes the use of several hydrogen "colours" (grey, blue, turquoise and green) as (supposedly) contributing to a net-zero economy.

In December 2022, this first strategy was complemented by the Green Hydrogen (GH2) Commercialisation Strategy developed by the Department of Trade, Industry and Competition (dtic, 2022). It builds on the Hydrogen Society Roadmap, yet "provides detail and granularity differentiating between short and long term actions by public and private sectors". The strategy highlights two main opportunities for South Africa in terms of increased industrial competitiveness: proprietary Fischer-Tropsch technology (which is essential for Power-to-Liquid conversions) and the resources of PGMs. Moreover, it identifies the manufacture of equipment and components – for example fuel cells and electrolysers, heavy-duty fuel cell vehicles, ammonia cracking and the industrialisation of the renewable energy manufacturing supply chain

– as concrete opportunities for industrial development. The decarbonisation of local industry (steel, petrochemicals, mining) is seen as a necessary step to make these industries fit for the future. The strategy offers a long list of “catalytic projects” with investors, most of which are currently conducting pre-feasibility or feasibility studies.

In addition to these strategies, there are several regional initiatives. Here, we present the two most advanced regional initiatives: The Hydrogen Valley project and the Northern Cape Green Hydrogen Strategy.

The Hydrogen Valley project (Engie Impact, 2021) seeks “to develop a major hydrogen development axis connecting three industrial hubs”:

- Durban/ Richards Bay on the southern coast, with demand or low-carbon fuel for port activities, oil refining and some export potential;
- the Johannesburg/Rustenberg/Pretoria industrial area, where chemical industries (ammonia, methanol, peroxide) as well as iron and steel, aluminium and cement industries need to shift towards low-carbon feedstocks; and
- the Mogalakwena/Limpopo mining region with an enormous demand for hydrogen to run fuel-cell-driven mega-trucks in the mines and heavy-duty fuel-cell trucks to transport minerals along the corridor to Johannesburg and Durban.

The Hydrogen Valley project has been co-designed with the strong engagement of leading South African and multinational firms, and it specifies nine concrete pilot projects, all at a highly ambitious scale.

The Northern Cape Green Hydrogen Strategy (Northern Cape Economic Development Agency [NCEDA], 2022) is export-focussed. The Northern Cape is a sparsely populated region with excellent solar irradiation conditions, abundant land and several mining projects, yet hardly any other industries. The strategy’s centre piece is the “Boegoebaai port and rail project, and adjacent green hydrogen SEZ, storage infrastructure, transmission grids and pipelines” (NCEDA, 2022). It includes construction of a new deep water port. The provincial government set the target of “5 GW of electrolysis capacity supported by 10 GW of renewable energy generation under construction in the Northern Cape by 2025 - 2026” (NCEDA, 2022). The region heavily bets on foreign investment, including “to attract heavy industry wishing to go green to relocate to South Africa” (NCEDA, 2022). Furthermore, it hopes to attract tier-1 solar PV panel and wind turbine manufacturers to increase local development spillovers from renewable energy parks.

Feasibility studies for the Boegoebaai project are ongoing. If those indicate its economic viability, questions still remain regarding its political feasibility. Large-scale energy investments that use additional energy for exports may be difficult to support in times of extreme domestic power shortages. To garner political support, such projects would have to plan considerable excess capacity (also in terms of seawater desalination) to be set aside for domestic consumption.

Summarising the strategy documents, robust political support and strong private-sector interest – including from South Africa’s leading industry players such as Sasol, Anglo American, PetroSA and Arcelor Mittal – is evident. Hydrogen is seen as a game changer for industrial development. Yet, from our perspective, two aspects still remain fairly vague in all strategies:

1. The relative importance of FDI-driven vs. domestic R&D-driven efforts. Both elements are mentioned, yet the amounts for national R&D spending have yet to be determined, and there is no mention of, for example, dedicated supplier development programmes. It will be interesting to observe to what extent South Africa combines FDI attraction with industrial

and innovation policies to indigenise and diversify hydrogen expertise beyond the expected in-house efforts by Sasol, Anglo American, Arcelor Mittal and others.

2. Although all documents explicitly and prominently refer to the objective of a Just Transition, the mechanisms for benefit-sharing are not specified. Even though all studies offer (optimistic) estimates for employment effects and tax revenues, there is no mention of earmarking for social spending or regional adjustment projects, and no concrete measures are included to encourage local enterprise development or community shareholding. Hence, there seems to be an implicit, yet questionable, assumption about the automatic trickle-down effects leading to the justice part of the transition.

11 Opportunities for value creation

Overall, these strategies aim to exploit all the potentials for value creation mentioned in Part A of this discussion paper.

11.1 Ambitious roll-out of renewables and electrolysis, including backward linkages

Renewable energy needs to be scaled up at a massive level to overcome South Africa's current energy shortages *and* to produce the additional electricity required for green hydrogen and derivatives production. This provides opportunities for technological development and industrial development in renewable energy technologies. In fact, South Africa has tried to localise the production of manufactured inputs through local content requirements and other requirements in project tenders. Yet, these attempts largely failed. Producers of wind towers and blades were set up but then closed down again, partly due to erratic policy changes (Bazilian, Cuming, & Kenyon, 2020). "Foreign-owned players have complied with local content rules by setting up subsidiaries in South Africa to act as project developers, operation and maintenance providers and EPC contractors, or by forming joint ventures or other strategic alliances with local players. In addition, they have contracted local companies for services such as catering and logistics" (Bazilian et al., 2020). For the South African wind energy sector, Hansen, Nygaard, Morris and Robbins (2022) confirm that linkage-building has been more successful in services than manufacturing, yet also relatively modest. However, this may change with the envisaged economies of scale in renewable energy projects and if the policy environment becomes more predictable.

Additional backward linkages are expected in PGMs: As mentioned, South Africa is the world's largest producer of PGMs (platinum, palladium, ruthenium, rhodium, iridium and osmium), producing more than 75 per cent of global PGM output. PGMs are important resources in crucial elements of hydrogen systems, such as electrolysers and fuel cells. Most PGMs are beneficiated outside of South Africa. This begs the question to what extent South Africa may become a provider of PGM-based devices for the green hydrogen economy, specifically PEM electrolysers and fuel cells for a variety of applications. The South African Hydrogen Society Roadmap (DSI, 2022, pp. 23-24) lists some potential applications that South Africa should target: a fuel cell locomotive for mines and forklifts for filling stations, hydrogen-powered scooters and three-wheelers, and hydrogen solutions for the power supply of off-grid communities, schools and hospitals. It should be noted that already by 2007 South Africa had launched the Hydrogen South Africa (HySA) programme, aimed at developing technological capabilities around the hydrogen and fuel cell economy. This led to the establishment of small, yet competitive membrane-producing companies. Similarly, firms such as Isondo Precious Metals and Bambili

Energy – a black-owned and female-headed local enterprise – aim to manufacture electrolyser stacks, membranes and catalysts locally with support from the state.

To date, these are only potentials and promising opportunities. Whether South Africa can gain a foothold in the growing global market for PEM electrolysers and fuel cells remains to be seen. Mineral endowments in no way guarantee success in complex downstream industries, where highly specialised and mostly R&D-intensive capabilities in chemistry and process technologies are essential, which are typically the domain of specialised multinationals. A realistic strategy would probably offer incentives for such multinationals to produce in South Africa, combine with industrial and innovation policies to develop certain specialised capabilities (such as customer-specific membranes) and produce lower-tech products (such as small fuel cells for off-grid uses). Attracting electrolyser multinationals to South Africa should be possible, given the access to PGMs (and in the best case scaled local membrane production), the potentially large hydrogen market, a relatively low industrial wage level and a workforce trained in engineering industries (especially automotive). With regard to specialised niches, Anglo American has developed an interesting innovation: a prototype of the world's largest fuel cell heavy-duty mining truck (Randall, 2022). Even here, however, the sophisticated technologies have been developed by foreign specialist companies.

11.2 Chemical conversion into derivatives, including for export

According to the development plans, two opportunities stand out in the field of hydrogen derivatives: ammonia and synthetic fuels, initially mainly for export markets. Success here critically depends on the levelised cost of green hydrogen, which could be among the lowest worldwide due to South Africa's natural conditions.

Green ammonia is in high demand internationally, especially for nitrogen fertiliser production, and it is currently the most technologically mature option for indirectly exporting green hydrogen from South Africa. Several major projects for green ammonia export are currently being prepared, mainly by Sasol. The Boegoebaai project, which is currently a feasibility study, aims at producing up to 400 kilotons of hydrogen per year using nine GW of renewable energy. Another major project being explored by Sasol is green ammonia production in Sasolburg. Nitrogen fertilisers might also be produced in South Africa for regional markets. Soaring gas prices have increased fertiliser prices and made nitrogen fertiliser prohibitively expensive for many farmers across Africa. Based on Sasol's chemical process capabilities, South Africa could become a producer of green nitrogen fertiliser in a rather short time, counteracting the fertiliser-food crisis that has already set in.

Synthetic fuels are also in high demand, especially aviation fuel, as the aircraft industry is willing to pay high premiums for low-carbon fuels. South Africa has already for some time now built up technological capabilities in coal liquefaction via the Fischer-Tropsch process, which includes the handling and processing of hydrogen and the conversion of Power-to-Liquid. Sasol, as a South Africa-based multinational company, is a world leader in Fischer-Tropsch technology and could become a major provider of green synthetic fuels once green hydrogen is available. In fact, Sasol has entered into a consortium with Enertrag, Linde and the 80 per cent black-owned local company Hydregen for the export of SAF at its plant in Secunda to be sold at the H2Global auctions (DSI, 2022, p. 77). Regarding the public sector, R&D is carried out at Cape Town University and the Council for Scientific and Industrial Research.

A study by Bole-Rentel, Chireshe and Reeler (2022) identifies SAF as a particularly promising economic option for South Africa that could "replace the use of conventional jet-fuel domestically up to a maximum blending threshold of 1.2 billion litres per annum, while also providing 2–3.3 billion litres for export". SAF may be produced from three sources:

1. biomass (most promising in South Africa: sugarcane A-molasses), oilseeds (such as Solaris), agricultural waste or alien woody plants that are invading open grasslands and should anyway be removed to retain traditional ecosystems;
2. CO-rich industrial waste gases; or
3. e-fuels that use green hydrogen as well as a carbon source. In the medium-term this can be oilseeds or lignocellulose, hence it requires a harvested input and thereby creates agricultural employment; the alternative to bio-based carbon is direct air capture, but this is far from being commercially viable.

SAF production would hence create employment at the farm level, unless carbon comes from industrial off-gases or direct air capture. Adding to this the direct and indirect employment in industrial processing and trucking, SAF may "create over 100,000 direct green jobs along the SAF supply chain" (Bole-Rentel, Chireshe, & Reeler, p. 5), making it probably the most labour-creating activity linked to green hydrogen (see also WWF, 2019).

11.3 Decarbonisation of domestic industries and transport

South Africa is committed to reducing GHGs. The 2021 update of its NDCs specify targets for 2025 and 2030. These include targets for hard-to-abate sectors requiring green hydrogen, in particular:

- fossil fuel activities, including coal liquefaction, refineries and power plant;
- steel manufacturing;
- the mining industry; and
- heavy-duty fuel-cell trucks and buses.

With the looming threat of tariffs on exports of carbon-intensive goods to industrialised countries with more ambitious carbon-pricing schemes, especially under the EU's CBAM, South African firms and the government are fully aware of the export problems if they do not decarbonise.

Some of South Africa's largest firms are thus facing challenges, most importantly Sasol (coal liquefaction), PetroSA (refineries), Eskom (coal-based electricity), ArcelorMittal South Africa (steel) and AngloAmerican (mining). At the same time, their involvement opens up major opportunities for creating domestic industrial capabilities for the green hydrogen economy. These are specified in the national strategies, which already mention a number of concrete projects at the level of feasibility studies.

Sasol has announces several green hydrogen projects, some partnering with ArcelorMittal South Africa to explore green hydrogen production for steelmaking. This would include capturing of unavoidable CO2 emissions. The large mining sector has an enormous demand for heavy-duty fuel-cell vehicles, both for moving ores within mines and trucking minerals over long distances to ports and local industry clusters, for example from the Mogalakwena/Limpopo mining region to Johannesburg and Durban (Engie Impact, 2021). For such traffic, fuel cells are more efficient than electric vehicles. Industrial development opportunities comprise the fuel-cell charging infrastructure, input manufacturing (such as membranes) and potentially the manufacture of fuel-cell trucks and buses and specialised equipment such as Anglo American's hydrogen-powered mining truck (see above).

11.4 Attraction of foreign direct investment in energy-intensive industries

If, based on its excellent solar irradiation conditions, South Africa achieves a) the roll-out of renewable energy projects far beyond its domestic energy needs and b) a levelised cost of hydrogen comparable to the lowest cost producers in the world (dtic, 2022), it may attract investments in some highly energy-intensive industries, including smelters, steel manufacturing, fertiliser production, certain auto parts as well as data centres. These opportunities will grow, as industries in the Global North are faced with increasingly ambitious decarbonisation targets, encouraging them to seek low-carbon supplies. This opportunity is not (yet) mentioned as a primary objective in South Africa's national strategies – with one exception: the Northern Cape strategy (NCEDA, 2022).

12 Recommendations for Germany's development cooperation with South Africa in the area of green hydrogen

South Africa's Just Energy Transition needs financial and technical support from the international community. At COP 27, President Ramaphosa launched the new Just Energy Transition Investment Plan covering three priorities for financial support through a range of instruments, including grants and concessional finance: energy, electric vehicles and green hydrogen. The International Partners Group, of which Germany is a member, pledged USD 8.5 billion for the first phase of the programme over the next three to five years (Presidency of South Africa, 2022). This complements the German–South African Energy Partnership, established in 2013. The cooperation and topics of the partnership include:

- developing a green energy infrastructure
- promoting low CO2 power generation through renewable energy
- increasing energy efficiency
- hydrogen and fuel cell technology, PtX (technologies, for example, for producing electricity-based liquid fuels)
- structural change in coal mining regions/ Just Transition
- research collaboration
- supporting German energy transition companies in South Africa, business-to-government dialogue

The Energy Partnership combines political dialogue with practical project support. Involving the German and South African private sectors is a key element in the approach.

These programmes provide a solid base for future collaboration. In the following, we suggest a number of aspects that, in our view, deserve special emphasis when negotiating future German contributions.

Gradual entry strategy. In line with South African strategies, we suggest supporting a gradual strategy towards green hydrogen – gradual in two ways: First, assigning priority to the roll-out of renewable energy and improvements to grid infrastructure rather than ambitious export projects. Renewables will be needed in any case ("no regret") to overcome the current energy crisis with frequent load shedding at an enormous cost for the South African economy, while at the same time laying the energy foundations for future hydrogen projects. A "Renewables First" policy would prioritise energy security and avoid foreseeable societal contestation of hydrogen export projects using renewable energy sources while load shedding prevails in the rest of the society. The second way is to build up hydrogen capabilities through small to medium-sized projects that combine hydrogen generation, transport and off-take on the domestic market as well as through research projects and private-sector experiments rather than primarily entering the hydrogen field via large-scale FDI-driven projects. This would build up local capabilities while the international green hydrogen economy approaches technological maturity. Today, many issues around the international trade of green hydrogen are still unresolved. This includes technology choices in production and transport and the future cost effectiveness of competing technologies. Moreover, demand is uncertain in terms of market structure (relative demand for LH2, ammonia and liquid-organic hydrogen carriers; geographic distribution of off-takers) and prices. The earlier South Africa supports major infrastructure investments, the higher the risks of investing in the wrong technology and ending up with stranded assets.

Stronger focus on technological learning and value creation. Large-scale export projects are promising for improving trade and fiscal balances, but they tend to evolve into technological enclaves. This is because projects tend to be driven by international tenders, structured by foreign project developers and involve technologies owned by leading foreign corporations that are highly capital-intensive. The potential for entering into joint ventures, involving local suppliers and hiring local experts is therefore limited, unless domestic capabilities in the respective specialised technologies are developed. Enhancing local industrial capabilities – such as local manufacturing of equipment and components for renewable energy projects, fuel cells and electrolysers and ammonia crackers – is an explicit focus of the proposed South African Green Hydrogen (GH2) Commercialisation Strategy, yet this objective has not yet been translated into concrete policy roadmaps.

German cooperation can contribute here through various mechanisms. Project finance, for example through KfW and H2Global, should encourage projects that are accessible for local bidders, even if this comes at the expense of project size and involves higher transaction costs. Technical cooperation could support the operationalisation of a hydrogen industrial policy and facilitate international knowledge-sharing on this topic. This could be complemented by concrete technology transfer projects, incubators and start-up programmes. Germany has gathered expertise since the 1990s in supporting university spin-offs with comprehensive services (EXIST Programmes of BMBF). GIZ may assist the transfer of experiences from these programmes to the universities involved in the HySA strategy (Cape Town, Western Cape and North West) and possibly beyond. BMZ's develoPPP programme can target hydrogen investments with particularly promising development effects. BMBF can target "2 plus 2" projects for South African hydrogen. In the 2 plus 2 format, projects are funded that involve one publicly funded partner and one private-sector partner from both countries. GIZ can provide preparatory and accompanying support here through information and networking activities. Physikalisch-Technische Bundesanstalt should be a strategic partner when it comes to supporting technical standards on the national level and South Africa's participation in the relevant ISO Technical Committees internationally.

Building technology assessment capacity. The global green hydrogen economy is unfolding in a highly dynamic way. There is a race for securing supplies as well as allocating and attracting international investments. At the same time, as stated earlier, many uncertainties about technologies and markets remain. This is typical of major technological disruptions when competing technologies are tested before one or two of them become the "dominant design" that manage to exploit economies of scale and set the de-facto industry standards. Betting early on one technology thus bears huge investment risks. South Africa might, for example, gain hugely from early investments in platinum refining and building up industry-specific capabilities for PEM electrolysers, but it may also lose enormously if alkaline electrolysers become the dominant design or if platinum-saving membrane technologies are developed. Similarly, port and shipping infrastructure investments are very different for LH2, LOHC and ammonia as derivatives for export.

Technology assessment is therefore essential to assess the opportunities and challenges related to the emerging global green economy and from this, derive practical next steps for the country in terms of value addition, technological learning, industrial linkages and employment creation. South Africa is relatively well-positioned here, with considerable expertise in the Council for Scientific and Industrial Research, the DSI, the Trade and Industrial Policy Strategies institution and other research centres, yet it lacks the type of critical mass of specialised experts as, for example, Germany has in its dedicated Fraunhofer Institutes. Although GIZ in South Africa already plays an important role in mobilising international expertise for technical studies on an ad-hoc basis, the emphasis should shift towards long-term institution-building for technology assessment. Since 2020, South Africa is one of three African countries involved in an UNCTAD (United Nations Conference on Trade and Development) pilot project to build up technology assessment capacities specifically in the field of agricultural and energy technologies. This project is advised by experts from the Institute for Technology Assessment and Systems Analysis at Karlsruhe Institute of Technology and the German Institute of Development and Sustainability (IDOS). The South African partner is DSI, the Line Ministry of the Hydrogen Society Roadmap. This might be used as a starting point for the long-term support of technology assessment capacities for green hydrogen – and, potentially other areas of disruptive change.

Supporting innovative mechanisms for benefit-sharing. So far, direct development spillovers from renewable energy projects in South Africa in terms of new firms, capabilities and permanent employment have been quite modest. For the reasons pointed out earlier, adding electrolysers, ammonia plants and seawater desalination facilities is unlikely to change this, unless South Africa succeeds in deepening its industrial structure. To make the development of South African hydrogen just and inclusive and garner political support, the country needs to invest in a socially inclusive industrial policy. This, however, will only yield tangible results in the medium to long term. Short-term investments into a Just Energy Transition are therefore needed, such as earmarking tax incomes for regional development funds, including community benefits as hard criteria in tenders or even direct cash payments to citizens (see Part A, Section 6.3). So far, there is surprisingly little discussion in South Africa about these kinds of benefit-sharing, despite anticipated conflicts over access to energy, water and land. The hydrogen commercialisation study (dtic, 2022) mentions the development of a “GH2Socio-economic plan to enhance local content inclusion of small, medium and micro enterprises and entrepreneurs and empower previously disadvantaged groups” as a necessary next step. German cooperation might, as a contribution to the Just Energy Transition Partnership, prioritise support for this upcoming task by collecting evidence from benefit-sharing schemes around the world and helping to organise discussions about appropriate solutions for the South African context. Similarly, German cooperation might support exchange on pro-poor designs of carbon-pricing and fossil-fuel subsidy reforms. Such reforms are envisaged in South Africa as a prerequisite for a renewable energy transition, including the reallocation of subsidies to green hydrogen development. Yet this may come with additional burdens on poor households and thus needs to be combined with safeguards and social assistance (Malerba, 2023). Support may be offered either via technical cooperation or policy-based lending.

Financial cooperation helps in supporting the energy transformation in the country and the required fast expansion of renewable energy generation. This seems to be a no-regret option, as the need for new and carbon-free energy generation in South Africa is insatiable – be it with or without green hydrogen generation – to ensure a just and safe phasing-out of coal-fired power generation. KfW should also offer grants and concessional project finance for hydrogen and its derivatives whenever they meet the development criteria outlined in the BMZ strategy. In addition, depending on South Africa’s priorities, policy-based lending may be scaled up (and closely aligned with GIZ’s Technical Cooperation) for a variety of hydrogen-related reform agendas, ranging from energy-sector reform and environmental fiscal reform to innovative forms of benefit-sharing, as outlined in Part A, Section 6.3. As always, such support needs to be aligned with international partners, such as the World Bank's "Scaling Solar" facility.

South-South knowledge exchange. GIZ in particular has long-standing expertise in organising international knowledge exchange on different topics. GIZ's PtX Hub (International PtX Hub, s.a.) supports the development and implementation of green hydrogen strategies in several countries, some of them (e.g. Chile, Argentina, Brazil, India) with comparable opportunities and challenges. Stakeholders from these countries can be given the opportunity to share their experiences in different policy fields related to green hydrogen, such as industrial policy, FDI attraction, benefit-sharing and technical standards. In addition to high-level exchanges, such as the Berlin Energy Transition Dialogues, there is a need for more in-depth expert exchanges, for example between Ministries of Industry and Trade and their think tanks or between standards authorities.

In the case of South Africa, regional cooperation with Namibia may also become a possibility. The Hyphen Energy project in Namibia and the Boegoebaai project in South Africa, which is at the feasibility study stage, are geographically very close. GIZ may want to activate its networks on both sides of the border to scale up knowledge exchange and joint planning.

References

Ahmed, H. (2018). New trends in the application of carbon-bearing materials in blast furnace iron-making. *Minerals, 8*(12), 561. https://doi.org/10.3390/min8120561

Altenburg, T., Corrocher, N., & Malerba, F. (2022). China's leapfrogging in electromobility: A story of green transformation driving catch-up and competitive advantage. *Technological Forecasting and Social Change,* (183), article 121914.

Altenburg, T., & Lütkenhorst, W. (2015). *Industrial policy in developing countries – failing markets, weak states*. Northampton, MA, and Cheltenham: Edward Elgar Publishing.

Altenburg, T., Wenck, N., Fokeer, S., & Albaladejo, M. (2022). Green hydrogen: Opportunities for industrial development through forward linkages from renewables. *Research Network Sustainable Global Supply Chains.* Retrieved from https://www.sustainablesupplychains.org/green-hydrogen-opportunities-for-industrial-development-through-forward-linkages-from-renewables/

Altmann, M., Cloete, L., Diehl, L., Rubbers, E., Walwyn, D., Wurster, R., & Zeiss, J. (2022). *Regulations, codes and standards in the frame of promoting the development of a hydrogen economy for South Africa. Final report*. Dresden: Ludwig Bölkow Systemtechnik.

Arrow, K. (1962). The economic implications of learning by doing. *The Review of Economic Studies, 29*(3), 155-173. https://doi.org/10.2307/2295952

Asimeng, T., & Altenburg, T. (2022). *How does urban rail development in China and India enable technological upgrading?* (IDOS Discussion Paper 14/2022). Bonn: German Institute of Development and Sustainability (IDOS).

Aurora Energy Research. (2023, January 24). *Renewable hydrogen imports could compete with EU production by 2030*. Retrieved from https://auroraer.com/media/renewable-hydrogen-imports-could-compete-with-eu-production-by-2030/

Auty, R. (1993). *Sustaining development in mineral economies: The resource curse thesis*. London: Routledge.

Baffes, J., & Koh, W. C. K. (2022). *Fertilizer prices expected to remain higher for longer* (World Bank Blogs). Washington, DC: World Bank. Retrieved from https://blogs.worldbank.org/opendata/fertilizer-prices-expected-remain-higher-longer

Bazilian, M., Cuming, V., and T. Kenyon (2020). Local-content rules for renewables projects don't always work. *Energy Strategy Reviews*, *32*, 100569. https://doi.org/10.1016/j.esr.2020.100569

Bole-Rentel, T., Chireshe, F., & Reeler, J. (2022). *Fuel for the future: A blueprint for the production of sustainable aviation fuel in South Africa.* Cape Town: WWF South Africa. Retrieved from https://rsb.org/wp-content/uploads/2022/05/fuel_for_the_future-1.pdf

Bourne, J. K. (2022). Global food crisis looms as fertilizer supplies dwindle. *National Geographic*. Retrieved from https://www.nationalgeographic.com/environment/article/global-food-crisis-looms-as-fertilizer-supplies-dwindle

Brandon, N. P., & Kurban, Z. (2017). Clean energy and the hydrogen economy. *Philosophical Transactions of the Royal Society A, 375*(20160400). http://doi.org/10.1098/rsta.2016.0400

CertifHy Consortium. (2021). *CertifHy*. Retrieved from https://www.certifhy.eu/wp-content/uploads/2021/10/CertifHy_folder__leaflets.pdf

Chatterjee, S., Parsapur, R. K., & Huang, K.-W. (2021). Limitations of ammonia as a hydrogen energy carrier for the transportation sector. *ACS Energy Letters, 6*(12), 4390-4394. https://doi.org/10.1021/acsenergylett.1c02189

Climate Watch. (2023). NDC enhancement tracker. Retrieved from https://www.climatewatchdata.org/2020-ndc-tracker

Cordonnier, J., & Saygin, D. (2022), *Green hydrogen opportunities for emerging and developing economies: Identifying success factors for market development and building enabling conditions* (OECD Environment Working Papers 205). Paris: OECD Publishing. https://doi.org/10.1787/53ad9f22-en

COSATU. (2011). *A just transition to a low-carbon and climate-resilient economy.* Retrieved from https://justtransitionforall.com/wp-content/uploads/2022/08/Naledi_A-just-transition-to-a-climate-resilient-economy.pdf

Dell'Anna, F. (2021). Green jobs and energy efficiency as strategies for economic growth and the reduction of environmental impacts. *Energy Policy, 149*, 112021. https://doi.org/10.1016/j.enpol.2020.112031

DSI (Department of Science and Innovation). (2022). *Hydrogen society roadmap for South Africa 2021*. Retrieved from https://www.dst.gov.za/images/South_African_Hydrogen_Society_RoadmapV1.pdf

dtic (Department of Trade Industry and Competition). (2022). *Proposed South African green hydrogen (GH2) commercialisation strategy.* Retrieved from http://www.thedtic.gov.za/wp-content/uploads/Powerpoint-Summary-Green-Hydrogen-Commercialisation-Strategy.pdf

El-Sayed, A. M., Faheim, A. A., Salman, A. A., & Saleh, H. M. (2021). Introductory chapter: Cement industry. In H. M. Saleh (Ed.), *Cement industry: Optimization, characterization and sustainable application*. London: IntechOpen. https://doi.org/10.5772/intechopen.95053

Energy Efficiency & Renewable Energy. (s.a.). *Hydrogen shot*. Hydrogen and Fuel Cell Technologies Office. Retrieved from https://www.energy.gov/eere/fuelcells/hydrogen-shot

Energy Information Administration. (2020). *Off-grid electricity development in Africa: Uncertainties and potential implications for electric power markets*. Retrieved from https://www.eia.gov/outlooks/ieo/pdf/IEO2020_IIF_Africa.pdf

Engie Impact. (2021). *South Africa hydrogen valley. Final report*. Retrieved from https://www.dst.gov.za/images/2021/Hydrogen_Valley_Feasibility_Study_Report_Final_Version.pdf

EU (European Union). (2020). *Hydrogen generation in Europe: Overview of costs and key benefits.* Retrieved from https://op.europa.eu/s/x5Ib

European Commission. (2023). *Hydrogen*. Retrieved from https://energy.ec.europa.eu/topics/energy-systems-integration/hydrogen_en

Evans, P. (1995). *Embedded autonomy: States and industrial transformation*. Retrieved from http://www.jstor.org/stable/j.ctt7t0sr

Federal Ministry for Economic Cooperation and Development. (s.a.). *A just transition: Towards low-carbon economies and lifestyles. Climate change and development.* Retrieved from https://www.bmz.de/en/issues/climate-change-and-development/just-transition

Gas for Climate, Wang, A., Jens, J., Mavins, D., Moultak, M., Schimmel, M., & Buseman, M. (2021). *Analysing future demand, supply, and transport of hydrogen*. Retrieved from https://www.h2knowledgecentre.com/content/policypaper2256?crawler=redirect&mimetype=application/pdf

Global Wind Energy Council. (2022). *Global wind report 2022*. Retrieved from https://gwec.net/global-wind-report-2022/

Hansen, U., Nygaard, I., Morris, M., & Robbins, G. (2022). Servicification of manufacturing in global value chains: Upgrading of local suppliers of embedded services in the South African market for wind turbines. *The Journal of Development Studies, 58*(4). https://doi.org/10.1080/00220388.2021.2017892

Hanto, J., Krawielicki, L., Krumm, A., Moskalenko, N., Loffler, K., Hauenstein, C., & Oei, P.-Y. (2021). Effects of decarbonization on the energy system and related employment effects in South Africa. *Environmental Science and Policy, 124*, 73-84.

Hasanbeigi, A. (2021, May 17). *Global cement industry's GHG emissions*. Retrieved from https://www.globalefficiencyintel.com/new-blog/2021/global-cement-industry-ghg-emissions

Hidalgo, C. A., Balland, P.-A., Boschma, R., Delgado, M., Feldman, M., Frenken, K., …Zhu, S. (2018). The principle of relatedness. In A. Morales, C. Gershenson, D. Braha, A. Minai, & Y. Bar-Yam (Eds.), *Unifying themes in complex systems IX*. ICCS 2018. Springer proceedings in complexity. https://doi.org/10.1007/978-3-319-96661-8_46

Hidalgo, C. A, & Hausmann, H. (2009). The building blocks of economic complexity. *Proceedings of the National Academy of Sciences of the United States of America (PNAS), 106*(26), 10570-10575. https://doi.org/10.1073/pnas.0900943106

Hornby, S., & Brooks, G. (2021). Impact of hydrogen DRI on EAF steelmaking. *Midrex*. Retrieved from https://www.midrex.com/tech-article/impact-of-hydrogen-dri-on-eaf-steelmaking/

Hydrogen Council. (2021). *Hydrogen for net-zero. A critical cost-competitive energy vector*. Retrieved from https://hydrogencouncil.com/wp-content/uploads/2021/11/Hydrogen-for-Net-Zero.pdf

Iberdrola. (2022). *Iberdrola commissions the largest green hydrogen plant for industrial use in Europe*. Retrieved from https://www.iberdrola.com/about-us/lines-business/flagship-projects/puertollano-green-hydrogen-plant

IEA (International Energy Agency). (2019a). *The future of hydrogen*. Retrieved from https://www.iea.org/reports/the-future-of-hydrogen

IEA. (2019b). *South Africa. Key energy statistics, 2019*. Retrieved from https://www.iea.org/countries/south-africa

IEA. (2021a). *Global hydrogen review 2021*. Retrieved from https://iea.blob.core.windows.net/assets/5bd46d7b-906a-4429-abda-e9c507a62341/GlobalHydrogenReview2021.pdf

IEA. (2021b). *Cement*. Retrieved from https://www.iea.org/reports/cement

IEA. (2021c). *Ammonia technology roadmap*. Retrieved from https://www.iea.org/reports/ammonia-technology-roadmap

IEA. (2021d). *Hydrogen projects database*. Retrieved from https://www.iea.org/reports/hydrogen-projects-database

IEA. (2022a). *Global hydrogen review 2022*. Retrieved from https://www.iea.org/reports/global-hydrogen-review-2022

IEA. (2022b). *Chemicals.* Retrieved from https://www.iea.org/reports/chemicals

IEA. (2022c). *Norway 2022: Energy policy review*. Retrieved from https://iea.blob.core.windows.net/assets/de28c6a6-8240-41d9-9082-a5dd65d9f3eb/NORWAY2022.pdf

IEA. (2022d). *Solar PV global supply chains*. Retrieved from https://www.iea.org/reports/solar-pv-global-supply-chains

International Air Transport Association. (2021, October 4). *Net-zero carbon emissions by 2050* (Press Release 66). Retrieved from https://www.iata.org/en/pressroom/pressroom-archive/2021-releases/2021-10-04-03/

International Maritime Organization. (2018). *Initial IMO strategy on reduction of GHG emissions from ships*. Resolution MEPC. 304 (72), adopted on 13 April 2018. Retrieved from https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/Resolution%20MEPC.304%2872%29_E.pdf

International PtX Hub. (s.a.). Homepage. Retrieved from https://ptx-hub.org/

IRENA (International Renewable Energy Agency). (2020). *Green hydrogen cost reduction: Scaling up electrolysers to meet the 1.5° C climate goal*. Retrieved from https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Dec/IRENA_Green_hydrogen_cost_2020.pdf

IRENA. (2021). *Decarbonising end-use sectors: Practical insights on green hydrogen.* Retrieved from https://www.irena.org/publications/2021/May/Decarbonising-end-use-sectors-green-hydrogen

IRENA. (2022). *Geopolitics of the energy transformation: The hydrogen factor*. Abu Dhabi: Author.

ITC (International Trade Centre). (2021). *Global trade indicators*. Retrieved from https://www.trademap.org/Index.aspx

ITC. (2023a). Trade map. List of importing markets for a product exported by South Africa. Product: 2701 coal; briquettes, ovoids and similar solid fuels manufactured from coal. Retrieved from https://www.trademap.org/Country_SelProductCountry_TS.aspx?nvpm=1%7c710%7c%7c%7c%7c2701%7c%7c%7c4%7c1%7c1%7c2%7c2%7c1%7c2%7c1%7c1%7c1

ITC. (2023b). Trade map. List of importing markets for a product exported by South Africa. Product: 7110 platinum, incl. palladium, rhodium, iridium, osmium and ruthenium, unwrought or in semi-manufactured forms, or in powder form. Retrieved from https://www.trademap.org/Country_SelProductCountry_TS.aspx?nvpm=1%7c710%7c%7c%7c%7c7110%7c%7c%7c4%7c1%7c1%7c2%7c2%7c1%7c2%7c1%7c1%7c1

Joint Research Centre. (2021). *Assessment of hydrogen delivery options* (Science for Policy Briefs JRC124206). Retrieved from https://joint-research-centre.ec.europa.eu/system/files/2021-06/jrc124206_assessment_of_hydrogen_delivery_options.pdf

Kakoulaki, G., Kougias, I., Taylor, N., Dolci, F., Moya, J., & Jäger-Waldau, A. (2021). Green hydrogen in Europe – A regional assessment: Substituting existing production with electrolysis powered by renewables. *Energy Conversion and Management, 228*(113649). https://doi.org/10.1016/j.enconman.2020.113649

KfW, GIZ, & IRENA (German Credit Institute for Reconstruction, German Agency for International Cooperation, & International Renewable Energy Agency). (2020). *The renewable energy transition in Africa. Powering access, resilience and prosperity*. Retrieved from https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2021/March/Renewable_Energy_Transition_Africa_2021.pdf

Klevstrand, A. (2023). Firm contracts: World's leading clean-hydrogen buyers largely focused on replacing existing dirty H2. *Hydrogen Insight*. Retrieved from https://www.hydrogeninsight.com/industrial/firm-contracts-worlds-leading-clean-hydrogen-buyers-largely-focused-on-replacing-existing-dirty-h2/2-1-1395117

Kurrer, C. M. (2020). *The potential of hydrogen for decarbonising steel production.* Retrieved from https://www.europarl.europa.eu/RegData/etudes/BRIE/2020/641552/EPRS_BRI(2020)641552_EN.pdf

Li, L., Steinlein, A., Kuneman, E., & Eckardt, J. (2022). *Hydrogen factsheet – China*. Retrieved from https://www.adelphi.de/en/publication/hydrogen-factsheet-%E2%80%93-china

Lv, C., Zhong, L., Liu, H., Fang, Z., Yan, C., Chen, M., ...Yu, G. (2021). Selective electrocatalytic synthesis of urea with nitrate and carbon dioxide. *Nature Sustainability, 4*(10), 868-876. https://doi.org/10.1038/s41893-021-00741-3

Malerba, D. (2023). *The role of social protection in environmental fiscal reforms* (IDOS Discussion Paper, in press). Bonn: German Institute of Development and Sustainability (IDOS).

Marine Insight. (2022, February 4). World's first ammonia ready vessel 'Kriti Future' delivered. *MI News Network*. Retrieved from https://www.marineinsight.com/shipping-news/worlds-first-ammonia-ready-vessel-kriti-future-delivered/

Methanol Institute. (2023). About methanol. Retrieved from https://www.methanol.org/

Mien, E., & Goujon, M. (2022). 40 years of Dutch disease literature: Lessons for developing countries. *Comparative Economic Studies*, *(64)*, 351-383. https://doi.org/10.1057/s41294-021-00177-w

Miller, D., Armstrong, K., & Styring, P. (2022). Assessing methods for the production of renewable benzene. *Sustainable Production and Consumption, 32*, 184-197. https://doi.org/10.1016/j.spc.2022.04.019

Minke, C., Suermann, M., Bensmann, B., & Hanke-Rauschenbach, R. (2021). Is iridium demand a potential bottleneck in the realization of large-scale PEM water electrolysis? *International Journal of Hydrogen Energy, 46*(46), 23581-23590. https://doi.org/10.1016/j.ijhydene.2021.04.174

NCEDA (Northern Cape Economic Development Agency). (2022). *Northern Cape green hydrogen strategy. A pathfinder for South Africa's national green hydrogen initiatives.* Northern Cape, SA: Author.

Neary, P. (2003). Competitive versus comparative advantage. *World Economy, 26*(4), 457-470. https://doi.org/10.1111/1467-9701.00532

Norwegian Ministry of Petroleum and Energy / Norwegian Ministry of Climate and Environment. (2020). *The Norwegian government's hydrogen strategy – towards a low emission society*. Oslo: Author.

Olk, J., & Scholz, C. (2022, August 23). Eon und Uniper wollen grünes Ammoniak aus Kanada beziehen. *Handelsblatt*. Retrieved from https://www.handelsblatt.com/unternehmen/energie/energiewende-eon-und-uniper-wollen-gruenes-ammoniak-aus-kanada-beziehen/28619990.html

Oni, A. O., Anaya, K., Giwa, T., Di Lullo, G., & Kumar, A. (2022). Comparative assessment of blue hydrogen from steam methane reforming, autothermal reforming, and natural gas decomposition technologies for natural gas-producing regions. *Energy Conversion and Management, 254*(115245). https://doi.org/10.1016/j.enconman.2022.115245

Patel, M. (2018). *Desalination in South Africa: Panacea or peril for industrial development?* Pretoria: Trade & Industrial Policy Strategies (TIPS).

Presidency of South Africa. (2022). South Africa's Just Energy Transition Investment Plan (JET IP) for the initial period 2023–2027. Retrieved from https://www.thepresidency.gov.za/download/file/fid/2649

Quarton, C. J., Tlili, O., Welder, L., Mansilla, C., Blanco, H., Heinrichs, H. ...Samsatli, S. (2020). The curious case of the conflicting roles of hydrogen in global energy scenarios. *Sustainable Energy & Fuels, 4*(1), 80-95. https://doi.org/10.1039/C9SE00833K

Randall, C. (2022, May 9). Anglo American presents fuel cell heavy-duty mining truck. *Electrive*. Retrieved from https://www.electrive.com/2022/05/09/anglo-american-presents-fuel-cell-heavy-duty-mining-truck/

Riemer, M., Zheng, L., Pieton, N., Eckstein, J., Kunze, R., & Wietschel, M. (2022). *Future hydrogen demand: A cross-sectoral, multiregional meta-analysis* (HYPAT Working Paper 04/2022). Karlsruhe: Fraunhofer-Institut für System- und Innovationsforschung (ISI).

Rodrik, D. (2015). *Premature deindustrialization*. Retrieved from https://drodrik.scholar.harvard.edu/files/dani-rodrik/files/premature_deindustrialization_revised2.pdf

Roland Berger. (2021). *Hydrogen transportation: The key to unlocking the clean hydrogen economy* (Focus). Retrieved from https://www.rolandberger.com/en/Insights/Publications/Transporting-the-fuel-of-the-future.html

Royal Society. (2020). *Ammonia: Zero-carbon fertiliser, fuel and energy store* (Policy Briefing). Retrieved from https://royalsociety.org/-/media/policy/projects/green-ammonia/green-ammonia-policy-briefing.pdf

Samadi, S., Lechtenbömer, S., Viebahn, P., & Fischer, A. (2021). *Conceptualisation of the potential renewables-pull effect: A result of topic area 3 "Scenarios and transformation pathways" of the research project SCI4climate.NRW.* Wuppertal: SCI4climate.NRW. Retrieved from https://www.energy4climate.nrw/fileadmin/Service/Publikationen/Ergebnisse_SCI4climate.NRW/Szenarien/2021/SCI4climate.NRW-2021-Conceptualisation-of-the-potential-Renewables-Pull-Effect-cr-sci4climatenrw.pdf

SASOL. (s.a.). Homepage. Retrieved from https://www.sasol.com/

Schippert, J., Runge, P., Farhang-Damghani, N., & Grimm, V. (2022). *Greenhouse gas footprint of blue hydrogen with different production technologies and logistics options.* Retrieved from https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4153724

Schneider, S., Bajohr, S., Graf, F., & Kolb, T. (2020). State of the art of hydrogen production via pyrolysis of natural gas. *ChemBioEng Rev, 7*(5), 150-158.

Schnurr, E. et al. (2023). *Analysis and recommendations for improving the regulatory framework and strategic planning basis in South Africa in the context of a favourable policy for green hydrogen / PtX production, application and export*. South Africa, Intermediate Report. GFA.

Sharpe, R. (2021, October 20). Fertiberia backs Swedish green ammonia project. *Argus Media*. Retrieved from https://www.argusmedia.com/en/news/2265442-fertiberia-backs-swedish-green-ammonia-project

Sguazzin, A. (2020, March 17). The world's biggest emitter of greenhouse gases. *Bloomberg Green: Energy and Science*. Retrieved from https://www.bloomberg.com/news/features/2020-03-17/south-africa-living-near-the-world-s-biggest-emitting-plant?leadSource=uverify%20wall

Siemens Energy. (2022). *E-methanol's giant step forward*. Retrieved from https://www.siemens-energy.com/global/en/news/magazine/2022/zero-emission-fuel-ramps-up-for-shipping.html

Simas, M., & Pacca, S. (2014). Assessing employment in renewable energy technologies: A case study for wind power in Brazil. *Renewable and Sustainable Energy Reviews, 31*, 83-90. https://doi.org/10.1016/j.rser.2013.11.046

SRU (German Advisory Council on the Environment). (2021). *Wasserstoff im Klimaschutz: Klasse statt Masse: Stellungnahme Juni 2021*. Retrieved from https://www.umweltrat.de/SharedDocs/Downloads/DE/04_Stellungnahmen/2020_2024/2021_06_stellungnahme_wasserstoff_im_klimaschutz.pdf;jsessionid=9CF689B04E5CD9A2BFB70D2D7CAEF7BB.intranet212?__blob=publicationFile&v=4

Stamm, A. (2023). *The sustainability transition requires extended and differentiated North-South cooperation for innovation. Background document to the Technology and Innovation Report 2023.* Geneva: UNCTAD. Retrieved from https://unctad.org/system/files/non-official-document/tir2023_background5_en.pdf

stats sa (Statistics South Africa). (2020). *How unequal is South Africa?* Retrieved from https://www.statssa.gov.za/?p=12930

stats sa. (2021). *Four facts about the mining industry (2019).* Retrieved from https://www.statssa.gov.za/?p=14682

stats sa. (2022). *South Africa's youth continues to bear the burden of unemployment.* Retrieved from https://www.statssa.gov.za/?p=15407

Swilling, M. (2022, September 26). As SA teeters on the brink of full-blown energy disaster, it's vital the right decisions are made – now. Power crisis op-ed. *Daily Maverick*. Retrieved from https://www.dailymaverick.co.za/article/2022-09-26-as-sa-teeters-on-the-brink-of-full-blown-energy-disaster-its-vital-the-right-decisions-are-made-now/

SystemIQ. (2022). *Namibia's green hydrogen opportunity. Key questions and initial answers.* Mimeo.

Thomann, J., Edenhofer, L., Hank, C., Lorych, L., Marscheider-Weidemann, F., Stamm, A., ...Weise, F. (2022). *Hintergrundpapier zu nachhaltigem grünen Wasserstoff und Syntheseprodukten* (HYPAT Working Paper 01/2022). Karlsruhe: Fraunhofer ISI. Retrieved from https://hypat.de/hypat-wAssets/docs/new/publikationen/HyPAT_Working-Paper_01-2022_Hintergrundpapier_nachhaltiger_gruener_Wasserstoff_Syntheseprodukten.pdf

Unruh, G. C. (2000). Understanding carbon lock-in. *Energy Policy, 28*(12), 817-830. https://doi.org/10.1016/S0301-4215(00)00070-7

Van de Graaf, T., Overland, I., Scholten, D., & Westphal, K. (2020). The new oil? The geopolitics and international governance of hydrogen. *Energy Research & Social Science*, *70*, 101667. https://doi.org/10.1016/j.erss.2020.101667

VOA. (2023). South Africa declares "state of disaster" over energy crisis. Retrieved from https://www.voanews.com/a/south-africa-declares-state-of-disaster-over-energy-crisis-/6956810.html

Wappler, M., Unguder, D., Lu, X., Ohlmeyer, H., Teschke, H., & Lueke, W. (2022). Building the green hydrogen market – current state and outlook on green hydrogen demand and electrolyzer manufacturing. *International Journal of Hydrogen Energy, 47*(79). https://doi.org/10.1016/j.ijhydene.2022.07.253

WEC (World Energy Council – Germany). (2022). *International hydrogen partnerships*. Retrieved from https://www.weltenergierat.de/publikationen/studien/international-hydrogen-strategies/

Wietschel, M., Zheng, L., Arens, M., Hebling, C., Ranzmeyer, O., Schaadt, A. …Pfluger, B. (2021). *Metastudie Wasserstoff – Auswertung von Energiesystemstudien*. Studie im Auftrag des Nationalen Wasserstoffrats. Karlsruhe, Freiburg, Cottbus: Fraunhofer-IEG/Fraunhofer-ISE/Fraunhofer ISI. Retrieved from https://www.isi.fraunhofer.de/content/dam/isi/dokumente/cce/2021/Metastudie_Wasserstoff_Abschlussbericht.pdf

World Bank. (2020). *Green hydrogen in developing countries*. Energy Sector Management Assistance Program. Retrieved from https://documents1.worldbank.org/curated/en/953571597951239276/pdf/Green-Hydrogen-in-Developing-Countries.pdfWorld Steel Association. (2021). *Climate change and the production of iron and steel*. Brussels: Author.

World Steel Association. (2023). *World steel in figures 2022*. Retrieved from https://worldsteel.org/steel-topics/statistics/world-steel-in-figures-2022/

WWF. (2019). *Taking off: Understanding the sustainable aviation biofuel potential in sub-Saharan Africa.* Cape Town: WWF South Africa. Retrieved from https://www.wwf.org.za/?26941/taking-off-understanding-the-sustainable-aviation-biofuel-potential-in-sub-saharan-africa