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THE OPPORTUNITIES, CHALLENGES AND POTENTIALS FOR HYDROGEN IN AFRICA

African-European partnerships for sustainable development

Anteneh G Dagnachew, Stephanie Solf, Samira I. Ibrahim, Harmen-Sytze de Boer

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Unit conversion

1 kg H_2 = 39.4 kWh H_2 High heating value
1 kg H_2 = 141.8 MJ H_2 High heating value
1 EJ H_2 = 7.1 Mt H_2 High heating value

List of abbreviations

AGHA	Africa Green Hydrogen Alliance	kWh	Kilo watt hour
ALK	Alkaline water	LCA	Life cycle assessment
AR6	Sixth Assessment Report	LLF	Light liquid fuel
AU	African Union	LOHCs	Liquid organic hydrogen carriers
CCUS	carbon capture, utilization and storage	Mt	Million tonnes
CO_2	Carbon dioxide	MWh	Megawatt-hour
CSP	Concentrated solar power	PEM	Polymer electrolyte membrane
DGIS	Directorate-General for International Cooperation	PIDA	Programme for Infrastructure Development in Africa
EBRD	European Bank for Reconstruction and Development	PPP	Public-private-partnership
EIB	Energy, industry and business	R&D	Research and development
EJ	Exajoule	SDG	Sustainable Development Goals
EU	European Union	SMR	Steam methane reformation
GCEW	Global Commission on the Economics of Water	SSPs	Shared Socioeconomic Pathways
GHG	Greenhouse gas	STEPS	Stated Policies Scenario
Gt	Gigatonne	UN	United Nations
GW	Gigawatt	USD	United States dollar
HLF	Heavy liquid fuel	VRE	Variable renewable energy
IEA	International Energy Agency	WACC	Weighted average cost of capital
IPFs	International patent families	WAGP	West African Gas Pipeline
IRENA	International Renewable Energy Agency	WWDR	UN World Water Development Report
Kg	Kilogramme		

FINDINGS

Findings: The Opportunities, Challenges and Potential for Hydrogen in Africa

Green hydrogen can complement energy efficiency and electrification in decarbonising parts of the energy system. The role of hydrogen in today's global energy mix is negligible, with most of the hydrogen being used as a feedstock in the chemical industry and in refineries. However, our model projection shows that green hydrogen contributes to decarbonisation of the energy system under all climate change mitigation scenarios. Energy efficiency and electrification are the primary strategies to reduce emissions and decarbonise various sectors in all scenarios. Hydrogen plays an integral role in decarbonising multiple sectors for which this is rather difficult to do via direct electrification, such as hard-to-abate high-heat industrial processes, heavy-duty and off-road transport, and heating systems of old buildings adding to the use of heat pumps. The actual supply of hydrogen remains limited due to associated high cost, hence, the use of hydrogen should be prioritised to sectors that are difficult to electrify directly.

More stringent climate policy and demand stimulation are the main driving forces behind an increase in hydrogen production and trade, globally. However, local consumption is also an important driver. While Europe is likely to be able to produce a share of its own hydrogen demand, it will need to rely on exporting regions in the coming decades, to meet its decarbonisation goal. Model output points to some minor hydrogen exports from the Middle East and Africa to Europe by 2050. A more significant trading country (both export and import) is China. Thus, a robust European hydrogen import strategy needs to consider factors of sectoral demand pulls, trade in hydrogen-based commodities and trade-relevant infrastructure. Africa does not appear as a strong trading hub, according to model results, due to technical challenges, capacity limitation, and financing gaps. While the production potential is enormous, it requires globally competitive production and export pathways next to national industries that can benefit from local green hydrogen production. A less explored, but potentially interesting option could be the relocation of certain industries (e.g. steel and cement) to hydrogen hubs in Africa, given a safe and competitive environment.

Green hydrogen will remain expensive under baseline conditions but could become competitive with grey and blue hydrogen under strict climate change mitigation policies, demand stimulation measures and enabling supply-side instruments. At the moment, most of the hydrogen is produced from natural gas onsite and used as feedstock rather than as an energy carrier. However, to harness the full benefits of hydrogen in decarbonising the energy system and accelerate the energy transition, low-carbon hydrogen production and trade needs to expand rapidly, which provides an opportunity to renewable resource-abundant locations. Declining renewable energy and electrolyser prices driven by learning coupled with increased load factors for renewable electricity plants and electrolysers push down production cost of green hydrogen. However, under baseline conditions, it remains too expensive to compete with grey and blue hydrogen. Improving the cost competitiveness requires policy backing, including stricter climate change mitigation policies and stimulating not only the production of renewable power and electrolysers, but also green hydrogen demand.

Green hydrogen has the potential to contribute to universal access to sustainable and modern energy in developing countries. Hydrogen could potentially be used to transport renewable energy over long distances from regions with high potential for cheap renewable energy, such as Africa, to regions with limited capacity or higher production costs. Given the high renewable energy potential in Africa, it offers a zero-carbon solution to the intermittency of renewable electricity and enhance access to clean and modern energy contributing to the sustainable development goals and Agenda 2063 aspirations, including climate, economic development, energy security, and energy sovereignty goals. However, the entire supply chain requires substantial development and challenges remain in reducing production costs, scaling up production, transportation and demand creation.

With projected decline in green hydrogen cost under strict climate change mitigation policies, several African countries could attract energy-intensive industries and accelerate industrialisation. The hydrogen economy could enable expansion of energy-intensive industries in aluminium smelting, steel making, fertilizer production, and so on, in addition to decarbonising already existing industry. African countries should not produce green hydrogen solely for export purposes that will lock their industries in fossil fuel technologies and affect the competitiveness of their industries in the global market as well as halt their own energy transition. The cost of energy and fossil fuel feedstocks accounts for the lion's share of total production costs in energy intensive industries. The production costs of ammonia are also dominated by the costs of the feedstock that amount to 70%–90% and could even be higher with strict climate change mitigation measures, forcing industries to look for locations with lower energy prices. The cost of transporting renewable energy or hydrogen is relatively high, which gives areas of significant renewable energy potential a competitive advantage to attract green industries, for both relocations and expansion of existing production capacity. Given these potential outlooks more research is needed beyond the hydrogen value chain towards strategies of hydrogen-based economies in Africa.

Despite the high technical potential and numerous advantages, there are several challenges for Africa to become a major player in the hydrogen market, such as access to affordable finance, technological expertise, infrastructure development, and stable policy frameworks. While abundant renewable energy potential is a necessary condition for a competitive green hydrogen economy, it is not a sufficient one. Larger socio-economic, geopolitical and infrastructure factors also need to be considered. Under business-as-usual trends, Africa will remain a net importer of hydrogen for the growing industrial demand. Even in scenarios where demand for new applications is implemented, the supply remains limited due to the technical and financial challenges of establishing and expanding the hydrogen ecosystem. Several challenges, including policy and technology uncertainty, complexity of the value chain, and lack of regulations and standards, still need to be addressed to harness the full potential of green hydrogen. There is also the need for coherent and transparent rules and standards for production and transport of hydrogen to ensure quality, safety and fair market access. It is imperative that hydrogen export projects demonstrate that they can meet their energy and water requirements from their own facilities and can even contribute to a sustainable resource nexus in the country, especially for the case of water.

Rapid expansion of the hydrogen economy requires substantial investment, access to affordable finance and a long-term commitment, but could kick start the African economy. Establishing a green hydrogen economy could support climate change and socio-economic ambitions in Africa. However, in several African countries, building the hydrogen economy requires the building of the whole new supply chain for electrolysers, renewable energy, conversion, storage and transportation. The high investment requirements of hydrogen production plants, especially when compared to the GDP of several African countries, is one of the obstacles of scaling up hydrogen. Building the hydrogen economy from the ground up will provide employment and significant economic benefits during the construction of the project, its operation, and in associated supply chains as envisioned in Agenda 2063. The opportunity created by green hydrogen has a much larger potential for kick starting the African economy. Expanding the regional industrialisation hubs linked to global value chains is an important goal under Agenda 2063, and it could benefit from a sustainable supply of green hydrogen. Highly capital-intensive in nature, the economic feasibility of green hydrogen projects remains grounded in bilateral and multilateral collaborations, existence of subsidy schemes, potential for industry coupling, and blended finance solutions.

There is investment needed in research, development, and demonstration that could bring down the cost of electrolysers and make large-scale green hydrogen production more competitive. Access to low-cost funding for African countries to strengthen local capacity in research, development and deployment, and creating ownership of projects is crucial for the sustainability of the hydrogen value chain. Green hydrogen technologies are sophisticated and require a high level of industrial know-how for their production, and these technology offers opportunities to specialise national exports and promote further green industrial diversification based on existing know-how. Hydrogen technology is too expensive to demonstrate at commercial scale and its feasibility remains uncertain. Hence, public and corporate funding for research, development and demonstration is of critical importance, in particular in countries with no experience in gas and oil production, since they lack the knowledge and experience related to the required infrastructure, safety measures, storage and transportation. Research and Development is also needed into sensors, testing facilities and certification to avert the risk in hydrogen use. In addition to funding, the role of public institutions extends to harmonising and adapting regulations, codes and standards to facilitate the expansion of the hydrogen economy.

Strategies to export green hydrogen from African countries requires a thorough understanding of the unique context of each country. There are some African countries positioned better to establish a green hydrogen economy. Some of these countries can export large quantities of the green hydrogen while they cover their local energy needs from other sources. Other countries need green hydrogen to fuel green industrialisation and ensure energy sovereignty. In addition, while some African countries have a history with oil and gas production which provides them with suitable and relevant infrastructure, knowledge, and experiences for green hydrogen production, other countries do not share that history and require large investments in building infrastructure and knowledge institutions. The position of the country relative to the European market plays a major role in their potential for exporting green hydrogen as well.

FULL RESULTS

1. Context and aim

This chapter presents background information on the role of hydrogen in the energy system, its opportunities and challenges in the African energy system and the objectives of the report.

The future of hydrogen

More than 190 countries have adopted the Paris agreement, which aims to limit global mean temperature rise to well below 2 °C from pre-industrial levels, and to strive for 1.5°C. The Agreement needs to be implemented at the national level. Many countries have therefore formulated Nationally Determined Contributions (NDCs) and committed themselves to net-zero emission targets. Clearly, high- and low-income countries are in different positions, in terms of historical responsibility, capability to reduce emissions but also priorities. Many low-income countries prioritise access to clean and modern energy to rapidly growing population, to sustain economic growth, to ensure energy sovereignty, and to improve the wellbeing of their citizens. At the same time, many also have joined the pledge to net-zero emission targets making low-carbon energy systems an integral part of the development path. The tremendous progress in renewable energy technologies offers an economically viable alternative to fossil fuels in several industries. However, some sectors require energy system technologies that offer flexibility and interconnectivity without compromising reliability and stability (Quarton, Tlili et al. 2020).

In this context, low-carbon hydrogen could provide value across numerous applications and play a central role in decarbonising the global energy system to reach the net-zero target by 2050. Hydrogen can be applied in various sectors, including energy-intensive industries, transport, and heat and power generation. It can be stored and transported to areas with high energy demand. In addition, hydrogen can be used in fuel cell vehicles, which emit only water, reducing emissions and improving air quality. Hydrogen is also used in the production of ammonia, which is a key ingredient in fertilizers and is critical for the agricultural sector. The increasing share of renewable electricity from solar and wind also makes the case for hydrogen as a storage solution. Hydrogen has a relatively high energy density per mass that can compensate for days of intermittency, can be stored close to the demand node, and is versatile, hence, not restricted to providing electricity back to the grid. In that way, hydrogen inhibits a large potential for power-to-x pathways which implies the usage of surplus renewables for hydrogen production for various target sectors.

The hydrogen industry is well established but at the moment hydrogen is largely made from unabated fossil fuels and consumed in refining and ammonia production and as a feedstock for industrial chemical processes. Clean hydrogen that generates zero emissions at production, on the other hand, is still at a nascent stage but is rapidly developing with possibly a large demand from transport, power and industry, as these sectors strive to decarbonise. There are over 680 large-scale hydrogen projects already announced globally, at a combined investment of USD 240 billion. As an energy carrier, hydrogen can be produced through various methods (IEA 2019). The resulting hydrogen is identified by a range of colours according to the production processes, feedstock and/or energy source (Wappler, Unguder et al. 2022). Related GHG emissions and other environmental impacts vary considerably depending on the production method, particularly when taking the whole value chain of hydrogen production into consideration.

Clean hydrogen, which generates little or no emissions at production, can play a vital role in the transition to a sustainable energy future, particularly in sectors that are hard to decarbonise such as transport, building and industry, and increase energy security by diversifying supply. Therefore, cleanest form of hydrogen will be the focus of this analysis. The production routes are discussed in detail in Chapter 3.

Africa and hydrogen

The current African energy landscape is dominated by biomass and fossil fuels. Access to affordable, clean and modern energy in Africa is one of the biggest challenges that the continent is facing. Addressing this challenge is the priority of several African countries and it is supported by the launching of the Africa Renewable Energy Initiative (AREI) in 2015. The ambition to develop a sustainable energy system by exploiting the abundant renewable energy resources forms one of the pillars of Agenda 2063: 'harnessing all African energy resources to ensure modern, efficient, reliable, cost effective, renewable and environmentally friendly energy to all African households, businesses, industries and institutions, through building the national and regional energy pools and grids, and Programme for Infrastructure Development in Africa (PIDA) energy projects. (AU 2014)'. The falling renewable energy technology costs could accelerate this transition and unlock the vast economic potential through direct electrification of different energy consuming sectors and the coupling of excess renewable electricity Power-to-X technologies, such as power to hydrogen.

Africa could harness its renewable energy resources for clean hydrogen production. Clean hydrogen has the potential to provide a range of benefits to Africa as an export product as well as for the domestic decarbonisation. Regarding export, Europe is among the regions investing most heavily in the process towards net-zero emissions. While hydrogen could play an important role in several scenarios, the capacity to produce hydrogen in many European countries is limited and most of the renewable energy potential will likely be used to produce clean electricity. There is, therefore, a growing interest in Africa's clean hydrogen potential from Europe as a key component of prosperous and stable European–African partnership (AbouSeada and Hatem 2022, AGHA 2022). Given the global energy transition outlook, Africa's clean hydrogen production can play a vital role for improved economic integration and decarbonisation of hard-to-abate industries in other regions. This creates a win-win situation for both exporting and importing countries.

At the same time, hydrogen could also be used for the domestic energy transition in Africa. The role of clean hydrogen in fostering a more robust economy, create jobs, and facilitate universal access to clean and modern energy is also acknowledged in the Africa Strategy of the Netherlands 2023–2032 (The Ministry of Foreign Affairs 2023). Building a strong hydrogen economy in Africa could reduce import dependency, create job hubs and tax revenue, increase electrification rate, reduce air, soil and water pollutions, improves water access if coupled with desalination plant, and reduce deforestation contributing to several sustainable development goals and to the key transformational outcomes envisaged in Agenda 2063. The advancement of clean hydrogen infrastructure through systemic reforms can contribute to food security (SDG2 and SDG3), foster resilient, inclusive, and sustainable industrialisation and innovation (SDG 9), improved opportunities for equitable livelihoods (SDG 8), decreased inequality (SDG 10), and the promotion of sustainable cities and communities (SDG 11) (Trüby, Douguet et al. 2023).

Goal of the report

The report is prepared at the request of the Directorate-General for International Cooperation (DGIS) of Dutch Ministry of Foreign Affairs. The objective of the report is twofold: 1) to explore the techno-economic opportunities and challenges of establishing a clean hydrogen economy that could accelerate the socio-economic development of African countries, and ii) to analyse the potential to establish a collaboration on clean hydrogen between Europe and Africa for mutual benefit. To address these objectives, we formulate three main research question divided into sub-questions:

1. What is the role of hydrogen in the future energy system?
    a. What is the role of hydrogen in the global energy system?
    b. What is the role of hydrogen in the African and European energy system?
2. What are the opportunities and barriers of establishing a clean hydrogen economy in Africa?
    a. What are the driving forces for a clean hydrogen economy in Africa?
    b. What are the barriers for establishing a clean hydrogen market in Africa?
    c. What are the opportunities for and benefits of establishing a clean hydrogen economy in Africa?
3. What is the potential for collaboration on clean hydrogen between Africa and Europe?

The report presents a scenario-based analysis of the opportunities and challenges of the hydrogen economy with the help of an integrated assessment model complemented by desk study and expert interviews. However, the use of models has its limitations as uncertainties in scenario development and model projections are inevitable. These uncertainties arise from incomplete data, methodological uncertainties, uncertainties in future scenario drivers that could affect the transition, and uncertainties from levels of aggregation within the model. Despite these limitations, the study does provide policy-relevant insights to guide the development of clean hydrogen economy in Africa by providing quantitative analysis of various interactions in the energy system. The results of this study also show the critical role that clean hydrogen could play in achieving sustainable development goals and Agenda 2063. The scenario implementation also does not cover the governance challenges and other technological barriers. However, part of the challenge is addressed in the report through desk study or expert elicitation.

Structure of the report

Chapter 2 describes the methods used in this study, including list of interviewed experts, model description and scenario choices. The technical and economic requirements and limitations of clean hydrogen are presented in Chapter 3. Chapter 4 addresses the cost of hydrogen production, the role of hydrogen in final energy mix, and its trade potentials and barriers based on a set of scenarios. European and African hydrogen policies and projects are reviewed in Chapter 5. The chapter also assess inclusiveness and just transition components of the hydrogen economy in Africa. Expert views on the role of hydrogen in the European energy system and the African European relationships in the context of hydrogen import and export are also included in Chapter 5.

2. Methods and tools

This chapter presents the methods and tools used for the study. It describes the tools and explanation of the scenarios and justification for the choice of scenarios. The section also presents assumptions behind the scenarios and possible policy measures. Complementary information can be found in the appendix.

2.1. Desk study and expert elicitation

This study is mainly based on scenarios analysis with the help of IMAGE modelling framework discussed below. The method also includes desk study to explore hydrogen-related technologies, policies and projects. Desk review has been conducted to collect data on various aspects of the hydrogen value chain and other future projections from research and policy organisations including peer-reviewed articles, manuals, reports, data bases, policies, regulations, and standards.
The results from desk study and model projections were supported by interviews with key stakeholders from several organisations. Expert elicitation is especially important in this study to explore possible future trajectories of the hydrogen economy as there is insufficient track record for large-scale deployment at the moment. It is also a way of evaluating the choices made in the modelling exercise and scenario designs. The interviews were conducted between August and October 2023. The list of interviewees is presented in the appendix.

2.2. Model

IMAGE (Integrated Model to Assess the Global Environment) integrated assessment modelling framework is used in this study. It is a useful tool to explore the interlinkages between society, the biosphere and the climate system to assess sustainability concerns such as climate change and biodiversity. The model framework provides a thorough depiction of the energy and land-use system, simulating key socioeconomic parameters for 26 global regions. Important inputs to the model are future developments of population, the economy, lifestyles, policies, and technology change. The strength of the IMAGE modelling framework is that it allows looking at the various aspects related to the energy transition in an integrated way, including modern energy demand and supply, and energy-related greenhouse gas emissions. The IMAGE model framework encompasses the TIMER energy-system simulation model (van Vuuren, van Ruijven et al. 2006). TIMER is designed to allow modelling long-term trends in energy consumption and generation and associated greenhouse gas (GHG) emissions (Daioglou, van Ruijven and van Vuuren 2012, van Ruijven, Schers and van Vuuren 2012, Dagnachew, Lucas et al. 2017). The model can be used to make projections about future energy demand, energy mix, and associated investment needs either under given scenario assumptions or for achieving specific goals. End-use energy demand is related to economic activity in industry, transport, residential, services and other sectors. The model is based on a temporal unit of years and a spatial resolution of 0.5° x 0.5° grid cells.

The hydrogen module covers the production, demand, infrastructure and technology dynamics of hydrogen-related technologies. The production costs are determined from three components where relevant: capital costs, fuel costs and CO_2 capture and storage costs. The total cost of delivering hydrogen to the end user include the production costs, the end-use capital cost, and infrastructure costs. Technology progress for hydrogen production is simulated by learning-by-doing curves whereby the cost decreases as a function of increasing global cumulative production capacity. The relative differences between the energy service costs of hydrogen and other energy carriers determine the market share of hydrogen (van Ruijven, van Vuuren and de Vries 2007). Hydrogen production technologies considered in this study are:

- Coal gasification with and without CCUS
- Steam methane reforming (natural gas) with and without CCUS
- Partial oxidation of heavy hydrocarbon (Oil) with and without CCUS
- Electrolysis of water with various sources of electricity
- Biomass gasification with and without CCUS

2.3. Scenarios

Scenarios are an essential part of climate change-related research. These scenarios can address the uncertainties surrounding the socio-technical evolution of energy system. This report presents the result of several scenarios based on the two Shared Socioeconomic Pathways, as implemented in IMAGE (van Vuuren, Riahi et al. 2017). These are pathways built by an international team of climate scientists, economists and energy systems modellers to examine how global society, demographics and economics might change over the next century (Riahi, van Vuuren et al. 2017). The SSPs depict five unique global socio-economic pathways outlining the future evolution of significant societal aspects, presenting a range of challenges for climate change mitigation and adaptation (Riahi, van Vuuren et al. 2017, van Vuuren, Riahi et al. 2017). The drivers of energy demand addressed in SSPs include population growth, economic development, rate of technology change, and urbanisation rates.

In this report we focus on SSP1 that describes a pathway toward a more sustainable world emphasising more inclusive development that respects perceived environmental boundaries, and SSP2 that describes a world where social, economic, and technological trends do not diverge significantly from historical patterns. The choice of the two groups of scenarios allows to cover two distinct population, GDP, and technological developments. In IMAGE, SSP1 and SSP2 reference scenarios are the bases for analysing the impact of climate change mitigation policies and associated changes in the global energy mix. Within these two socio-economic pathways, we explore the role of hydrogen under different level of stringency of climate change mitigation policies, varying demand for hydrogen outside of the traditional sectors, and differing roles of carbon capture technology in the energy system. Table 1 presents the description of the scenarios as implemented in this report.

Table 1: Description of scenarios

Scenario name	Description	Temperature target
SSP2 baseline	Middle of the Road scenario of the Shared Socioeconomic Pathways (SSPs), following historic trends.	None
SSP2 2-degree	Middle of the Road scenario reaching a 2.6 W/m2 radiative forcing level in 2100 by applying a cost-optimal carbon price	Compatible with 2 °C above pre-industrial level by 2100
SSP2 1.5-degree	Middle of the Road scenario reaching a 1.9 W/m2 radiative	Compatible with 1.5 °C above pre-industrial level by 2100

Scenario name	Description	Temperature target
	forcing level in 2100 by applying a cost-optimal carbon price	
SSP1 1.5-degree	Sustainability scenario reaching a 1.9 W/m2 radiative forcing level in 2100 by applying a cost-optimal carbon price	Compatible with 1.5 °C above pre-industrial level by 2100
SSP1 High hydrogen demand (SSP1 HHD)	Sustainability scenario reaching a 1.9 W/m2 radiative forcing level in 2100 in which the demand for hydrogen is increased for the industry and transport sector. In addition, (green) hydrogen production and trade follow more optimistic cost developments	Compatible with 1.5 °C above pre-industrial level by 2100
SSP1 Limited Carbon Capture and Storage (SSP1 LimCCS)	Sustainability scenario reaching a 2.03 W/m2 radiative forcing level in 2100 in which we limit the use of CCS to ~0.37 $GtCO_2$ per year in 2030, ~1.8 $GtCO_2$ per year in 2040, ~5.5 $GtCO_2$ per year in 2050 and ~7.3 $GtCO_2$ per year in 2100.	Slightly above 1.5 °C above pre-industrial level by 2100

2.4. Assumptions

The general population, GDP, and technological assumption for all scenarios are in line with the SSP projections as implemented in IMAGE. For the two scenarios that specifically look at demand side stimulation for hydrogen and limit the availability of CCS, we have additional assumptions as presented in Table 2 and Table 3. In the SSP1 HHD scenario, (very) optimistic assumptions on technology (cost) development are combined with policies to stimulate the use of hydrogen in the different demand sectors. This scenario can be considered a sensitivity experiment, to see how far hydrogen can be pushed in the IMAGE model. In Table 2, the implemented assumptions and measures are summarised.

Table 2: Assumptions in SSP1 HHD scenario

Sector	Scenario assumption	Possible policy measures
Transport	- Hydrogen targets for new vehicles in shipping and air transport have been added. The share of hydrogen in final energy demand grows to 50% in the aviation sector and to 50% in the shipping sector by 2070.	- Carbon price, other taxes and levies to fossil fuels - Climate goals to reduce greenhouse gas emissions - Low-carbon and/or renewable hydrogen capacity targets, emission reduction and intensity targets - Building and expand refuelling stations - Set CO_2 targets for new vehicles
Industry: cement, food processing,	- For these sectors, a premium factor to stimulate the use of hydrogen has been added	- Carbon price - Direct fiscal incentives for hydrogen investment

Sector	Scenario assumption	Possible policy measures
paper and pulp and other industry		- Offer tariffs, premiums and subsidies - Low-carbon and/or renewable hydrogen capacity targets, emission reduction and intensity targets
Industry: iron and steel	- From 2040 onwards only new hydrogen steel plants are allowed	- Carbon price - Bans and mandated phase-out of fossil-related activity - Low-carbon and/or renewable hydrogen capacity targets, emission-reduction and -intensity targets
Hydrogen	- Increasing share of hydrogen allowed into the existing natural gas grid: 5% in 2030, 25% in 2050 and 50% in 2100	- Carbon price - Clear long-term policy - Offer feed-in premiums and tariffs, and subsidies - Long-term contracts, binding quotas - Clear regulatory framework for hydrogen
	- 20% higher learning rates[1] to simulate additional efforts in reducing costs by e.g. increasing R&D budgets, which leads to decreasing capital costs faster when new capacity is installed	- Carbon price - Expedite planning & permitting processes - Offer affordable finance - Public support for research and development, and multilateral collaborations - Skilling and reskilling programs
	- A decrease in floor costs of 25% for all hydrogen supply technologies	- Carbon price - Fiscal incentives for electrolyser investment - Support scale-up of electrolyser production capacity - Set minimum electrolyser capacity targets - Offer tariffs, premiums and subsidies - A competitive price mechanism (auction)
	- More optimistic cost assumption for hydrogen trade	- Bilateral and multilateral trade agreements for hydrogen
Electricity	- The floor costs for non-biomass renewable energy technologies are set to 0. This is an optimistic assumption with regards to renewable cost development.	- Carbon price - Set minimum renewable capacity targets - Dedicated financial support

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[1] *Learning rate is directly changed to simulate the impact of all kinds of policies that might have impact on the learning rate.*

Sector	Scenario assumption	Possible policy measures
	Electricity sector renewables are also used in the hydrogen sector in combination with an electrolyser to produce hydrogen	- Low-carbon and/or renewable hydrogen capacity targets, emission reduction and intensity targets
Other	- Learning rates of non-biomass renewables have been increased with 25% in order to achieve faster costs reductions	- Public support for research and development, and multilateral collaborations

Similarly, in the SSP1 LimCCS scenario, the use of CCS is capped for the different energy sectors. Table 3 below shows the global CCS cap per year for SSP1 LimCCS scenario, the default CCS potential for other scenarios is based on Hendriks, Graus and Van Bergen (2004). Under SSP1 LimCCS scenario, the cap starts low in 2030 but is allowed to slowly increase towards 2100. Although this scenario does result in a substantial reduction of CCS use, it also results in a slight increase in global warming compared to the 1.9 W/m^2 radiative forcing goal in other scenarios.

Table 3: CCS availability assumption in the SSP1 LimCCS scenario

Year	CCS potential cap in LimCCS scenarios (in GtC)
2030	0.1
2040	0.5
2050	1.5
2100	2.0

3. Technical and economic considerations of clean hydrogen production in Africa

This chapter presents the options and requirements for the production, transport and storage of clean hydrogen with a focus on Africa. Understanding the possible production routes and inputs for hydrogen production is important to quantify the opportunities and challenges of establishing a green hydrogen economy. Critical determinants of green hydrogen production include the availability of renewable energy, water availability, land availability, availability of transport infrastructure and export paths to large demand centres. Overall, electricity costs present the single largest cost component in hydrogen production. This offers a grand opportunity to countries with abundant renewable resources and access to water to become players in the hydrogen economy by exploiting their competitive advantages.

3.1. Hydrogen production routes

Hydrogen is non-toxic, tasteless, colourless, odourless, and highly flammable under standard conditions. The lion's share of current hydrogen production is fossil-fuel based, either through steam methane reforming (SMR) of natural gas or coal gasification, while the share of hydrogen produced from renewable energy is negligible (IEA 2022). Hydrogen is used almost exclusively as a feedstock, and it is produced and consumed mostly on-site. The biggest share of hydrogen demand in industry comes from the production of ammonia largely used for fertilizer production, which accounts for around two-thirds of the industrial hydrogen demand.

Total global hydrogen production in 2021 reached 94 million tonnes (Mt), 62% of which is produced from natural gas without carbon capture, utilisation and storage (CCUS), 19% from coal, and 18% produced as by-product of naphtha reforming at refineries (IEA 2022). Currently, most of the hydrogen is used in petroleum refining and fertilizer production.

Hydrogen is the most abundant element on earth, but it is almost always found as part of another compound, such as water or methane. For use as an energy carrier, it has to be separated into pure hydrogen. There are various ways and processes of producing hydrogen from diverse resources, including fossil fuels, biomass, and water electrolysis with electricity. Here we briefly discuss the most common resources and processes.

Grey hydrogen

The most dominant production pathway currently is a reforming or gasification process based on fossil fuels. As it is currently the most cost-effective production method, it makes up 80% of today's total hydrogen production with a high emission intensity. Its first method of Steam Methane Reforming (SMR) uses high temperature steam (700–1000 °C) and methane sources, such as natural gas, which under a high pressure and heating process results in carbon dioxide (CO_2) and hydrogen. Natural gas so far has a high suitability given its availability and transportability.

Coal gasification (also known as brown hydrogen) takes raw materials like coal in combination with air, steam or oxygen which is resulting in syngas. Subsequently, it usually takes several gas clean-up processes to obtain pure hydrogen (Arcos and Santos 2023), releasing CO_2 in the process. Grey hydrogen is dominantly used in petrochemical industries and for ammonia production.

Hydrogen production through reforming and gasification can emit substantial GHG emissions from the production as well as from upstream and downstream components of the hydrogen value-chain. The life cycle emissions depend on how hydrogen is produced, transported, and used. The life cycle emission of grey hydrogen with natural gas SMR in Shanghai, for instance, is estimated to be around 13 Kg CO_2-eq per kg H_2 of which nearly 9.2 Kg CO_2-eq is during production (Zhou, Zhang and Li 2022).

Blue hydrogen

This pathway produces hydrogen by steam methane reforming with carbon capture utilisation and storage (CCUS), using natural gas or biomass, making it much more environmentally friendly as the CCUS serves as an additional purification stage. There are several possible CCUS methods at pre- or post-combustion level, based on biological, physical and chemical methods. It thus transforms the prior energy-intensive grey hydrogen production into a net-zero process (Arcos and Santos 2023).

The technology can capture up to 90% of the CO_2 emission produced, but still has substantial fugitive methane emissions from producing and transporting of natural gas and additional emission from energy used for the CCUS plant (Ajanovic, Sayer and Haas 2022). However, it is currently still more cost-effective than green hydrogen, hence the preferred option as a transition technology, especially for fossil-fuel producing countries. Usually, the CO_2 is then transported and stored underground, primarily in salt caverns or depleted oil and gas reservoirs. There are still several concerns about the use of CCS related to long-term storage of the captured carbon, cost uncertainties, and limited economies of scale that could limit deployment.

Green hydrogen

Green hydrogen counts as the cleanest, no-carbon hydrogen during production by using water electrolysis with electricity from renewable energy sources (Arcos and Santos 2023). It accounts for a very small fraction of current hydrogen production. The electrolysis process includes one of the four main technologies: alkaline water electrolysis (AWE), proton exchange membrane (PEM), solid electrolysis cell (SOEC), or anion exchange membrane (AEM). The AWE technology is so far the most tested and cost-effective one. Amongst the renewable energy sources, wind and solar power take the largest shares, while hydropower is increasingly being considered, as well (Arcos and Santos 2023). For wind energy, both on- and off-grid connected options can be used as input to water electrolyser. Life-cycle emissions of green hydrogen with renewable electrolysis in Shanghai is estimated at around 2 Kg CO_2 eq per kg H_2 with zero emission during the production (Zhou, Zhang and Li 2022).

3.2. Biophysical resource constraint of green hydrogen production

As the main inputs to the production of green hydrogen, renewable energy and water availability become the key technical factors to consider for geographical suitability of regions. This section discusses the availability of these key inputs for green hydrogen in Africa.

3.2.1. Renewable Energy

Africa has large land mass and considerable renewable energy potential. Most of the renewable potential exist particularly for North and South West Africa (Republic of South Africa and Namibia) for both solar and wind energy, see Figure 1 (AGHA 2022). Moreover, some more potential for wind energy generation is located in East and West Africa along the coastlines (IRENA 2021). These projections give only the technical/theoretical potential and leave other socio-economic and biophysical factors out of the analysis. For instance, it is not likely that solar power can be produced at a commercial scale in the middle of the Sahara Desert. Nevertheless, it is promising that the technical renewable energy potential is more than 1,000 times larger than projected energy demand in 2040. Hence, even with more limitations on actual renewable energy generation there is likely to be sufficient capacity for local and export demand of green hydrogen.

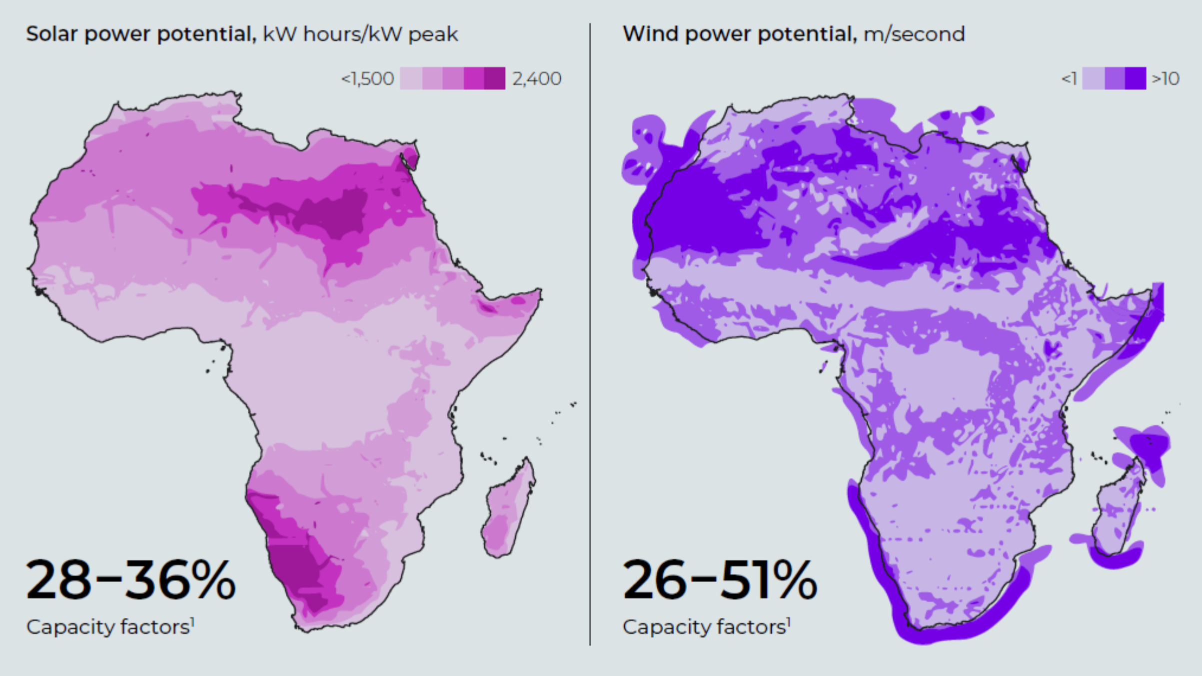

Figure 1: Renewables potential in Africa (AGHA 2022)

Several countries in North, West and Southern Africa receive an average annual solar irradiation in excess of 2100 kWh/m^2 (IRENA and AfDB 2022). Assuming a 1% land-utilisation factor, IRENA and AfDB (2022) estimate the total solar technical potential and the wind technical potential in Africa at 7900 GW and 461 GW, respectively. Africa's unexploited hydropower potential is estimated at 1753 GW (Hoes 2014), with most of the potential located in Angola, the Democratic Republic of the Congo, Ethiopia, Madagascar, Mozambique and Zambia. In addition, there is estimated 15 GW of geothermal resource found in the East Africa Rift System. The hydropower and geothermal potential can be exploited to provide a very stable electricity supply at high full load hours for hydrogen production.

3.2.2. Water requirements and availability

Water is a necessary condition for sustainable development. Unfortunately, water-related crises exist across the globe. In the report 'Future Water Challenges; Bending the Trend', Ligtvoet, Bouwman et al. (2023) explain that pressures on water systems are expected to increase in the coming decades. This is driven by factors such as population and economic growth and the demand for water in agriculture, industry and energy systems, as well as climate change (both gradual climate change and extreme events). In this context, it is urgent to rebalance the impact of human use and the functioning of such water systems. These water systems and their functioning are essential to achieving each of the SDG's, including affordable and clean energy (SDG7).

Much like electricity from renewable sources, water is a necessary input in the production process of green hydrogen. The impact of water consumption can be location specific. For illustrative purposes and from a technical perspective, water for the green hydrogen production is conceptualised as having a demand side and a supply side.

- On the demand side, the concern is about the quantity of water of sufficient quality that is required for this process (Farràs, Strasser and Cowan 2021).
- On the supply side, the focus is about the quantity of water of sufficient quality that is available for this process.

In areas in which water systems are or will be under pressure, it can be assumed that different water uses co-exist (e.g., for agriculture) and possibly compete, and as a result, only a fraction of the water present in the area might be available for green hydrogen production. Therefore, water supply available for green hydrogen production could severely limit production potential.

Demand

Regarding the demand side, there are different estimates of the total requirement of water for the production of green hydrogen, with a theoretical minimum of 9 kg water for every kg of hydrogen produced (Beswick, Oliveira and Yan 2021). Estimates vary according to the technology. Production with bioenergy requires low amounts of water while solar PV and wind require slightly higher amounts of water. Concentrated solar power (CSP) requires considerably higher amounts due to the extra water required for the operation of the CSP (Mukelabai, Wijayantha and Blanchard 2022). Moreover, estimates vary according to the scope of the analysis; namely, lifetime or life cycle. A study on Australia's hydrogen production and water requirements indicates roughly 15 kg of water as a required input for 1 kg of hydrogen (this includes water feedback mechanisms after purification) (Woods, Bustamante and Aguey-Zinsou 2022). Based on the study's number, with a forecasted global hydrogen production volume in 2050 of 530 Mt per year, the water requirement would be close to 30,100 litres of water per year. In contrast, the estimate from an analysis based on life-cycle assessments of solar-to-hydrogen water usage is around 43 litres per kg of hydrogen, a third of the average water requirement of extraction and refining of oil (Woods, Bustamante and Aguey-Zinsou 2022).

Supply

Regarding the supply side, a significant challenge that potential hydrogen production in Africa faces is the match between potential renewable electricity production and water stress. The regions with the highest potential for renewable electricity production tend to be the regions that are the most water stressed (Woods, Bustamante and Aguey-Zinsou 2022). While the water volumes estimated for the demand side of the process might appear moderate compared to other sectoral water requirements, these numbers gain a different meaning in the light of present and future water challenges in potential production locations. When coupling the growing's population demand for clean drinking water with the demand side of green hydrogen production, results show that especially North and Southern African countries would become (even more) water insecure. This is demonstrated by Figure 2 that shows the impact of hydrogen production on country level water availability assuming that all of the solar PV, wind, CSP, and bio-exploitable potential energy is utilised for the production of hydrogen (Mukelabai, Wijayantha and Blanchard 2022).

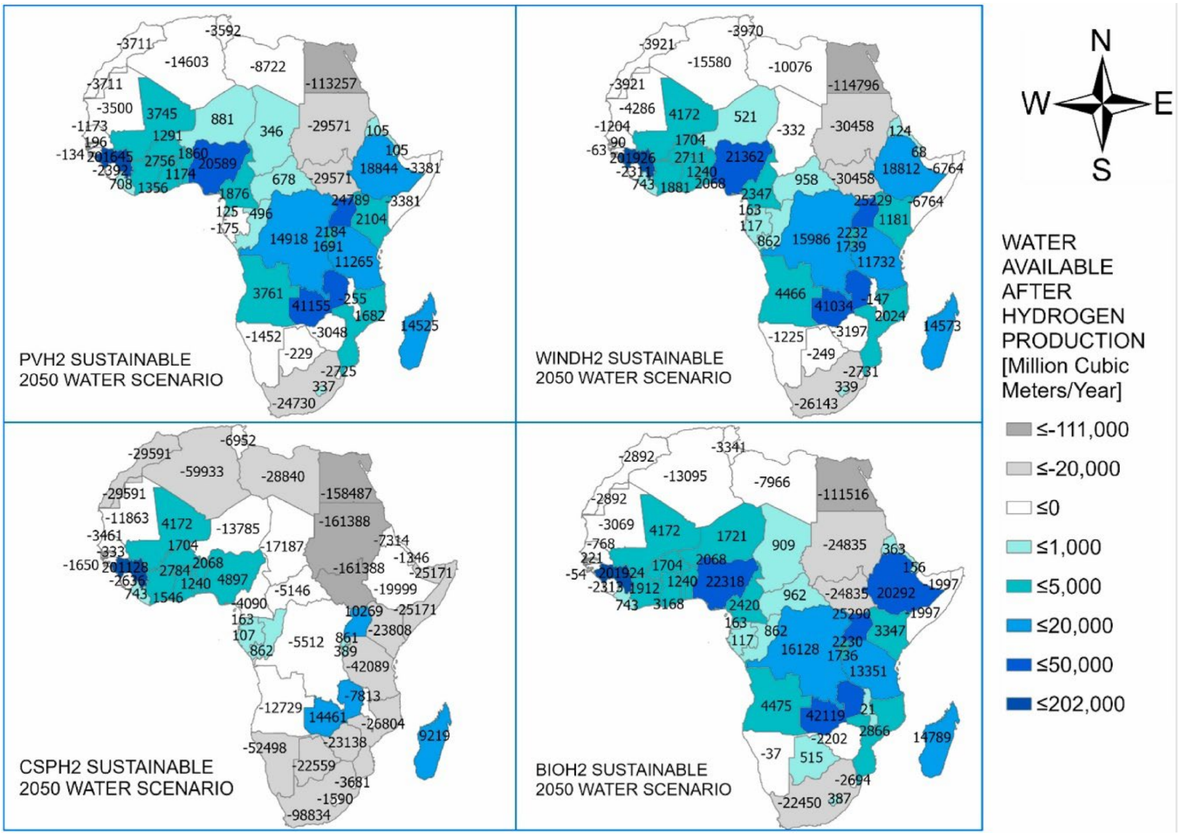

Figure 2: Country water availability scenario after hydrogen production with solar photovoltaic (PVH_2), concentrated solar power (CSPH_2), wind (WINDH_2), and bioenergy (BIOH_2) (Mukelabai, Wijayantha and Blanchard 2022)

There are different and complementary options to address these water-related challenges of green hydrogen production. These options range from technological innovation and application, from a demand and supply perspective to the governance of valuation and evaluation of water-related projects and plans.

Firstly, two examples of technological innovations and applications are the combination of sea water desalination with electrolysis and the use of tertiary effluent water. By using sea water to produce fresh water, desalination can reduce the demand for fresh water for the production of hydrogen. Some studies have explored the option to combine reverse osmosis, the most common method of desalination, with electrolysis; however, estimates of potential costs differ. Khan, Al-Attas et al. (2021) found the capital and operating costs of reverse osmosis to be negligible relative to the cost of commercial water electrolysis; namely, reverse osmosis increases the levelised cost of hydrogen by less than USD 0.1 per kg H_2. IRENA (2022) estimates the cost of reverse osmosis at around USD 1 per cubic meter of water, which adds up to less than 0.5% to the total cost of hydrogen production with electrolysis. Woods, Bustamante and Aguey-Zinsou (2022) assume a two-step treatment process which increases the desalination cost to 5% of total hydrogen cost (USD 2 per kg H_2).

Similarly, tertiary effluent water could in theory be used for hydrogen production. On a global level there is more than ten times the availability of wastewater than what would be required for hydrogen production (Woods, Bustamante and Aguey-Zinsou 2022). However, the technical suitability of tertiary effluent water is still undergoing testing. Furthermore, the potential to use tertiary effluent water from less efficient wastewater treatment systems, including from developing regions in Africa, remains uncertain.

Secondly, from a demand–supply perspective, the conceptualisation of water as an input to green hydrogen production helps illustrate the physical water inflow needed for the production process. However, beyond the production process, water is an essential component of global ecological systems, ecosystem (services) and societies. The 2021 UN World Water Development Report (WWDR) on Valuing Water (United Nations 2021) made explicit that water has many uses and many users. Similarly, water inspires and represents rich and sometimes contrasting values.

The 2021 UN WWDR (United Nations 2021) highlights that the energy, industry and business (EIB) sector tends to pay more attention to savings in the operation phase and to revenue impacts, with less attention being direct to the value of water in administrative costs, natural capital, financial risk, future growth and operations, and innovation. Interestingly, also in the private EIB sector, there are significant additional costs, lower earnings, and financial losses related to water risks. The report also points out that water-related metrics that are frequently used in the sector are relatively simple, such as units of currency per m^3, but there are also other aspects that are not easy to quantify or are not exclusive to water, such as the value of water to different stakeholders, job creation or new enterprises. Overall, there are many different methods for valuing water from different perspectives, and alignment between the EIB sector and integrated water management and broader planning efforts is crucial.

The need to recognise, make explicit, and incorporate the values of water in decisions and decision-making processes across sectors, continues to gain international momentum. The 2021 UN WWDR is an example hereof. So is the appointment and latest report of the Global Commission on the Economics of Water (GCEW) (GCEW 2023), the GCEW was established in May 2022 at the initiative of the Government of the Netherlands, from its role as co-host of the United Nations 2023 Water Conference.

In its latest report ‘Turning the tide’ (GCEW 2023), the GCEW argues that a sustainable and just water future requires transforming the economics and restructuring the governance of water. The report’s key points are relevant for green hydrogen production in Africa. Amongst other points, the GCEW argues that the global water cycle must be managed as a global common good; water is underpriced and proper pricing with targeted support is needed; reducing water footprints in manufacturing is necessary, and that multilateral governance of water must be reshaped. All these points highlight challenges that the dawn of a green hydrogen economy would face, but also the wealth of opportunities for intersectoral work in sustainability transitions that are inherently intertwined.

In ‘Future Water Challenges; Bending the Trend’, Ligtvoet, Bouwman et al. (2023) present conclusions in line with the 2021 WWDR and the GCEW’s report. Bending the trend of water-related challenges requires increasing urgency, innovative approaches, and improving global governance. The recommendations of the report, which are relevant for a green hydrogen economy, include that the importance and pivotal role of water needs to be recognised, water-related systems need to be valued with a broader scope, and that a new logic for decision-making is necessary.

To summarise, green hydrogen production is one of the alternatives that could advance the energy transition. The assessment and planning of green hydrogen production in Africa, and the potential dawn of a hydrogen economy, offers opportunities to integrate energy and water systems. Integrating the energy and water systems in a sustainable way requires recognising, making explicit, and incorporating the values of water in decisions and decision-making. To do this, intersectoral work at the nexus of water and energy will be crucial.

3.3. Hydrogen storage options

A safe, efficient and economical storage of hydrogen is one of the most important challenges to realising the hydrogen economy. Hydrogen production today is largely done with small-scale SMR and small-scale electrolysis close to where it is being used. As its share in the global energy system increases, hydrogen will not be produced on-site but at a central station and it will be stored either at the production site for further end-use distribution or once it has been delivered to the end user. Hydrogen has a very low density which makes large scale storage challenging and costly. The storage methods for hydrogen can be divided into two groups: physical hydrogen storage and chemical hydrogen storage. The former includes compressed gaseous hydrogen, liquid hydrogen or cryo-adsorption on high surface area material. Chemical storage processes encompass liquid organic hydrogen carriers (LOHCs) and metal hydrides among others. The encompassing problem for both hydrogen storage and transport is its low volumetric energy density and also its ability to permeate metal-based materials (Hren, Vujanović et al. 2023). The suitability of the storage technology is determined by various factors including the use, the volume of hydrogen to be stored, the duration of storage, the required discharge rate, and the local availability of storage options (Pérez 2022).

Physical hydrogen storage technology has an advantage of being low-cost, easy to discharge and can store large volumes hydrogen, however there is a concern about safety. The simplest and more proven method is physical storage in high-pressure and cryogenic tanks as it also allows for the repurposing of existing gas pipeline networks, next to vessel transport (Hren, Vujanović et al. 2023). This process of storage involves no strong chemical bonds between the hydrogen and the host compound. The physical storage of hydrogen in gaseous form is the most mature method and is employed in most fuel-cell powered cars (Eberle, Felderhoff and Schuth 2009). However, the density of this storage is relatively low compared to other techniques of hydrogen storage. The density of liquid hydrogen is very high, but the storage technique requires 25%–45% of the stored energy to liquify the hydrogen (Krishna, Titus et al. 2012). For small storage volumes, tanks or vessels could be used, while geological storages (such as salt caverns, depleted natural gas and oil fields, and aquifers) are more suitable for large amounts depending on the volume to be stored, the duration of storage, the required speed of discharge, and the geographic availability of different options (IEA 2019).

Chemical storage is seen as the safer option as it works with lower pressure levels but there are concerns about the slow discharge and impurity due to by-products. It is also limited in its transport options to mostly road, hence, cannot deliver hydrogen to far and high demand centres. Moreover, LOHCs induce significant, additional environmental footprints in its transformation steps. One of the popular hydrogen carriers is ammonia which can then be transported in pipelines and tanks. Its decomposition into pure hydrogen is however a highly energy-intensive process (Hren, Vujanović et al. 2023).

Analysing the environmental impact of the full hydrogen supply chain has yet received little attention, compared to techno-economic assessments of hydrogen production. One of the few studies conducting a Life-cycle analysis (LCA) of hydrogen production, storage and transport found gaseous hydrogen transported in pipelines to have the lowest Greenhouse gas (GHG) footprint, followed by liquid hydrogen transported by road (Hren, Vujanović et al. 2023). The environmental footprint of hydrogen gas increases in its pressure levels, however, remains far below the chemical process of liquifying it.

As one of the most cost-effective and accessible option, hydrogen storage in salt caverns has been studied most extensively globally. Based on this, hydrogen storage potential of salt caverns in Africa has been located in North and Southern Africa (van Wijk and Wouters 2021, Epelle, Obande et al. 2022). However, significant data gaps exist in determining location-specific volumes of hydrogen in salt caverns and its linkage to production locations and trading pathways. In particular, Morocco and Algeria show considerable salt cavern storage potential. While Morocco has been pushing the development of some sites for LPG storage, Algeria still requires further testing of sites in terms of cavern quality and depth (Braun, Frischmuth et al. 2023).

The currently most dominant chemical storage option in Africa is ammonia. It comes with the advantage of having several end uses besides hydrogen storage, such as fertilizer input, industry applications and transport fuel. Few studies have analysed the potential of (green) ammonia production in Africa based on cost projections and show regions in Northern and Southern Africa as especially suitable for ammonia production (Galimova, Fasihi et al. 2023), Initiatives like the East African Green Hydrogen and Fertilizer Corridor aim to develop renewable hydrogen and ammonia production in Southern and Eastern Africa[2]. This further opens up opportunities to leverage hydrogen storage potential in Africa and develop its trading hubs.

3.4. Innovation potential

Most of the decrease in future costs of hydrogen production is related to electrolysers, where the operating price is expected to decline sharply through improvements in efficiency, an increase in the number of load hours, a longer lifetime, a lower weighted average cost of capital (WACC) and lower operational and maintenance costs (Cammeraat, Dechezleprêtre and Lalanne 2022). Achieving this level of cost reduction requires research and development, scaling up, and learning-by-doing. Patent data is commonly used as a proxy measure of innovative activities, especially when it comes to climate change mitigation technologies. The data provides ample information the nature of the innovation, the patent applicant, and the location of innovation(Cammeraat, Dechezleprêtre and Lalanne 2022).

Countries leading in hydrogen innovation activity, measured by hydrogen patent developments, are by far China, followed by Japan, the United States, Korea and Germany. Among them, private enterprises were the largest recipient group against universities and research institutions (Delaval, Sharma et al. 2022). In contrast, IEA calculations of international patent families (IPFs) show that the European Union, Japan and the United States are leading in the overall patent development for hydrogen while China is far off. Europe and Japan then also stand out as regions that push patents

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[2] *Renewable ammonia & fertilizers in Sub-Saharan Africa – Ammonia Energy Association*

across the whole hydrogen value chain (IEA 2023). While Japan, Korea and the United States have a higher number of patents related to fuel cells, the European Union shows a stronger focus on hydrogen production and storage (Cammeraat, Dechezleprêtre and Lalanne 2022). The difference in country performance across patents and international patent families can be understood as IPFs include several patent applications relating to one innovation in several countries. These higher quality patent groups are still less developed in China and point to the differences in R&D funding strategies in green hydrogen as compared to Europe or the United States (Brown and Grünberg 2022). The number of single patent application in China surged in the past decades and are much higher than in Europe and the United States.

In overall hydrogen-related R&D spending, China is also strongly catching up and has increased its public spending sixfold between 2018 and 2019. This means it surpassed the joint United States and European Union volumes in this area. Moreover, part of its innovation strategy is the active support to consortia of universities, companies and international institutions (Brown and Grünberg 2022). Focal area of public funding is the development of electrolyser technologies contributing to a growing electrolyser market and business development along the full green hydrogen supply chain in China. For Europe, innovation in present hydrogen technologies happens predominantly in the chemical industry while for new technologies the automotive and chemical sectors are leading, focusing on electrolyser technologies (IEA 2023). Hence, it is likely to see extensive electrolysis manufacturing capacities developing within Europe in the coming years.

In Africa, South Africa launched the green hydrogen (GH_2) Research, Development, and Innovation strategy in 2008. This strategy stimulates and guides innovation along the hydrogen value chain and fuel cell technologies primarily driven by the government and in collaboration with research institutions and industry (GIZ 2016). There is, however, lack of sustainable funding and training and development on new and advanced technologies. Moreover, Morocco was the first African country to develop a R&D and innovation platform named ‘Green Hydrogen and Applications Platform — Green H2A’ (Mission Innovation 2023). One of its first activities evolved around pilot projects on green ammonia, led by a major Moroccan fertilizer company. In addition, the government liaised with IRENA on advancing green hydrogen studies and policy analysis in the country (Stouky 2022). Egypt follows to a lesser extent by setting up various pilot projects in the transport sector or on electrolyser development, mostly in cooperation with European companies (Stouky 2022). Moreover, South Africa and Egypt are setting examples by anchoring their research programmes also in their national universities to secure technical knowledge creation and learning. These country examples show that the research and development landscape in Africa is much more shaped by private actors and lacks major public financing, as in China or the European Union. Hence, strategic linkages between the governments, private companies and potential foreign direct investment will be key.

3.5. Logistics & trade paths

The cost and safety of the transportation of hydrogen from the production site to the end-use location are critical economic determinants due to its high diffusivity, extreme low density as a gas and liquid, and its broad flammability range (National Academy of Engineering 2004). Hydrogen can be stored and transported in various forms. Large industries in Europe and the United States transport large quantities of hydrogen through pipelines over long distances of 1100 km to 1600 km and there are smaller pipeline networks in South America, Asia and Africa. There is approximately 5000 km of pipelines dedicated for hydrogen transport worldwide, which seems very little compared to over 3 million kms of natural gas pipelines (IEA 2019). The cost of constructing a new pipeline depend on the cost of the material, construction and planning costs and vary considerably across regions from USD 300,000 to USD 1.5 million per km. Nevertheless, transporting large quantities of hydrogen through pipelines benefits from the economies of scale becoming the cheapest option for supplying hydrogen to continues demand with a high level of energy efficiency. At large volumes, if we compare it to renewable electricity, hydrogen pipelines can transport the same amount of energy at less than 2% of the cost (Cammeraat, Dechezleprêtre and Lalanne 2022). Pipelines also benefit from longer lifetime.

Given proximity and the already existing transport infrastructure, the European energy system can leverage the trade linkage between North Africa and Europe. The present natural gas transmission system can be repurposed for green hydrogen transport. The capacity in North Africa is seen as sufficient for EU 2030 emission targets and cost markups for transport are still economically justifying the export to Europe (Nweke-Eze and Quitzow 2022). Pure hydrogen exports through new and existing pipelines from North Africa could reach 17 Mt by 2050 (AGHA 2022). However, Falcone, Hiete and Sapio (2021) argues that the current transport capacity is limited to no more than 1 EJ (less than 7.1 Mt) per year, lower than the 10 Mt Euroepean Union import target. AbouSeada and Hatem (2022) determine that building a pipeline for transporting green hydrogen from North Africa to Europe at a cost of USD 0.22 per Kg of H_2 requires an investment of USD 19.14 billion. The West African Gas Pipeline (WAGP) network which is currently transporting gas from Nigeria to neighbouring countries bears potential for repurposing. The network could be further linked to the North African–Europe pipeline networks (Greenstream pipeline, Maghreb-Europe Gas Pipeline, Medgaz, and Trans-Mediterranean Pipeline) to strengthen the export potential of West Africa (Nweke-Eze and Quitzow 2022).

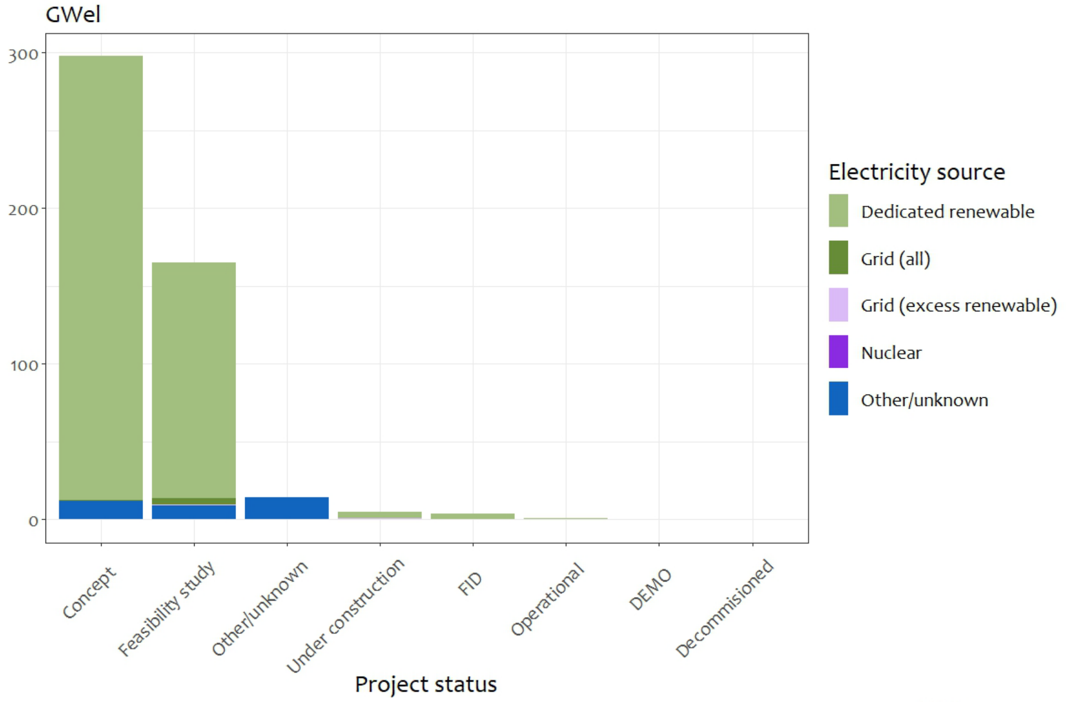
In the context of growing geopolitics and trade barriers, supply diversification is critical for importing sectors and countries. The low operation cost, the long lifespan and maturity of pipeline transport over large distance makes the case for repurposing existing pipelines and expanding the network. However, they also have a high initial capital requirement, long constructions periods, and complex permitting authorisation processes, especially if it crosses national boarders, that could constitute a major barrier (Weichenhain 2021).

Potential back up options are the existing shipping routes between South Africa and Europe. According to AGHA (2022), the shipping market for hydrogen and its derivatives imports is anticipated to increase fivefold to sixfold, between 2030 and 2050, to fulfil the increased demand from high-demand centres. Some countries in Southern Africa have high solar and wind potential and low domestic hydrogen demand and may target this space. Methanol and synthetic kerosene exports from southern Africa could reach 13 Mt by 2050 (AGHA 2022). However, in a comparative context with North Africa and the Middle East, they remain largely economically unviable (Hydrogen Council and McKinsey & Company 2022). Only in an optimistic hydrogen scenario towards 2050 by IRENA, South Africa is expected to be exporting to Asia via shipping (IRENA 2022).

The two dominant modes of transport here are indeed pipeline transport for regional linkages (55% of global hydrogen trade) and ammonia shipping (40%) for long-distance transport. This would imply that in 2050 about 36% of the total green hydrogen on the market can be globally traded (IRENA 2022). The current and prospective shares of these modes of transport are mostly determined by distance and volume factors. Especially repurposed pipelines are for now most cost-effective for distances up to 8,000 km and hydrogen volumes of 1.5 Mt per year. Beyond this, ammonia shipments, allowing a higher energy density than hydrogen, are the most viable transport mode.

3.6. Investments in hydrogen economy

The global electrolyser capacity stood at 300 MW, as of mid 2021, with Europe accounting for 40% of the current global installed electrolyser capacity. There is a growing number of pipeline projects for green hydrogen with actual deployment still to be determined, and if all projects that are under various stages of development materialise, the installed electrolyser capacity would reach 89 GW in 2030 (IEA 2019) with over USD 240 billion in direct investment, half of it is planned for green hydrogen production (Hydrogen Council and McKinsey & Company 2022). Europe accounts for over 30% of the globally proposed investment in hydrogen, followed by North America and Latin America with about 20% proposed investment each. Of the total proposed investment, nearly half are undergoing feasibility studies and 10% have reached a final investment decision (see Figure 3 below) (IEA 2022). The mobility sector and new industry applications as in the steel industry take the highest shares of the announced investment for hydrogen infrastructure with 30% each, followed by existing industry uses like ammonia and refining with about 25% (Hydrogen Council and McKinsey & Company 2022). The announced projects include low-carbon hydrogen production that, if realised, would increase annual production of low-carbon hydrogen to more than 24 Mt H_2 by 2030 (IEA 2022).



pbl.nl

Figure 3: All projects worldwide that have been commissioned since 2000 for the production of hydrogen for energy or climate change mitigation purposes (IEA 2022)

These investments are far below the projected demand for hydrogen to meet the global climate change mitigation targets. Hydrogen Council and McKinsey & Company (2022) analysis shows that cumulative investment in hydrogen grows to 1 trillion in 2030 and could grow tenfold between 2030 and 2050, i.e., to USD 10 trillion in 2050. Most of these investment goes to renewable hydrogen production (55%–60% from 2030 onwards), while 15% of the total investment goes to trade-related investments. Investments in renewable power generation from solar and wind account for over 75% of the hydrogen production investment, with investment in pipelines, reconversion facilities for carriers, and shipping will be growing after 2030 as countries with large demand points increasingly participate in global trade to complement domestic production (Hydrogen Council and McKinsey & Company 2022). By 2050, USD 140 billion per year is required to facilitate long-distance transportation.

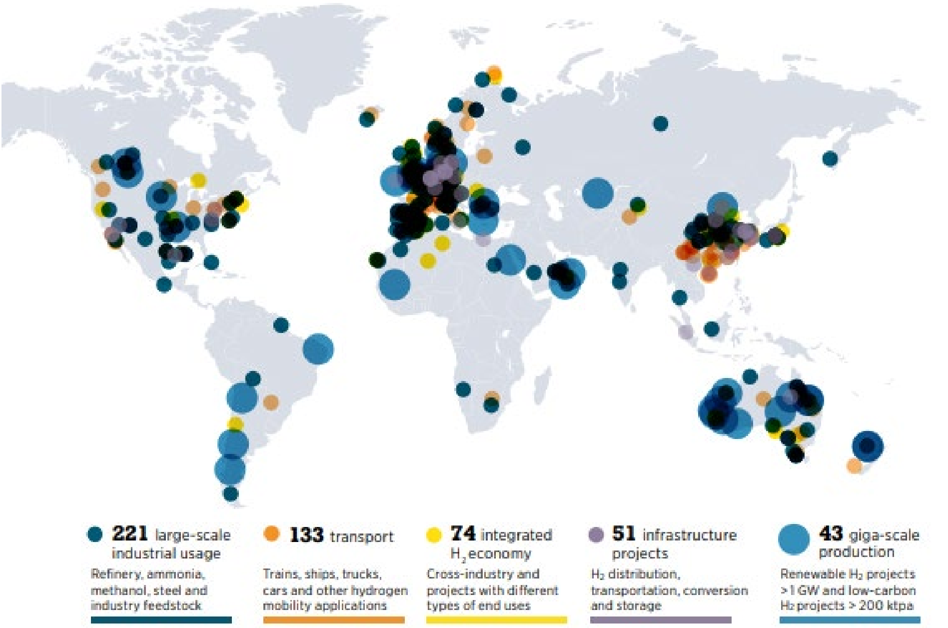


Figure 4: Large-scale clean hydrogen projects and investment as of November 2021 (IRENA 2022)

Figure 4 shows the distribution of clean hydrogen projects across the globe. The overall increase in hydrogen projects globally is also driven by larger investment flows towards Africa, especially since 2020. Several countries in Africa have considerable potential to produce green hydrogen that could build their own energy sovereignty and fuel economic development, while also supplying to the growing global demand. Democratic Republic of Congo, Egypt, Ethiopia, Kenya, Mauritania and Namibia are identified as regions with sufficiently favourable conditions for establishment of green hydrogen hubs by the African hydrogen Partnerships (Huegemann and Oldenbroek 2018).

The European Investment bank[3] sees hydrogen potential of EUR 1 trillion in Africa, specifically in Northern and Southern Africa, which could contribute to GDP growth, job creation and emission reduction of about 40%. So far, hydrogen investment projects in Africa are in an early implementation or planning stage. In 2021, Namibia announced an estimated USD 9.4 billion green hydrogen project, planned to start production in 2026. Part of the Just Energy Transition Partnership with South Africa of USD 8.5 billion is also contributing to the development of hydrogen infrastructure. In addition, South Africa announced green hydrogen projects totalling USD 17.8 billion between 2022 and 2032. Morocco and Egypt are the leading countries in North Africa, each holding several billion-dollar investment projects. In addition, Kenya and Nigeria are in the planning stage of integrating hydrogen in their energy mix[4]. Deloitte (2023) estimates that, for a

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[3] *New study confirms €1 trillion Africa's extraordinary green hydrogen potential (eib.org)*

[4] *Green hydrogen: A viable option for transforming Africa's energy sector | Africa Renewal (un.org)*

net-zero pathway, a cumulative investment of USD 9 trillion is required for the hydrogen supply chain. These investments include a significant share of USD 900 billion and USD 300 billion respectively for North Africa and Sub-Saharan Africa.

Despite existing pipeline infrastructure, significant investments along the hydrogen supply chain are still needed for developing a hydrogen-economy. Investments in energy transition technologies reached around USD 1.3 trillion in 2022 and have been on a steady increase for the past six years. Close to 80% of these is composed of renewable energy and electrified transport investments, the latter taking up a major share. Hydrogen investment, however, was only 0,08% of the total volume in 2022. This shows that while green hydrogen potential is assumed to be large, actual implementation and investment remains minor so far (IRENA and CPI 2023).

Existing profitability analyses of hydrogen projects are rather few, with a strong focus on China, and are conducted under various assumptions, making a cross-comparison difficult. Most analyses for energy-related projects make use of the net present value calculations that weigh investment risks against projected return flows. An analysis of Chinese hydrogen production projects yields positive net-present value after 10-12 years, under lower financial risks this period reduces to 8 years (Taghizadeh-Hesary, Li et al. 2021). This is under assumptions of 20 years of operation period and a discount rate of 8%. Another study analysed hydrogen production projects at different locations in China and found payback periods ranging between 3 to 8 years (Liu, Zhai and Hu 2023). Here again technological learning, demand factors and infrastructure development have great potential to improve the profitability time.

4. Hydrogen supply and demand scenario analysis

This chapter presents the current and future cost of hydrogen and the global demand and supply gap with an emphasis on Africa and Europe. The main input of this chapter is the scenario exercise and the outputs of the IMAGE framework (see methods section for more detail on models and scenarios), complemented with desk study of regional factors that could possibly affect the results. With the help of the IMAGE modelling framework, the section explores the future costs of hydrogen production, regional final energy mix, the role of hydrogen in end-use sectors and energy-related emissions under various scenarios.

4.1. Hydrogen supply costs

The future cost of hydrogen is a crucial determinant of adoption of hydrogen in various sectors. The total cost of delivering hydrogen to end users depends on several factors at various stages of the supply chain including the production, conversion, transport, distribution, storage and redistribution costs. The cost development also depends on the projected demand, especially in hard-to-abate sectors in industry and long-distance transport where hydrogen is projected to play a major role in decarbonisation. While storage and transport form the most matured section of the hydrogen value chain, conditioning hydrogen also incurs considerable energy and additional capital costs. The production cost of hydrogen is directly dependent on the cost of electricity, the cost of electrolyser, electrolyser utilisation, and the WACC. Green hydrogen production technologies are still new; hence, the future cost of production could be significantly reduced as the cost of renewable energy technology and electrolysers decline together with economies of scale.

Below, we discuss the cost implications of the different ingredients for hydrogen production and present the future cost of hydrogen as projected in IMAGE.

Costs components of producing hydrogen

The current production of hydrogen is dominated by fossil fuel driven by its lower cost (USD 1–2.5 per kg H_2 from unabated natural gas) compared to low-carbon hydrogen production (USD 1.5–3.0 per kg H_2 for natural gas with CCUS and USD 4–9 per kg H_2 for electrolysis with renewable electricity). However, a combination of factors such as consistent decline in the price of renewable electricity, learning, increased scale of production, and stringent climate change mitigation policies could make green hydrogen increasingly competitive.

For electrolyser cost, its size, operation scale and input materials are the most critical cost component. But also learning rates in its technology development play an important role and are seen to behave similar to solar PV (IRENA 2020). IEA estimates that the cost of electrolysers could reduce by 60%–64% by 2025, by 68%–72% by 2030, and by 78%–82% by 2050 (IEA 2022). As these prices also depend on the price of metals used in electrolyser production like nickel and platinum, the volatility of metal prices might complicate any scaling of green hydrogen production. In turn, due to the Russia–Ukraine war, the cost of producing hydrogen from unabated natural gas in 2022 has increased threefold relative to 2021 (IEA 2022), making hydrogen production from renewable electricity more cost competitive.

The most dominant and mature electrolyser technologies are proton exchange membrane (PEM) and alkaline water electrolysers. PEM electrolysers benefited from decades of research for application in fuel-cell electric vehicles and niche applications, while alkaline electrolysis has been used to produce hydrogen for manufacturing of chemical fertilizers with cheap electricity since the 1920s. In 2021, around 70% of installed capacity was alkaline electrolysis and 25% PEM electrolysis. While PEM electrolyser is even 50%–60% more expensive than alkaline, both are seen to inhibit substantial potential for cost reductions (IRENA 2020).

The cost of water is also an important cost component of green hydrogen production. The use of seawater is seen as a resource- and cost-effective option in electrolyser production. Water transport ways are an additional low-cost part that could distribute hydrogen production in a more equitable way. Moreover, the desalination process can be coupled to drinking water access which would contribute to the return on investment of the green hydrogen operation. Currently under development and tested on small scales is direct seawater electrolysis which would save desalination costs once fully viable.

Currently, there are significant differences between regional production costs for hydrogen. However, current cost differentials across regions will increasingly equalise over time, given technology and learning exchanges. Hence, it is mostly national or regional risk factors and related WACC differences that will continue to determine the pricing and trade structures of renewable hydrogen (IRENA 2022). It is therefore crucial to better understand the global differences in the cost of capital and its driving forces. WACC itself represents the expected return of an investment. It is composed of a base rate which is a global benchmark return rate while the added premium is composed of systemic and non-systemic risk rates. Systemic risks relate to more structural, national or governance factors influencing the return in a specific location. Non-systemic risks relate to a single technology or project subject to investment (IEA 2021). Macroeconomic indicators like the value of government bond yields can give a rough indication of the systemic risk premiums. Over the years these have fallen across many countries while the WACC in developing countries can still be up to seven times higher than in the United States or Europe. Moreover, the capital structure for different energy sectors varies, making it difficult to draw direct conclusion from WACC calculations on solar PV to hydrogen financing costs developments.

Model projections

Figure 5 shows the IMAGE model projections that depict a trend of declining prices for green hydrogen in Africa at a cut-off production price of USD 5 per kg H_2. Under *SSP2 baseline*, green hydrogen production costs USD 2.8–3.2 and USD 1.1–1.5 per kg H_2 in 2050 compared to USD 5.5–6.5 and USD 1.8–2.0 per kg H_2 in 2020 for solar PV and onshore wind, respectively. This is mostly a result of declining renewable energy and electrolyser prices driven by learning. But the cost of green hydrogen remains higher than that of fossil-based hydrogen production. With stringent climate mitigation policies under *SSP2 2-degree and SSP2 1.5-degree scenarios*, the cost of green hydrogen declines fast but remains slightly above blue hydrogen. Demand for green hydrogen in these scenarios accelerate after 2030 as the delayed climate change mitigation action require a faster deployment of green hydrogen relative to SSP1 climate scenarios.

With stringent climate change mitigation policy and high demand for hydrogen, in the *SSP1 HHD scenario*, the cost for solar PV declines to USD 0.8–1.0 per kg H_2, while the cost for on-shore wind remains similar, making green hydrogen cheaper than natural gas-based hydrogen that costs USD

3.4–4.5 per kg H_2 and blue hydrogen costing USD 1.1–2.4 per kg H_2 in 2050. In addition to learning, increased load factors for renewable electricity plants and electrolysers drive the price of green hydrogen down. Low-cost green hydrogen enables large industries to decarbonise by replacing natural gas based on-site hydrogen production with (imported) green hydrogen. The benefits of a lower levelised cost for hydrogen goes beyond direct application of hydrogen for energy purposes. The cost decline most likely translates to reduction of production costs for hydrogen derivatives such as ammonia, methanol and synthetic kerosene (AGHA 2022). Using ammonia from cheap green hydrogen could reduce emissions from fertilizer production, facilitate local production of fertilizers, reduce fertilizer prices hence contribute to food security, and decouple fertiliser production from natural gas price fluctuation.

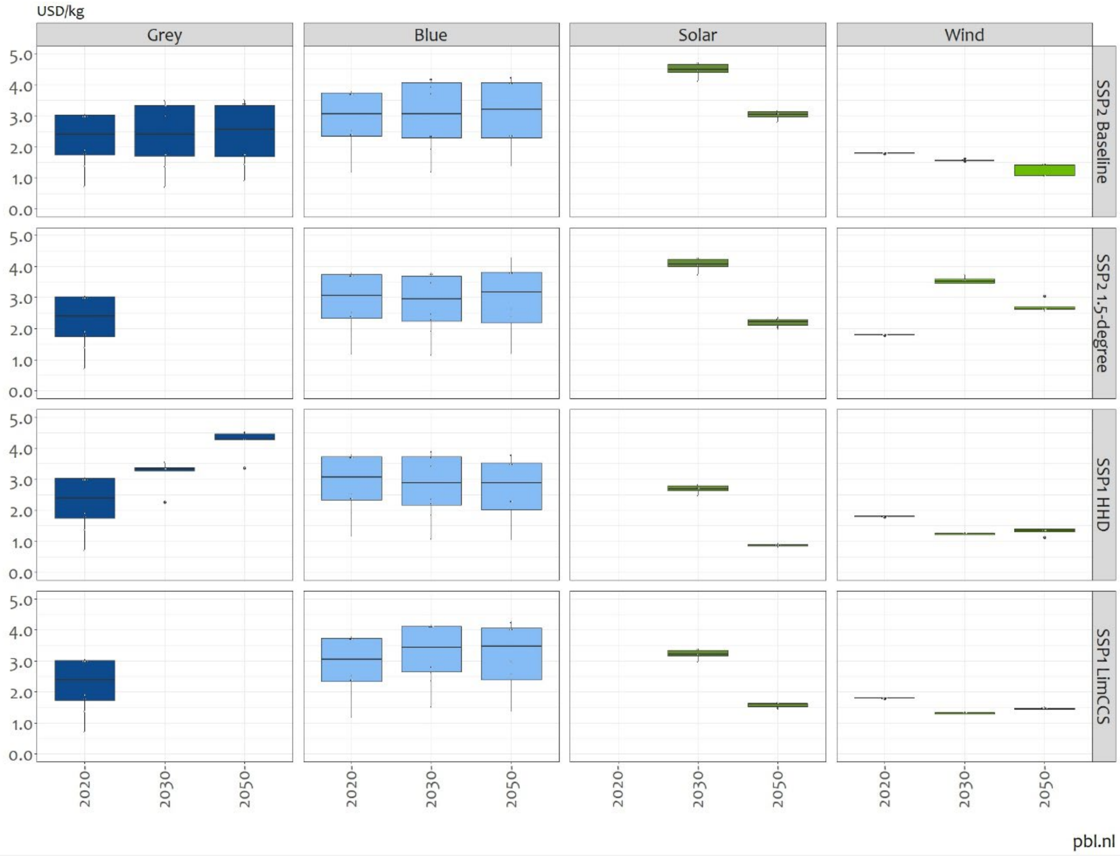

Figure 5: Levelised cost of hydrogen (LCOH) under SSP2 baseline, SSP2 1.5-degree, SSP1 high hydrogen demand, and SSP1 limited CCS scenarios in Africa.

**The ranges present the values in the five sub-regions of Africa*
**Grey and blue hydrogen include natural gas, coal and oil*
**The plot shows production under USD 5 per kg of hydrogen*

These model projections show that green hydrogen becomes increasingly competitive with grey and blue hydrogen under stricter climate mitigation policies. While in the short term, fossil fuels remain the cheapest option for hydrogen production, after 2030 renewable energy-based electrolysis becomes increasingly competitive, especially wind energy-based production. In the *SSP1 HHD scenario* where demand-side measures stimulate the use of hydrogen in various sectors or in *the SSP1 LimCCS scenario* where there is a limit to the availability of CCUS, renewable energy-based hydrogen production becomes increasingly competitive with grey and blue hydrogen and even cheaper by 2050 (see Figure 5 and (IEA 2019, IRENA 2020)). Under these scenarios, with increased capacities, which requires considerable financial and regulatory support, the cost of hydrogen production declines as technology learning is accelerated and benefits from economies of scale are acquired. Hence, under net-zero climate ambitions and a continuing weakened fossil fuel market as in 2022, the potential for solar- and wind-based hydrogen production is a given. A similar analysis in the IEA scenario on net-zero emissions by 2050 also shows that solar PV technology for hydrogen production has the highest potential to outcompete natural gas with CCUS technology by 2030 (reaching levelised costs below USD 1.5 per kg H_2).

Distribution cost

The discussion so far only covered the production cost of hydrogen, but the future development of hydrogen production technologies depends on the cost of storage and transport in addition to the cost of the production itself. For the overall cost of hydrogen, two additional cost components need to be considered: transport and reconversion costs. IEA (2019) estimates that, while taking capital and operating costs into account, the cost of transporting hydrogen as a gas for 1500 km to be around USD 1 per kg H_2 and transporting hydrogen as ammonia would cost USD 1.5 per kg H_2 including conversion cost. Shipping hydrogen over 1500 km costs in the range of USD 0.6–2 per kg H_2 depending on the cost of conversion to liquid organic hydrogen carriers (LOHCs), ammonia, or liquid hydrogen. According to IRENA (2022), the levelised cost in 2050 could be between USD 0.9 and USD 1.4 per kg H_2 for Sub-Saharan Africa with South Africa doing even slightly better. The region in North Africa is leading the levelised cost projections with cost ranges between USD 0.6 and USD 1.3 per kg H_2.

Fundamental cost disadvantages remain given the low energy density by volume of hydrogen compared to other energy carriers. These make transport costs a very relevant cost parameter in hydrogen trade, particularly for liquid hydrogen, which, even though is more energy dense in volume thus more mobile, requires several energy-intensive conversion steps (Jackson, Fothergill et al. 2020). Ammonia has an even higher volumetric energy density and is therefore the most suitable carbon-free carrier of hydrogen. IRENA (2022) determines countries' trading incentives based on their national supply and demand scenarios until 2050. The resulting trade patterns between Europe and Africa are strongly limited to pipeline transport between Southern Europe (Spain and Italy) and North Africa (assumption of pipeline repurposing). A very limited, minor but high potential role is ascribed to Sub-Saharan Africa for global hydrogen trade given the continuously high WACC estimates (now there is only a single trade flow from South Africa to Asia available).

4.2. The role of hydrogen in future energy systems

Current hydrogen applications include oil refining, iron refining, for ammonia, methanol, and other alcohol production, in the food industry (for hydrogenation of oils and fats), metals refining, glass production, electronics fabrication, and in fuel cells. Hydrogen use as energy carrier is minor. Though uncertainties remain, the consensus about the key role of low-carbon hydrogen in decarbonising the global energy system is growing. Hydrogen is a promising energy carrier to decarbonise hard-to-abate sectors where electrification is not suited, such as shipping, and parts of industry involving high-temperature processes. Hydrogen can also be applied as an energy storage to provide flexibility to renewable-based power system, but this should be the last application due to associated losses during reconversion to electricity and substantial storage requirements. It also has potential use in heating buildings and long-distance trucking. This section presents scenario projections on final energy demand and mix, sectoral demand for hydrogen, and the role of hydrogen in reaching climate targets.

4.2.1. Final energy demand

Business as usual — SSP2 baseline

Global final energy demand in 2020 was 400 EJ, a decrease of 7% from the previous year due to the COVID19 pandemic. However, in 2021 energy demand quickly rebound reaching 420 EJ, 6% increase relative to 2020. The global final energy mix was dominated by oil (39%) in 2020, despite the significant decline of oil demand relative to 2019 due to reduced road transport activity, followed by coal (12%), natural gas (16%), electricity (19%), and traditional biomass (9%). Modern biomass, secondary heat, and hydrogen cover the rest of the supply. The global final energy demand is expected to increase by 22% in 2030 and 46% in 2050 relative to 2020 under business-as-usual trends. Most of the growth is projected to happen in Central & South America, the Middle East, and Africa where the final energy demand increases by 70% to 110%. Though the share of electricity shows a steep incline, fossil fuels remain dominant in the final energy mix under *SSP2 Baseline*. The share of hydrogen in the final energy remains trivial except for Europe and China.

In 2020, 17% of the global population lived in Africa but accounted for just 6% of the final energy consumption. A continuing challenge is the provision of reliable electricity access to the African population. Overall, 43% of the total African population lack access to electricity, while rates vary strongly across the continent (IEA 2022). Energy needs are currently covered by biomass and fossil fuels with electricity production mainly based on natural gas (40%), coal (30%) and hydropower (16%). Around 70% of final energy demand in Africa is accounted to the residential sector for cooking, cooling, heating and other appliance use (AbouSeada and Hatem 2022). The continent's population is projected to grow by 60% and the economy by 150% between 2020 and 2050, under the *SSP2 baseline scenario*. In the same period, final energy demand is projected to double, while electricity use grows nearly fourfold and demand for fossil fuels grows nearly threefold. Most of the growth comes from the transport sector. The growth represents 10% of the global final energy demand and 9% of the global electricity demand. So far, under baseline projections, universal access to sustainable and modern energy remains beyond reach. Studies (Dagnachew, Lucas et al. 2018, IEA 2022) show that renewable energy-based generation is the least-cost scenario for large parts of the continent that offers to leapfrog to a cleaner energy system and avoid carbon lock-in.

The final energy demand in Europe shows a decline in fossil fuels with demand for modern bio, hydrogen and electricity increasing. Europe is largely dependent on the international supply chain for gas imports and for critical metals needed for the energy transition, hence, the effort is to improve energy efficiency and increase the share of renewable energy as stated in the Fit-for-55 proposal. That is seen in the projections as final energy demand in all scenarios declines in 2050 relative to 2030. This also leads to increasing shares for renewables, hydrogen and modern biofuels. Electrification is a cheap and efficient alternative to decarbonise applications that require low- and medium-temperature heating and road transport. As such, electricity demand in Europe increases by over 40% in 2050 relative to 2020 under *SSP2 Baseline scenario*. Electricity demand in transport grows fivefold in this period, while commercial and residential uses also increase. The European plan to expand renewable energy capacity under REPowerEU (European Commission 2022) proposal requires energy storage solutions such as power-to-x and hydrogen. Hydrogen or hydrogen derivatives are preferred solutions for some applications where electrification is difficult as discussed later.

Climate policy scenario

All climate policy scenarios have lower global final energy demand in 2050 relative to the baseline, demonstrating the important role of energy efficiency in climate change mitigation. Under *SSP2 2-degree scenario*, the global final energy demand shows a modest increase of 15% in 2050 relative to 2020. While fossil fuels cover 50% of the demand in 2050, hydrogen accounts for a mere 1.5% of the final energy demand. Here again, most of the demand increase happens in Central & South America, the Middle East, and Africa where it grows by 25%-50% while most other regions show a decrease in final energy demand. Global final energy demand remains close to 2020 levels in 2050 in all 1.5 °C scenarios (*SSP2 1.5-degree, SSP1 1.5-degree, SSP1 HHD, and SSP1 LimCCS*). Central and South America show an increase of 10% to 20% and Africa 20% to 30% by 2050 under these scenarios, while the demand in most other regions declines.

Electrification is a cheap and efficient alternative to decarbonise applications that require low- and medium-temperature heating and road transport; hence its demand increases in all regions. For instance, in Europe, electricity demand in transport will grow fivefold by 2050 relative to 2020, while commercial and residential uses will also increase. Hydrogen accounts for 4% to 16% of the final energy demand by 2050, depending on the socio-economic projection. The highest estimate for hydrogen demand in 2050 is similar to IRENA's 1.5 °C scenario projection (IRENA 2022). Figure 6 below presents the final energy demand under various scenarios in 2030 and 2050 using the IMAGE model.

Under stringent climate policy (i.e., *SSP2 1.5-degree and SSP1 1.5-degree scenarios*) final energy demand in Africa increases by 20% to 30% by 2050, relative to 2020. Demand for hydrogen grows fast in the transport and commercial sector under all scenarios, though from a very low start. Energy demand by industry sectors is highest for iron and steel industries, followed by mining and quarrying and petrochemical and chemical industries. For both domestic and industrial uses an increase of 2% annually in total primary energy until 2040 is forecasted, with biomass playing a lesser role. Hence, the consideration of hydrogen in filling this for some parts of the economy in Africa becomes apparent while also contributing to the African Union's 2063 agenda (AbouSeada and Hatem 2022).

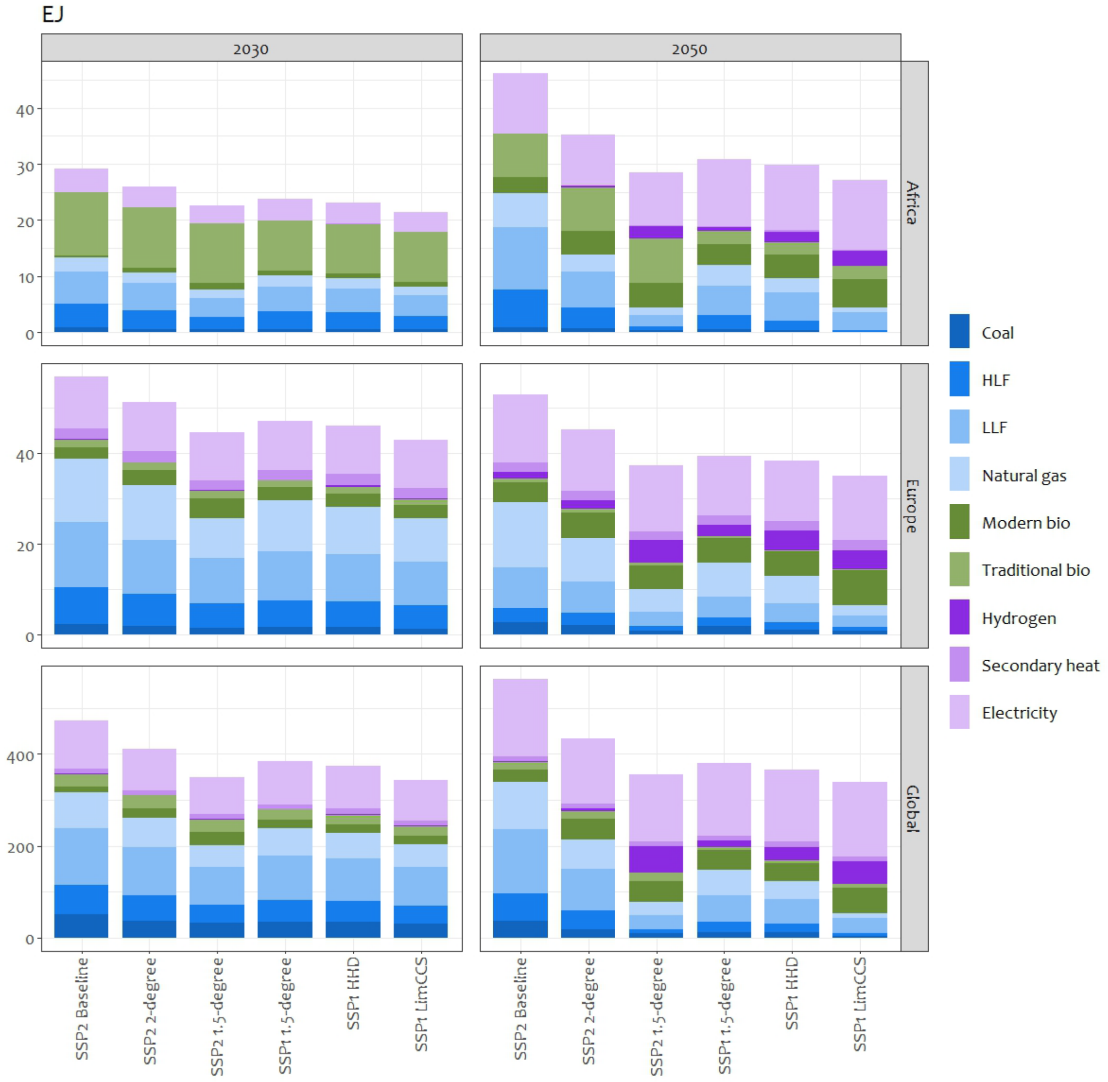

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Figure 6: Global final energy demand in 2030 and 2050 under various scenarios in selected regions

4.2.2. Hydrogen demand in end-use sectors

Hydrogen is a versatile energy carrier that can be used in its pure form, as the basis for synthetic fuels. Currently, hydrogen is used predominantly in the chemical sector, oil refining and iron and steel production. Beyond these primary uses, hydrogen provides extensive application potential in heating and transport, however, still requires more comprehensive analyses for the African context (Hydrogen Council and McKinsey & Company 2022). In addition, the use of ammonia as a hydrogen carrier allows and facilitates the inclusion of the chemical and fertilizer sector in Africa. Fertilizer is currently mostly imported and therefore subject to variation in global prices and quantities. Developing fertilizer production capacities for green ammonia and distribution channels in an increasingly local fertilizer market therefore seems like a promising side strategy for electrolyser production, supporting economic growth and, especially, African food security (REVOLVE 2022).

It is difficult to determine the exact amount of hydrogen that is being produced today due to its application in non-energy use, and not as fuel for energy applications in end-use sectors. IEA (2022) estimates that nearly 94 Mt of hydrogen is used globally in 2021, including non-energy applications. The largest share of this hydrogen (~80%) is produced from fossil fuels resulting in 900 Mt CO_2

emissions. According to the report, 33% of the total global hydrogen demand is consumed by fuel refineries and is responsible for 20% of total refinery emissions. IMAGE output estimates global hydrogen consumption for energy use in 2020 at 420 TJ, the largest demand coming from industry (77%) and transport (23%).

Business as usual — SSP2 baseline

Figure 7 shows the sectoral hydrogen demand shares in 2030 and 2050 under various scenarios and Figure 8 presents projected global hydrogen demand and share of production technologies under various scenarios. In IMAGE, hydrogen demand for energy application is projected to rapidly increase to up to 250 PJ in 2030, further increasing to more than 2 EJ in 2050, under *SSP2 Baseline scenarios*. This estimate is exclusively for energy use and does not include traditional non-energy application that are included in IEA and IRENA forecasts. In this scenario, the production is dominated by grey hydrogen with a small share of blue hydrogen, hence the climate benefit is minimal. In 2050, transport and domestic heating dominate the hydrogen demand in most regions, while industrial use in Africa and China is projected to grow. The share of hydrogen in the energy system in Africa, however, remains under 1% in *SSP2 baseline scenario*.

Globally, the transport sector consumes 45 PJ and 390 PJ hydrogen in 2030 and 2050, respectively, offering a low- or zero-carbon alternative to fossil fuels for all modes of transport complementing the role of electricity and biofuels in decarbonising the sector. Particularly, long-haul and heavy duty are attractive applications for hydrogen continuing the current trend. With the volume of international shipping expected to more than triple by 2050, hydrogen and hydrogen-based fuels could also play a key role in decarbonising maritime transport. The number of hydrogen fuel cell cars is also growing, but they are mainly concentrated in the Global North, which contributes to reducing air pollution, particularly in large cities. Hydrogen plays an important role in heating energy-intensive old buildings, complementing the role of heat pumps, depending on the rate of renovation. There is already a pilot running in the Netherland where homes are heated with green hydrogen from a small-scale electrolysis facility that replaced natural gas completely (Chowdhury 2020). It is also crucial for decarbonisation of industries, particularly iron and steel and ammonia sectors, as well as medium- and high-temperature applications replacing the use of natural gas.

Climate policy scenario

Hydrogen complements electrification and biofuels for decarbonizing the transport sector including the production of synthetic fuels in aviation. Direct use of hydrogen in aviation remains limited due to its lower energy density by volume and its large storage requirements. Under the *1.5-degree scenarios*, the demand for hydrogen grows to 28–58 EJ (equivalent to 200–405 Mt) by 2050, depending on the projected socio-economic development and the efficiency of the energy system. The large share of the demand in all scenarios comes from the transport sector that demonstrates the significant role that hydrogen can play as fuel for transportation, mainly for fuel cells in heavy-duty vehicles. Green hydrogen is also crucial in decarbonising the building sector, especially for space and water heating in old buildings (complementing the use of heat pumps), as well as for the hard-to-abate industries such as steel, cement and the chemical industry, which cannot readily be electrified. Other similar model projections (AGHA 2022, IEA 2022, IRENA 2022) show that hydrogen has a role to play in all sectors beyond today's industrial applications due to its ability to diversify energy supply and enable the transition to low-carbon energy systems.

As can be expected, the highest demand comes under *SSP2 1.5-degree scenario* as demand for clean energy from several sectors grows fast to make up for delayed action and higher final energy demand. North America and China are the largest consumer of hydrogen accounting for 13%–15% and 23%–30%, respectively, of the global demand in 2050, specifically for industry and transport. Most of the hydrogen demand is met by green or blue hydrogen technology (see Figure 8). This shows the big potential that hydrogen and its derivatives could play in meeting the global climate target.

In Europe, residential and commercial buildings show the largest relative increase in hydrogen application driven by a growing demand for low-carbon heating alternatives. The share of hydrogen in the final energy demand in building ranges from 14% under *SSP2 2-degree scenario* to 31% under the *SSP1 HHD scenario* where hydrogen demand in various sectors is stimulated. Transport is another main hydrogen consuming sector where hydrogen is projected to provide up to 35% of the final energy demand. The European Union has set a target of domestic production and import of 20 Mt per year of green hydrogen by 2030 to assist the energy transition (European Commission 2020). This is equivalent to 3 EJ or 8% of the EU's final energy consumption in 2020. Several regulations support the development of green hydrogen in Europe including the CO_2 standards for cars, the alternative fuel infrastructure regulations, the fuelEU maritime proposal, the EU emission trading system proposal, and the energy taxation directive.

The African economy requires 2 to 3 EJ of hydrogen by 2050 to accelerate the socio-economic development that is envisioned in the 2063 Agenda while at the same time meeting the global climate targets. Under climate change mitigation scenarios (*SSP2 1.5-degree and SSP1 1.5-degree variants*), the share of hydrogen in the final energy demand reaches 4%–7% by 2050. Transport and industry account for 80%–90% of the hydrogen demand in 2050, depending on the socio-economic projections and stringency of climate mitigation policies. The feasibility of the growth in green hydrogen demand depends on the development of the cost of renewable electricity technologies, electrolysers, and infrastructure availability.

The role of hydrogen in the energy system in Africa varies depending on the socio-economic development and climate change ambition of the scenarios. Three-quarters of final energy use in buildings in Africa is used for space heating, water heating and cooking, most of which generated by traditional biomass and fossil fuels. Low-carbon hydrogen shows considerable contribution for the energy transition in buildings, especially for energy-intensive old building, and for decarbonising the sector in the medium and long term. Green hydrogen in Africa could play a role in attracting and decarbonising energy intensive sectors, facilitating the integration of large amounts of variable renewable energy (VRE), and allowing decoupling of VRE generation and consumption through the production of transportable hydrogen (IRENA 2018). A well-developed hydrogen economy could cater to agenda 2063 that aspires to build a prosperous Africa, based on inclusive growth and sustainable development (AU 2014).

In the IEA Stated Policies Scenario (STEPS), a scenario that reflects current policy and policies announced by governments around the world, estimates hydrogen demand to reach 115 Mt (equivalent to 16 EJ) by 2030, largely for traditional applications. The Announced Pledges Scenario (APS), which assumes that all climate commitments will be met in full and on time, estimates slightly higher demand for hydrogen of 130 Mt (~18 EJ) by 2030, where a quarter would be for new applications and the use of low-emission hydrogen in traditional applications. On the other hand, the Net-zero Emission Scenario, that explores a pathway for the global energy sector to achieve net-zero CO_2 emissions by 2050, total hydrogen production is estimated to reach more than 200 Mt (~28 EJ) by 2030, and further increases to 500 Mt (~70 EJ) in 2050 (IEA 2022). Similarly, IRENA’s 1.5-

degree scenario requires 614 Mt of hydrogen (~86.5 EJ) to meet 12% of the projected final energy demand in 2050 driven by demand growth in industry and transport, as well as, providing flexibility to the power system. This requires electrolyser capacity to grow to 4–5 TW by 2050 from the current level of just 700 MW (IRENA 2022).

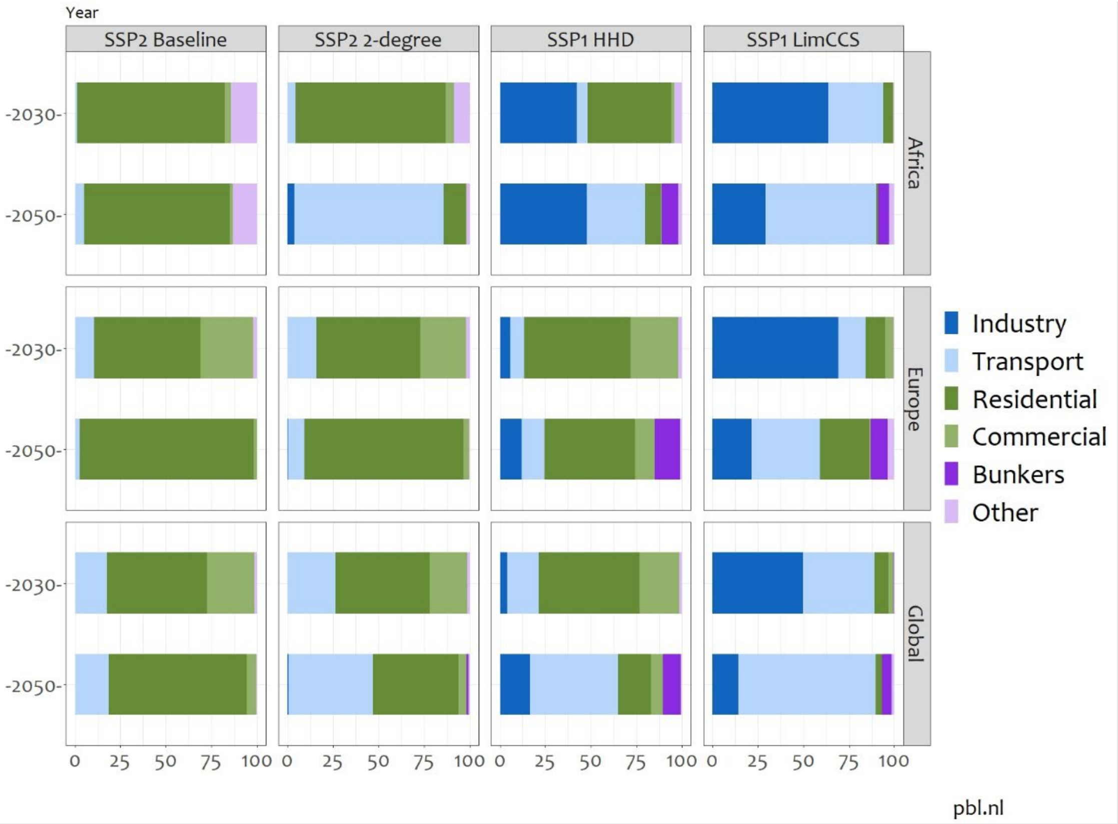
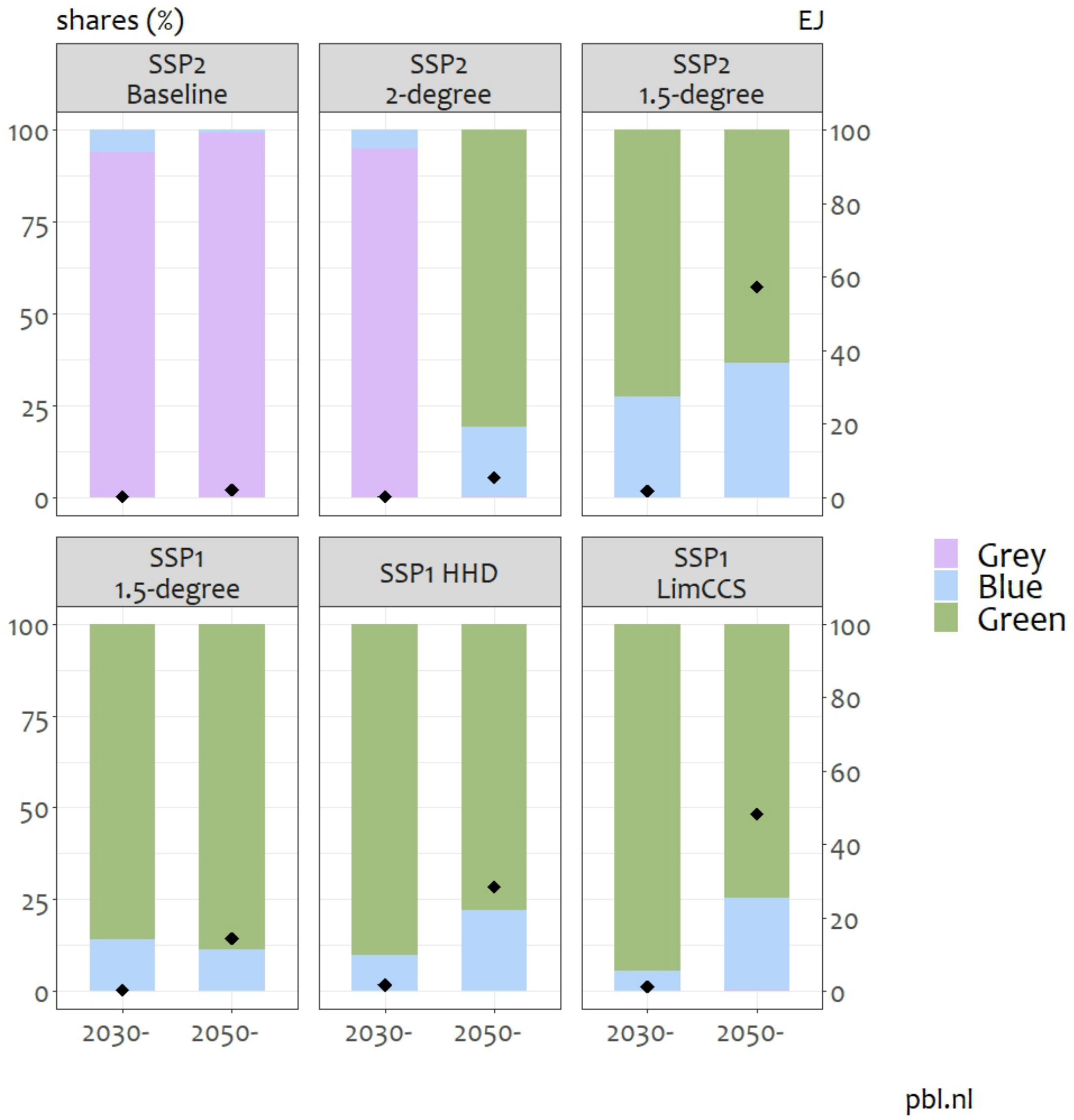


Figure 7: Regional sectoral hydrogen demand shares in 2030 and 2050 under various scenarios



◆ *gives the absolute hydrogen demand in 2030 and 2050 under the scenarios.*

Figure 8: Global hydrogen production technology shares in 2030 and 2050 under various scenarios

4.2.3. Energy use-related emissions

Global energy use-related CO_2 emissions in 2020 were 34.3 Gt CO_2, with North America, Europe and China together accounting for nearly 60%. In terms of sectors, power generation accounts for more than 42% of the emission, while transport and industry account for 18% and 17%, respectively. This emission is projected to increase by 33% in 2050 relative to 2020 (to 46 Gt CO_2) under baseline, with emissions in Russia and North America declining slightly. Energy-related emissions in Central and South America, the Middle East and Africa are projected to increase 65%–115% by 2050 driven by population increase and economic growth. Global power sector emissions grow by nearly 50% in the same period as emissions from residential building decline by 6% and industry emissions stagnates. In decarbonisation scenarios with stringent climate change mitigation policies, global energy-related emissions decline to between −4 to +0.3 Gt CO_2 by 2050, depending on the socio-economic and technology projections. Figure 9 presents the Global, European and African emission path under various scenarios.

Low-carbon hydrogen can play an integral role in reducing energy use-related emissions in several countries and sectors contributing to the net-zero ambitions by mid century. Hydrogen is especially relevant to sectors that are difficult to electrify due to the associated high cost or technical difficulty including aviation, shipping, iron and steel sectors, heating in buildings, other high temperature industry, and long-distance transport. Hydrogen Council and McKinsey & Company (2022) analysis shows that hydrogen can provide 80 Gt CO_2 of cumulative abatement by 2050, with industry and transport together accounting for 70 Gt of cumulative abatement.

The role of green hydrogen in decarbonising the energy systems is demonstrated by the lower emission path of the high hydrogen demand scenario where the use of hydrogen is stimulated in sectors other than the traditional use of hydrogen (see Figure 9 *SSP1 HHD scenario*). In all regions, we see that the *SSP1 HHD scenario* follows a lower emission path from early on reducing the risk of delayed emissions reduction and facilitating net-zero at the middle of the century.

In Africa the total GHG emissions from energy use amounted to 1.5 Gt CO_2e, and these emissions are projected to reach up to 3.6 Gt CO_2e by 2050 without additional climate change mitigation measures, amid rapid population growth and economic development. These emissions largely come from power generation and transport, that account for 48% and 17% of the emissions, respectively, in 2050. Emissions from oil account for more than 45% of the energy related emissions on the continent, followed by natural gas that account for nearly 30% and solid fuels accounting for 25%. The *SSP2* and *SSP1 1.5-degree scenario* projections with stringent climate change mitigation policies to keep global temperature increase below 1.5 °C, result in a near zero (and in some scenarios even negative) emissions from energy-use in 2050. In these scenarios, emissions from fossil fuels reduces by 85%–125% in 2050 relative to the *SSP2 baseline* projections. Hydrogen plays a considerable role in decarbonising industry and transport (see Figure 7).

Energy-related emissions in Europe in 2020 were around 3.7 Gt CO_2e and are projected to remain at that level under baseline in 2050. Emissions decline from transport and residential sectors considerably, while emissions from power generation, industry, and bunkers increase relative to 2020. Under the stringent climate change mitigation scenario, these emissions decline to -100 to 300 Mt CO_2e in 2050. Emission from power generation shows the largest decline relative to baseline, followed by industry and transport. This is also demonstrated by the growing role of hydrogen in industry, transport and domestic heating, as shown in Figure 7, coupled with strong energy efficiency performance.

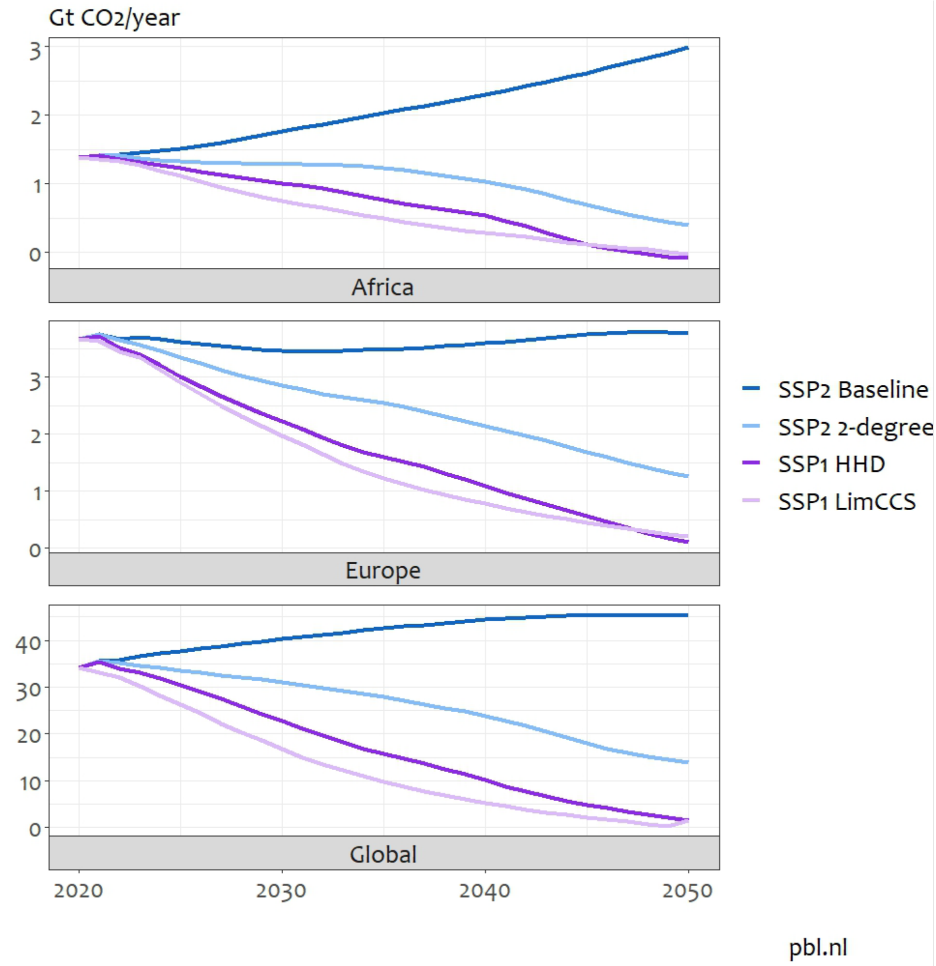


Figure 9: Regional energy-related CO_2 emissions for various scenarios

Given the importance of green hydrogen for emission reductions in various sectors, it is important to note that no clear emission reduction requirement (legally) exist. Hence, the emission intensities across and per the different hydrogen production technologies and supply chains vary considerably. Available hydrogen certification schemes set emission reduction requirements for green hydrogen between 60% and 75% as compared to fossil fuel-based hydrogen (Jensterle, Narita et al. 2019). Moreover, approaches on considering fossil fuels with CCUS and nuclear energy for hydrogen diverge across these existing certification schemes. As a very promising approach, the EU CertifHy schemes are being developed by a group of hydrogen companies and research institutes to set forth a Guarantees of Origin (GoO) certification scheme. This will set standards for green hydrogen and low-carbon hydrogen, eligible for production technologies with emission intensities of at least 60% below fossil-fuel based hydrogen. While CertifHy and other schemes are a starting point for standard setting, they are leaving out other impact factors such as land, water availability or even social impact. However, in order to make it a truly sustainable assessment of hydrogen these factors as mentioned above need to be brought together with emission intensity (Jensterle, Narita et al. 2019).

4.3. Global hydrogen trade potentials and barriers

The importance of the hydrogen trade is highlighted by the mismatch between sites with high low-carbon hydrogen supply potential and high-demand centres. A study by Ikonnikova, Scanlon and Berdysheva (2023) shows that, taking comparative resource advantage and competitive cost advantages into consideration, several countries could be players in the hydrogen economy where some produce blue hydrogen from their own natural resource or from imported natural gas, while other show tremendous potential for green hydrogen production. However, there is a large gap between the current level of trade and the role that hydrogen is expected to play in the global energy system in the future. As most of the green hydrogen potentials area situated in greenfield locations, there is major investment required for the energy transition and the hydrogen economy at a time of uncertainties in the global trade relations.

Today, hydrogen is produced and consumed on-site for cost and logistic reasons. But that needs to change if hydrogen, especially green hydrogen, is to contribute for decarbonisation and the energy transition. IRENA (2022) estimates that about a quarter of the total global hydrogen demand in 2050 could be traded internationally of which 55% would travel by pipeline, where ammonia, methanol, and sustainable aviation fuels, which are easier to transport over long distances, are the most common products. As one of the of the preconditions for global resource trade, there is already a steady increase in international (trade) agreements for hydrogen since mid 2020. These agreements point to Germany, Japan and the Netherlands as the potentially biggest importers in international hydrogen trade (IRENA 2022). The exporting countries are more diverse and include countries in South America, Southern Europe, Northern Africa, and the Middle East, as well as Australia.

China, North America, the Middle East and Europe are the biggest consumers of hydrogen in climate change mitigation scenarios in 2050 collectively accounting for half total global hydrogen demand. The fundamental driver for increased use of hydrogen is reduction of emissions and meeting climate change mitigation targets. But only a few of these regions can produce low-carbon hydrogen at a competitive cost, hence, will resort to imports to meet the growing demand. A scenario with strict climate change mitigation measures requires up to 30 times hydrogen in the global final energy mix in 2050 compared to the baseline development, reaching to 60 EJ.

Where the potential is available, producing hydrogen locally is favoured as it will keep the cost down by avoiding conversion and reconversion, which could add significantly to the overall cost. However, this disadvantage is less visible when it comes to hydrogen derivatives that, regardless of location, need to be converted. In the next few years, hydrogen derivatives take the largest share of long-distance transportation of hydrogen as pipelines are developed and repurposed making them cost competitive for long distance transport (Hydrogen Council and McKinsey & Company 2022). While in 2030, grey hydrogen has the largest share of the global trade, it will be completely phased out by 2050 with stringent climate change mitigation policies and green hydrogen takes accounts for 70%–95% of total hydrogen use, the rest covered with blue hydrogen.

Figure 10 present global hydrogen trade in 2050 under various climate change mitigation scenarios. Under these scenarios, China is the biggest producer and consumer of hydrogen. Our analysis shows that trade-routes vary by scenario. Under the *SSP2 2-degree scenario*, blue hydrogen dominates the global trade largely coming from the Middle East and Russia. The cost of green hydrogen remains higher than blue hydrogen and struggles to take significant share in the trade. Export potentials of Africa, where there is a substantial potential for green hydrogen production, remains very limited as the cost of production remains too high.

Under a stricter climate change mitigation scenario, the cost of green hydrogen becomes a strong competitor to blue hydrogen and starts to take considerable shares in the global trade. However, blue hydrogen should only be a short-term solution for the energy transition and the ultimate benefit comes from green hydrogen only, and countries should exercise caution while investing in CCUS technologies to avoid lock-in. As IEA (2019) and our model results show, green hydrogen could become competitive against blue hydrogen around 2030 in climate policy scenarios, increasing the risk of fossil fuel-based hydrogen production assets becoming stranded.

In theory, given the enormous renewable energy potential and massive land area, Africa has the potential to produce several times the projected global hydrogen demand in 2050. Governments and companies increasingly recognise the hydrogen potential and opportunity on the continent and some countries will see green hydrogen production particularly for exports. Announced investments in Africa today amount to USD 30 billion in the hydrogen value chain and nearly USD 70 billion for renewable energy infrastructure needed for hydrogen production. Examples include Mauritania's 10 GW Project Nour by 2030; Angola's hydropower-based renewable ammonia production; South Africa targeting a 4% global market share by 2050 with 15 GW electrolysis capacity installed (2030–2040). North and Northwest African countries have the advantage of being located to large demand centres in Europe and existing natural gas infrastructure that can be cost effectively retrofitted to transport hydrogen. Southern Africa can leverage attractive solar and wind resources and existing port infrastructure to export hydrogen derivatives such as ammonia and synthetic fuels. The financial requirements of these infrastructure developments for production, conversion, storage and logistics are enormous and are more likely to build on bilateral and small multilateral agreements between producers and off-takers to minimise the risk of capital (IPHE 2022). Despite this enormous potential for green hydrogen, development of an export market should not come at the expense of other development priorities of the continent, particularly providing universal access to clean and modern energy.

The scenario analysis by Hydrogen Council and McKinsey & Company (2022) shows that reducing long-distance trade increases capital expenditures requirements and hydrogen costs. Facilitating long-distance transport and global hydrogen trade could save over USD 5 trillion in aggregate capital expenditures and operating expenditures across the value chain when compared to a system without trade by taking advantage of areas with high potential for cheap green hydrogen production and economies of scale (Hydrogen Council and McKinsey & Company 2022).

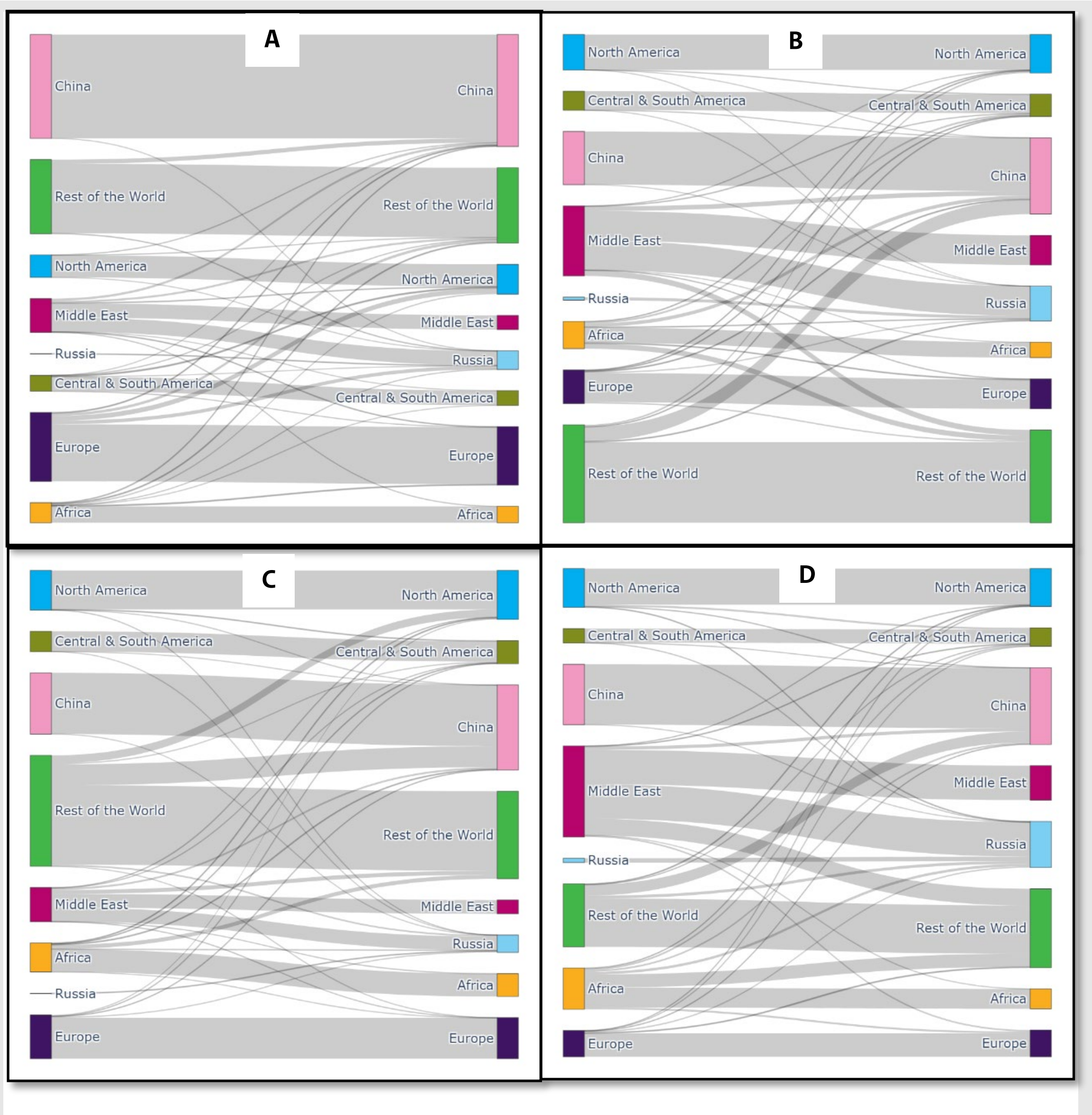


Figure 10: IMAGE hydrogen trade in 2050 under SSP2 2-degree scenario (panel A), SSP2 1.5-degree scenario (panel B), IMAGE hydrogen trade in 2050 under SSP1 HHD scenario (panel C), and SSP1 LCCS scenario (panel D)

It is important to keep in mind that while hydrogen has many advantages, there are also difficulties and factors to consider when it comes to its cost-effectiveness, storage, and transportation, factors that are discussed in detail the previous sections. To overcome these obstacles and fully realise hydrogen trade's potential as a sustainable energy alternative, considerable infrastructural investment, clear standard and policy support, certification of origin and carbon intensity, and international cooperation are necessary. Absence of demand pull is one of the main barriers to hydrogen trade. Hence, creating economic policies in terms of subsidy schemes or tax benefits for hydrogen technologies in both European and African countries will become key. Current demand trends are so far still geared towards energy efficiency and current technology development instead of technology switch. In addition, current pricing structure distorts trade as installed technologies are valued by long-term lease agreements and immature hydrogen technologies lack market information to accurately determine prices (IRENA 2022).

5. Policies and partnerships for green hydrogen

The European Union is committed to accelerating the energy transition and climate change mitigation in Europe and development partners and assisting the broader social and economic development. To help the European decarbonisation, the European Union seeks to produce 10 million tonnes of renewable hydrogen by 2030, while at the same time import the same amount by 2030. This is expected to lead to 13%–14% of hydrogen in the European Union's energy mix by 2050, from the current 2% share. This requires collaboration with regions that have potential for green hydrogen production, such as Africa, as stated in the European Green Deal. In July 2020, the European Commission released a Hydrogen Strategy and the EU Strategy for Energy System Integration.

The intertwining of efforts to address global climate change and promote sustainable development via the production of green hydrogen is often hailed as a mutually beneficial scenario. The term 'tomorrow's oil', attributed to green hydrogen by Wehrmann (2020), serves as an appropriate metaphor, setting the stage for this chapter. It underscores how a too optimistic perspective on collaborative hydrogen technology can shape policymaking. Contrary to this optimism, the chapter suggests that those involved in partnership planning should heed the cautionary tale found in the history of oil development. This history, as explored by Lindner (2022) warns that oil, rather than being a blessing, has often proven to be a curse for many in the Global South.

An analysis of policy documents on green hydrogen, as of April 2022, reveals that explicit mentions of collaboration with countries in the Global South are limited to the European Union (European Commission 2020) and, sometimes specifically Germany (BMWi 2020), as outlined in the analysis by Lindner (2022). Notably, the European Union's hydrogen strategy, recognising the developmental challenges in neighbouring regions and the potential repercussions of political instability and increased migration, places a distinct emphasis on the mutually beneficial aspects of collaboration with Eastern Europe and Africa (Lindner 2022). The early stage of current green hydrogen partnerships presents an opportunity for governance intervention guided by principles of energy justice. Such interventions should account for the unique circumstances of energy transitions in the Global South countries and learn from past experiences with ineffective technological interventions (Lindner 2022).

This chapter is structured as follows: Firstly, the current EU policies on green hydrogen will be discussed, with a specific focus on the policies regarding Africa. Secondly, an overview and analysis will be provided of the existing green hydrogen policies in several African countries. The similarities and differences between these policies will be highlighted. Thirdly, the importance of ensuring a just and inclusive hydrogen economy will be discussed and finally, suggestions will be provided for missing and further green hydrogen policies.

To provide actual insights on this topic of green hydrogen policies, several key figures have been interviewed and the outcome of these interviews is incorporated in this chapter (see Table 5 in the appendix for the list of interviewees).

5.1. Policy design for Green Hydrogen

Green hydrogen is hydrogen produced via water electrolysis using renewable electricity. Its applications include electricity generation/storage, space heating, transport, and industrial processes. These applications, currently at a pre-commercial stage of development, introduce uncertainty regarding the timeframe for cost-effective deployment. Navigating this uncertainty is crucial for policy formulation, particularly in accurately directing interventions if green hydrogen becomes a component of the energy transition (Farrell 2023).

Policy intervention becomes imperative for various reasons. Firstly, relying solely on market incentives may lead to a transition pace driven by private profit maximisation rather than broader societal goals. Secondly, achieving the 2050 decarbonisation targets necessitates a more accelerated pace of technology development given the urgency of the issue (Farrell 2023). To address these challenges, policies must initially outline possible green hydrogen applications in a cost-optimal decarbonisation pathway. Identifying impediments that hinder the cost-effective deployment of green hydrogen is crucial. Subsequently, policies should be tailored to tackle these impediments as close to the source as possible. Determining the appropriate timescale for such interventions, taking lead-in times into account, is crucial (Farrell 2023). Studies (Farrell 2023) propose a set of policy priorities for the rapid and sustainable expansion of a green hydrogen economy that are outlined below:

- *The widespread adoption of hydrogen hinges on the uncertain trajectory of production capacity evolution.* While a return to pre-COVID levels in global production supply chains may not immediately result in significant bottlenecks for hydrogen technologies, the potential for localised and supply chain-related bottlenecks in storage and transport persists, particularly given the geographical concentration of production. Such bottlenecks could lead to the short-term accrual of economic rents to producers, potentially at the expense of consumers and public funding organs. In the long term, this dynamic could signal the need for capacity expansion. Interfering with short-term economic rents is considered a second-best policy, as it may undermine the incentive for longer term capacity investment. The optimal outcome is to proactively prevent capacity constraints. Therefore, policy should anticipate local bottlenecks and implement measures to address the root causes of any identified constraint, such as offering production incentives and removing barriers to transport and market entry. This proactive approach becomes particularly crucial when implementing demand stimulus.

- *The cost competitiveness of hydrogen is contingent upon a substantial scale-up in production.* Specifically, achieving cost competitiveness depends on deploying electrolysers at a rate that is 1000 times higher than today by the year 2040. This ambitious deployment rate, while holding the potential for cost-competitiveness in various applications, also introduces a low to medium likelihood of success. Consequently, pursuing hydrogen applications is considered high-risk, particularly when there are alternative options that may offer cost-effectiveness with greater certainty.

- *In hydrogen production, the scaling of production and cost reductions linked to deployment carry greater significance than laboratory-based research and development (R&D).* Investments in public innovation should be closely aligned with subsidies that facilitate deployment rather than those focused on laboratory-based activities. This strategic alignment is justified by the fact that many opportunities for cost reduction are tied to the standardisation of production processes and the realisation of economies of scale. The operational experience gained through the operation of pilot plants is crucial for optimising system design. While laboratory research remains valuable, its emphasis should be on initiatives such as reducing the operating temperature for solid electrolysis cells (SOECs) and developing new system designs like proton exchange membrane (PEM) stacks tailored for higher pressure or differential pressure operation—both important for direct integration with renewable energy sources. Therefore, research and development efforts should be directed towards lowering capital costs and simplifying system complexity.

- *Implementing policies to support hydrogen-based heating systems represents a high-risk strategy.* The cost-effectiveness of hydrogen-fuelled space heating relies on the realisation of two uncertain outcomes: the deployment of electrolysers at large-scale rates (approximately a thousand times greater than present) and significant levels of learning-by-doing. Moreover, there is a prolonged lead-in time to complete the adoption and decarbonisation process, resulting in a narrow and uncertain window for deployment. Choosing to pursue a hydrogen-based heating strategy may necessitate action either before achieving cost-parity or when there is limited time left to achieve decarbonisation goals by 2050. This introduces inherent risks that should be carefully considered in the decision-making process for policy development.

- *Whenever feasible, the implementation of technology-neutral supports is recommended.* Given the uncertainties in costs and the existence of potential alternative technologies, policy need not overly focus on hydrogen-specific supports. Opting for technology-neutral supports offers several advantages, as (1) it eliminates the risk of backing a technology that may not be cost-effective, and (2) it upholds individual liberties. Similarly, the adoption of hydrogen-fuelled vehicles should be driven by consumer preferences and market prices, and technology-specific policies should refrain from distorting these decisions. While hydrogen is a leading candidate for decarbonised Heavy-Duty Vehicles (HDVs), the balance between hydrogen and non-hydrogen Light-Duty Vehicles (LDVs) and private cars remains uncertain and should be determined by consumer preferences. Although price supports and adoption incentives naturally align with technology neutrality, challenges may arise when policy aims to support specific developments, such as hydrogen transport refuelling infrastructure. In many cases, market forces can naturally propel infrastructure development. If public support is deemed necessary for early-stage development, a technology-neutral approach can be achieved through competitive Research and Development (R&D) awards or auction schemes.

- *Many applications, particularly those related to electricity and industrial processes, are inherently market-driven.* In response, policy intervention should be directed towards facilitating the timely adoption of these technologies. The strategy for market-driven applications, such as those in electricity and industrial processes, is straightforward and immediate: minimise transaction costs and establish clear, efficient regulatory processes. In an environment where these conditions are met, timely adoption is likely to follow cost-competitiveness. In the realm of electricity, hydrogen may play a role within a mixed technology portfolio. The specific contribution, challenging to predict by policy, may be incentivised through clear energy and capacity market signals. Therefore, the role of policy is to ensure the implementation of a well-functioning, technology-neutral capacity procurement process that is calibrated to the evolving requirements of a decarbonising grid.

- *The ongoing policy discourse should pivot away from blue hydrogen in favour of prioritising green hydrogen.* Many current policies contemplate the short to medium-term utilisation of 'blue' hydrogen. While there is a possibility that blue hydrogen might be low-carbon and aid the transition to green hydrogen in the long run, recent research urges caution against relying on it as a bridging strategy. Emissions from hydrogen production systems based on natural gas or coal could be significant, even with the incorporation of carbon capture and storage (CCS). Moreover, evidence suggests that the cost of CCS may be higher than commonly assumed. Electrolysis utilising renewable energy has the potential to become more cost-effective in the long term through substantial deployment and production economies. This outcome may be more likely if policy emphasis is directed towards green hydrogen rather than blue hydrogen.

5.2. EU Green Hydrogen Policies and initiatives

Green hydrogen has become an important renewable energy carrier for Europe, in particular after publishing the EU Hydrogen Strategy in 2020 (European Commission 2020). In the realm of policy emphasis, achieving a substantial expansion within a relatively brief timeframe necessitates the enhancement of the European Union's support mechanisms and the encouragement of investments to establish a comprehensive hydrogen ecosystem. The European Union's objective by 2030 is to establish a transparent and competitive hydrogen market, promoting unimpeded cross-border trade and the efficient distribution of hydrogen resources across various sectors. In the subsequent phase spanning from 2030 to 2050, the focus shifts towards advancing renewable hydrogen technologies to a state of maturity, facilitating their extensive deployment in hard-to-decarbonise sectors where other alternatives might not be feasible or have higher cost. Concurrently, there is a need for a substantial increase in renewable electricity production, as approximately one-fourth of the total renewable electricity output is envisioned to be allocated for renewable hydrogen production by the year 2050.

It should also be noticed that the EU energy policies changed after the war in Ukraine in 2022, resulting in accelerating the green energy transition including the green hydrogen economy, as demonstrated in Figure 11. Since the beginning of 2022, European support for hydrogen projects in Africa has intensified not only in response to decarbonisation targets, but also because of threats to energy security brought into focus by the ongoing conflict in Ukraine. Two initiatives, the Mediterranean Green Hydrogen Partnership and the H_2Global Mechanism, seek to build upon Africa's hydrogen potential through ‘hydrogen diplomacy’ and funding, increasing investment in Africa's electrolysis capacity and the underlying renewable energy projects necessary to facilitate green hydrogen production (Clifford Chance 2023). This sudden acceleration of the hydrogen economy is also a concern of one of our interviewees. According to the interviewee, a Dutch climate envoy, the safe usages and storage of green hydrogen are overlooked in the process of strategy development and policymaking and there is a need for more adequate research and planning. In this section we summarise current EU policies on green hydrogen.

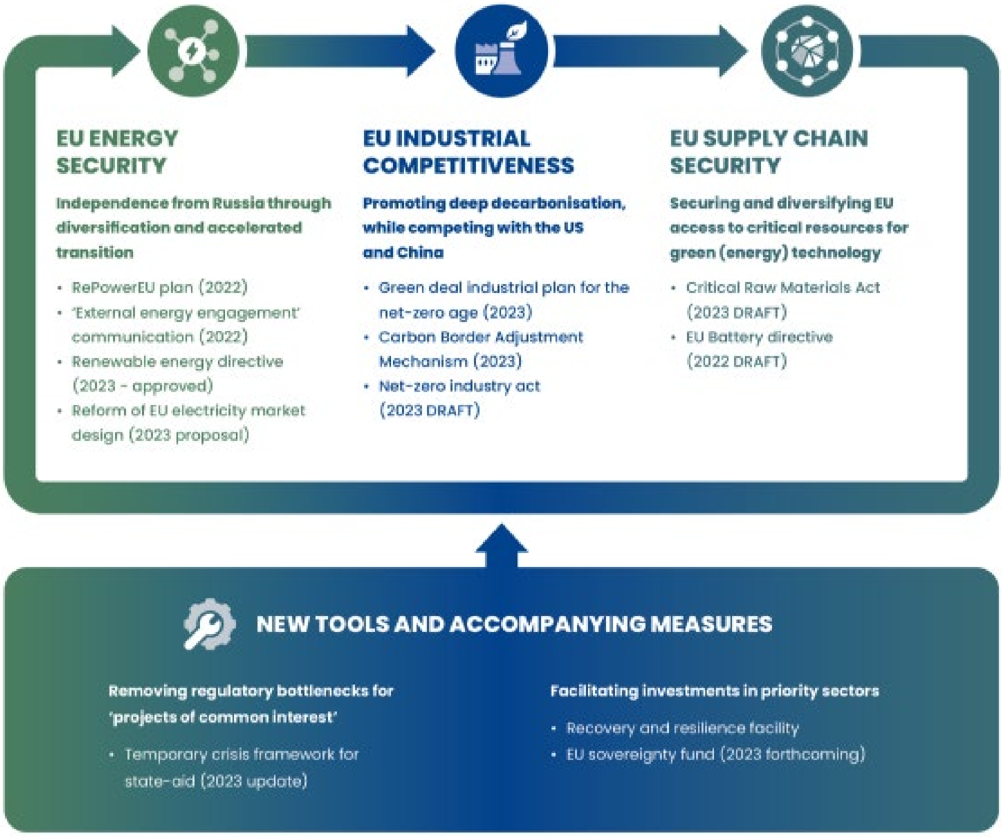


Figure 11: EU Policy shifts since the war between Russian and Ukraine in 2022 (Karkare and Medinilla 2023)

5.2.1. Africa–Europe Green Energy Initiative:

The Africa–Europe Green Energy Initiative aims to facilitate collaboration between European and African sectors in both the public and private sectors. The primary objectives include expanding electricity production, improving energy access, fostering energy efficiency, supporting regulatory reforms conducive to private investment, and promoting market integration. As a vital element of the Global Gateway in Africa, this Team Europe Initiative brings together the European Union (EU), its Member States, European financial and development institutions, and the private sector. Key partners in this collaborative effort include the European Investment Bank (EIB) and the European Bank for Reconstruction and Development (EBRD). The overarching goal is to synergise efforts in advancing sustainable energy solutions and fostering mutually beneficial partnerships between Africa and Europe.

In 2023, the West African Power Pool coordination centre was inaugurated in Benin. Agreements with the European Investment Bank (EIB) were signed for Burundi, Cabo Verde, and Djibouti. A call for proposals is underway for a hydrogen power plant in Morocco, aligning with the Africa–EU Green Energy Initiative. As part of this initiative, preparations are ongoing for a Power-to-X (P2X) hydrogen power reference plant in Morocco through a public–private partnership (PPP). This project, in line with European and German hydrogen strategies, aims to strengthen Morocco's position in the sector. The project's volume includes a grant of up to USD 110 million (EUR 100 million) to de-risk and facilitate the PPP approach, attracting private investment for the development of a green hydrogen economy in Morocco.

5.2.2. A hydrogen strategy for decarbonising Europe

Hydrogen is the bridge to close the emission gap after large share of the European energy consumption is decarbonised with renewable electricity. Renewable and low-carbon hydrogen is seen as a solution to reduce greenhouse gas emissions, boost the EU economy, and achieve a climate-neutral economy by 2050. The EU hydrogen strategy, introduced in July 2020, aims to establish a framework for the production, distribution, and use of hydrogen as a clean energy carrier within the European Union. The strategy focuses on three key objectives: decarbonisation, competitiveness, and the building of a hydrogen ecosystem. Hydrogen is seen as a crucial tool in decarbonising hard-to-abate sectors, such as heavy industry, transport, and heating. At the same time, the European Union intends to position itself as a global leader in hydrogen technologies by fostering research, innovation, and investment in hydrogen-related technologies, infrastructure, and markets to boost competitiveness. This includes promoting the development of a domestic hydrogen industry, improving cost-effectiveness, and ensuring the competitiveness of European businesses in the sector. The strategy also envisions the creation of an integrated hydrogen market across the European Union, connecting regions with abundant renewable energy resources to areas with higher hydrogen demand. This entails the development of a comprehensive infrastructure network for hydrogen production, storage, transportation, and distribution, that emphasises the need for international cooperation and partnerships to facilitate the deployment of hydrogen technologies (European Commission 2020).

5.3. Ensuring an inclusive and a just energy transition

The topic of ensuring a just and inclusive energy transition is a top priority for the European Commission. During the 2021 State of the Union Address, the president stated the aim to ‘invest with Africa to create a market for green hydrogen that connects the two shores of the Mediterranean’ and to ‘create links and not dependencies!’ (Lindner 2022). In addition, the European Union's hydrogen strategy emphasises the mutual benefits of collaboration between Europe and Africa, which it referrers to as the ‘Southern and Eastern Neighbourhood partners’ (Lindner 2022).

The book by Weijnen, Lukszo and Farahani (2021) advocates for a socially inclusive energy transition and demonstrates how professionals in engineering and public policy can play a crucial role in shaping an inclusive energy transition, drawing on a socio-technical systems engineering approach. While achieving a net-zero greenhouse gas emissions economy by 2050 poses a formidable challenge, the book emphasises the significance of examining the energy transition's challenges through the lenses of technological innovation, public policy, social values, and ethics.

The narrative underscores two often overlooked gaps in the design of public policy interventions aimed at decarbonising the energy system. Firstly, the compartmentalised structure of public administration neglects the numerous interdependencies between the energy sector, mobility systems, digital infrastructure, and the built environment. Effective cross-sector coordination of policies and policy instruments becomes imperative to prevent potential conflicts with other social and economic objectives that could impede the energy transition. Secondly, energy and climate policies frequently neglect the social values inherent in the energy transition. Addressing these gaps enables decision-makers involved in the energy transition to view it as an opportunity to foster a more inclusive and just society (Weijnen, Lukszo and Farahani 2021).

Green hydrogen is poised to play a pivotal role in decarbonising the economy, as indicated by the scenario analysis in the previous chapter. As we transition toward a system dominated by variable renewables such as solar and wind, hydrogen emerges as a link connecting electricity with diverse applications like industrial heat, materials production (e.g., steel and fertilizer), space heating, and transport fuels. Moreover, green hydrogen offers the advantage of seasonal storage and cost-effective long-distance transportation, largely using existing natural gas infrastructure.

Together with renewable electricity, green hydrogen has a potential to completely replace hydrocarbons. Given Europe's limited size and population density, it is obvious that a portion of the required renewable energy may need to be imported. While hydrogen imports can originate from various regions with favourable solar and wind resources, an exciting prospect is the import from North Africa. Currently, a significant share of Europe's natural gas and oil supply already comes from North Africa, with 60% of the region's oil exports and 80% of its natural gas exports directed to Europe (Eurostat 2023). This existing energy relationship positions North Africa as a potentially strategic partner in Europe's green hydrogen aspirations.

There is a potential for mutual benefit through establishment of a collaborative hydrogen economy between Europe and North Africa. The proximity of the two regions, separated only by the Mediterranean Sea, enables the cost-effective transportation of hydrogen through pipelines, a more economical option compared to shipping. Embracing hydrogen imports from North Africa could advance and streamline Europe's transition to a sustainable energy system, aligning with its commitments to the Paris Agreement in a faster and more cost-efficient manner.

Beyond the environmental advantages, a joint European–North African green hydrogen initiative fosters inclusiveness and justice. This collaborative approach has the capacity to stimulate economic development, create robust employment opportunities, and enhance social stability in North African countries. An additional positive outcome could be a potential reduction in the number of economic migrants from the region. By linking their efforts in a shared energy vision, Europe and North Africa can address climate goals while also promoting economic growth, job creation, and social well-being in both regions (Weijnen, Lukszo and Farahani 2021).

The JUST GREEN AFRH2ICA initiative aims to promote a just transition to green hydrogen in Africa through developing a green hydrogen just transition roadmap based on AU–EU stakeholder consultation. It seeks to avoid ‘new EU hydrogen colonisation’ but to ensure a mutual beneficial cooperation ‘towards the development of independent and collaborative hydrogen economies, R&D ecosystem and value chains’.

5.4. Policies, challenges and opportunities in African Countries

The availability of abundant renewable energy resources and large land mass positions several countries in Africa as potential locations to produce green hydrogen. Availability of space and experience in oil and natural gas production are the two main criteria used by Port of Rotterdam to assess a country's potential for hydrogen production (interview with Director Port of Rotterdam

International, René van der Plas). The experience with oil and natural gas production is important as these countries have a better knowledge, infrastructure, and basics to realise the transition to hydrogen. Below we discuss six countries in Africa: Algeria, Egypt, Mauritania, Morocco, Namibia and South Africa. These countries have high potential for green hydrogen production, already have electrolyser investments, and are strategically position in terms of resources, infrastructure or proximity to Europe. The opportunities and challenges are summarised in Table 4.

Algeria

Algeria is an aspiring regional leader in the production and export for green hydrogen. It has big potential for transport to the European Union since it already has a pipeline connecting the country with the European continent. In addition, it has other existing infrastructure supporting export of green hydrogen. However, there are also several challenges and barriers. According to interviewee 3, the main challenge for Algeria lies in the fact that the current investment climate is very discouraging.[5] This has mainly because of the high taxation and high share of revenue appropriated by the national government. In addition, there is a risk of weak regulation of various economic sectors and political instability.[6]

Egypt

Egypt started with the production of green hydrogen in the 1960s. At that time, the Egyptian Chemical Industries (KIMA) started to produce green ammonia by using the hydropower from the Aswan Dam (Choksi, Meeraus and Stoutjesdi. 1980). Although Egypt has a large population, considerable share of the future production of green hydrogen might be exported due to existing long-term contracts with domestic industries for the supply of grey hydrogen, which cannot be terminated. This makes Egypt a potential exporter of green hydrogen to Europe. The Suez Canal also provides great opportunities for transporting green hydrogen to Europe through shipping. Furthermore, Egypt's current climate is more competitive for the generation of green hydrogen because of regulations that attracts investments. Challenges in the context of Egypt also exist. First, although Egypt has attractive investing regulations for producing renewable energy, the economic liberalisation project in Egypt is not yet completed. Secondly, the expected water stress Egypt will face in the near future can also affect the production of green hydrogen. And lastly, the currency devaluation of the currency can scare off investors. On the other hand, it can also be in favour of investors as it will make labour cheaper.[7]

Mauritania

Mauritania, often referred to as 'Africa's Global Green Hydrogen Hub,' is emerging as a key player in the prospective hydrogen market, leveraging its substantial renewable energy assets. By the year 2035, Mauritania's full potential for generating green hydrogen is estimated at 12.5 million tons annually, presenting opportunities to meet local demands, propel domestic economic advancement, uplift communities, and facilitate exports to global markets. The progression of the AMAN green hydrogen project in Mauritania holds the promise of significantly enhancing the nation's GDP and employment opportunities (AGHA 2022). The project could contribute to a 40%–50% GDP increase by 2030 and a subsequent 50%–60% rise from 2035 onward. Moreover, the

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[5] *Interviewee 3, interviewed in August 2023*

[6] *Paper Cardinale*

[7] *Interviewee 3, interviewed in August 2023*

initiative has the potential to elevate industry employment by 23%, thereby mitigating national unemployment levels by almost a third by 2035, owing to the creation of jobs associated with the project's construction and operation.

An important challenge for Mauritania is the limited renewable energy infrastructure. Green hydrogen production relies on a stable and abundant source of renewable energy, such as solar or wind power. Mauritania has substantial solar potential, but the infrastructure for harnessing and transmitting this energy needs to be expanded and improved. In addition, Developing and operating green hydrogen facilities requires specialised knowledge and expertise. Other challenges include water scarcity and the absence of clear regulatory and policy frameworks. A clear and supportive regulatory and policy framework is essential to attract investment and promote green hydrogen development.

Morocco

The Netherlands initiated conversations with Morocco on exporting green hydrogen to Europe. However, lately, these discussions have been taken over by German parties. Morocco runs two huge hydrogen projects. The first is in the Southwest of Morocco and operated by MASEN, the Moroccan Agency for Sustainable Energy. A national agency with great ambitions when it comes to the production of hydrogen and other sustainable and renewable forms of energy. The second hydrogen project will start in Tanger where a new port is being built. The Port of Rotterdam is closely following this project and have plans to start cooperation. Tanger port will provide great opportunities for Europe when it comes to exporting hydrogen from Morocco to Europe. However, one of the challenges in the case of Morocco is that a large amount of the produced hydrogen will be needed locally. As such, not much will be left of the hydrogen to export to Europe.

Namibia

The Netherlands and Namibia have formed a partnership to cooperate on green hydrogen infrastructure that will lead to new hydrogen supply chains from Lüderitz to Rotterdam and its hinterland.[8] Namibia is a very promising option when it comes to potential countries for green hydrogen production and export. It enjoys both political stability and a great investing environment. In addition to that, it has small population, which provides the opportunity to export lots of produced hydrogen since it will not be needed to cover local demands. A challenge in the case of Namibia is that it has no previous history in the oil and natural gas industry. This means that the country lacks infrastructure for production and transport of energy. Moreover, it lacks the experience and knowledge in producing and transporting energy.

South Africa

South Africa is actively pursuing ambitious goals in the field of green hydrogen production. To initiate a robust hydrogen economy, the government, in collaboration with the private sector, has identified four pivotal projects. These encompass the Platinum Valley Initiative (also known as the South African Hydrogen Valley), the CoalCO_2-X Project, the Boegoebaai Special Economic Zone (SEZ), and the Sustainable Aviation Fuels (SAF) project. The successful implementation of these flagship projects is anticipated to yield approximately 500kt of hydrogen annually and generate a

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[8] *The Netherlands forms green hydrogen partnership with Namibia - Offshore Energy (offshore-energy.biz)*

minimum of 20,000 jobs by 2030. Furthermore, these initiatives aim to contribute at least USD 5 billion to the Gross Domestic Product (GDP) of the economy by the year 2050.

A significant advantage for South Africa lies in the extensive land and space available for the production and storage of green hydrogen. However, several challenges pose obstacles to investment, including pervasive corruption, political instability, and a fragile energy grid within the country. These factors serve as substantial deterrents for potential investors, such as the Port of Rotterdam, in engaging in green hydrogen projects in Africa.

Table 4 : Opportunities and challenges of green hydrogen programs in Africa

Country	Strategic Plans Green Hydrogen	Opportunities for the European Union	Challenges
Algeria	Instalment of 22 GW of renewable energy by 2030, and to achieve 27% of electricity produced from renewable energy, expanding the electricity network by additional 20,000 km by 2030, the objectives are to alleviate the pressure on a declining natural gas production, to create a new industry that contributes to employment and economic growth, as well as to reduce 193 million tons of CO_2 emissions.	- potential cost advantage in transporting green hydrogen to Europe given an overcapacity in its existing natural gas infrastructure, which could be repurposed	- Needs to improve investment climate (now: higher taxation and a higher share of revenue appropriated by the national government, and weak regulation and political instability)
Egypt	experience in green hydrogen production since the 1960s, Considerable share of the future production of green hydrogen might be exported due to existing long-term contracts with domestic industries for the supply of grey hydrogen	- more competitive in the generation of renewable power, a key input of green hydrogen - Suez Canal provides great opportunities for transport through shipping	- Liberalisation started but not yet completed - Water Stress - Devaluation of the currency
Mauritania	It has signed a memorandum of understanding with CWP Global for a $40 billion green hydrogen project called AMAN	- Opportunity to export huge amounts of green hydrogen - complete potential for producing green hydrogen is evaluated at 12.5 million tons per year by 2035	- Limited Renewable Energy Infrastructure - Lack of Technological Expertise - Water Scarcity - Absence of a Regulatory and Policy Framework
Morocco	Masen has great ambitions when it comes to hydrogen production, it runs a big project in Southwest Morocco where Germany is also involved.	- A new port under construction in Tanger, which is promising for hydrogen transport to Europe, the Port of Rotterdam is involved in this project.	- A big share of the produced hydrogen is needed locally in Morocco, exporting hydrogen which is produced in Morocco is thus a challenge.

Country	Strategic Plans Green Hydrogen	Opportunities for the European Union	Challenges
Namibia	The Netherlands and Namibia have formed a partnership to cooperate on green hydrogen infrastructure that will lead to new hydrogen supply chains from Lüderitz to Rotterdam and its hinterland	- Political stability - Great investing environment - small population that provides opportunity to export most of the hydrogen	- No previous history in the oil and natural gas industry, hence, lack of experience with producing energy, lack of infrastructure.
South Africa	Four projects were identified by the government through engagements with the private sector, through the implementation of these projects, South Africa produces approximately 500kt of hydrogen and creates at least 20 000 jobs annually by 2030, and a Gross Domestic Product (GDP) contribution of at least USD5 billion to the economy by 2050.	- Large space for hydrogen production and great opportunities for hydrogen production	- difficult country with lots of corruption, political instable, and unstable power grid

5.5. Potential for collaboration between Africa and Europe

Hydrogen can be produced almost anywhere in the world; however, the economic competitiveness varies by region and country. At the same time, there is a big gap between where the high demand for low-carbon hydrogen is and where the potential for large amounts of low-carbon hydrogen supply is. Several countries in Africa have the potential to produce enormous amounts of green hydrogen given the abundance of renewable energy, vast land mass, existing pipeline networks, and strong drive for climate neutral development.

While renewable electricity can be easily exported to neighbouring countries through a regional grid system, hydrogen offers an opportunity to export renewable energy over much longer distances through pipelines and shipping. Transporting a chemical fuel does not suffer from losses and benefits from economies of scale. But the economic competitiveness of green hydrogen to other forms of hydrogen remains limited for the next couple of decades. However, that will change in the middle of the century with rapidly declining technology costs, stringent climate change mitigation measures, and demand side measures. Therefore, it is important to step-up investment flows into research and development, capacity building, expanding renewable electricity generation, and transport and storage infrastructures.

There is a high potential for greater cooperation between Europe and Africa, and the two regions could become more interdependent. Green hydrogen offers new opportunities for the energy transition in Africa demonstrating synergies with several sustainable development goals and Agenda 2063 aspirations. It is a key component of the European Green Deal and it is projected to play a major role in decarbonising the energy system. It is therefore of critical importance to make long-term commitments, financially and politically, to ensure a sustainable and resilient basis for a hydrogen economy in Africa and beyond.

African countries see the opportunities in the hydrogen economy for both local economic development and as an export commodity. These two roles could either strengthen each other or be in competition. Establishing a hydrogen economy should prioritise domestic electricity access and local economic development either by directly contributing to these goals or by reinvesting export earning into electrification projects and other development programs. The investments of European countries in hydrogen generation and export infrastructure in Africa could at the same time be used to stimulate a hydrogen industry for the domestic market. If that does not happen there could be a competition for limited resources.

In developing the hydrogen economy in Africa, the country specific context in terms of electricity access challenges, energy and water resources availability, and technical and economic capacity should be carefully considered. The collaboration between Africa and Europe should focus on addressing the lack of sustainable (affordable) funding, providing training, and supporting research and development for technologies in the hydrogen value-chain. This collaboration should also acknowledge country heterogeneity in terms of local potentials and constraints and think critically beyond the traditional (fossil) energy markets.

Europe and Africa are at different stages of the energy transition. The demand for hydrogen in Africa at the moment is small but it is projected to pick-up in the long term. Large-scale, secure investment in green hydrogen production could help decarbonise fertilizer production and provide alternative clean energy for energy intensive industrial development such as steel production, in the long term. In the short term, the focus could be the export to the European market, given that the concerns associated with energy access challenges, water scarcity, and fairness issues are properly addressed. Existing natural gas export routes between Africa and Europe could be leveraged for transporting green hydrogen and its derivatives.

In addition to transporting hydrogen as ammonia and methanol, a promising pathway for importing hydrogen is though commodities such as steel and cement, two industrial products that account for a large share of industrial emissions. Economic competitiveness is the main consideration before deciding between relocating hydrogen consuming industries to the hydrogen production site or producing the hydrogen in areas with high renewable energy potential and transporting it to end users. Relocating energy intensive industries to areas with excellent renewable energy resources could be a cost-effective way of decarbonising the sector.

While there are largely favourable conditions, it will be the interplay of actors in government, business and research that will shape the success of green hydrogen across Europe and Africa. The focus of the collaborative hydrogen strategy should be green hydrogen, for two main reasons; (1) to get the maximum decarbonisation potential for Europe and (2) to utilise the big resource potential in Africa and ensure energy sovereignty. The strategy should also enable an integrated approach from new and existing demand sectors that requires cross-sector coordination of policies and policy instruments to benefit from economies of scale. This partnership should be for mutual benefits, recognise local characteristics, ensure that the environmental, social and economic concerns are properly addressed, and enable social and economic development of Africa.

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Appendices

1. Interview protocol

1. What potential do you see for hydrogen in your sector?
2. Hydrogen infrastructure — transport and storage, available technologies, their risks and opportunities in the short, medium and long term
3. What is the most viable supply chain?
4. What are the key hydrogen policies in Europe and Africa?
5. Hydrogen investment- Where is it coming from? What part of the supply chain?

2. List of interviewees

Table 5: key persons. organizations interviewed

Organisation	Position	Country/region
The European Commission	Policy Officer on Hydrogen	European Union
University College London and the American University in Cairo	Assistant Professor on Green Hydrogen Economy in Africa	Egypt, United Kingdom
Port of Rotterdam	Director International Port of Rotterdam	Netherlands
Technical University of Delft	Professor and Author in Green Hydrogen and Just Energy Transitions	Netherlands
The Competence Center Energy Policy and Energy Markets	Professor and Head of center	Germany