PBL Netherlands Environmental Assessment Agency

The Green Hydrogen Dilemma

The risks, trade-offs, and co-benefits of a green hydrogen economy in low- and middle-income countries

Anteneh G. Dagnachew & Stephanie Solf

July, 2024

PBL

Colophon

The Green Hydrogen Dilemma. The risks, trade-offs, and co-benefits of a green hydrogen economy in low- and middle-income countries

The Hague, 2024

PBL publication number: 5534

Corresponding author

Anteneh.dagnachew@pbl.nl

Authors

Anteneh G. Dagnachew & Stephanie Solf

Acknowledgements

We would like to thank Anne Gerdien Prins for the constructive comments and guidance throughout the process, as well as Detlef P. van Vuuren for his valuable comments in the earlier versions of the policy brief, which greatly improved the outcome. We are also grateful to Andries Hof, Paul Lucas, Lucy Oates, and Edo Abraham for reviewing the policy brief and providing us with constructive, comprehensive, and substantial feedback that improved the quality, validity, and significance of the research.

Production coordination

PBL Publishers

Accessibility

PBL attaches great importance to the accessibility of its products. Should you encounter any access-related problems when reading them, please contact us at info@pbl.nl, stating the title of the publication and the issue you are experiencing.

Contents

Summary

This policy brief, based on literature review, discusses frequently mentioned risks, trade-offs, and co-benefits of establishing a green hydrogen economy in low- and middle-income countries. The main findings are:

- **The water- and land-related risks of the green hydrogen economy are largely local and are felt by the producing country**. It is, therefore, very important to identify project-based risks including competition with other water uses, environmental flows, and land use conflicts as well as develop good practices for managing these risks within the context of the local socio-economic situation. The local context, including the current and future water cycle, the geology, and climate values, should be embedded within water and land management strategies as part of the plan to establish a green hydrogen economy. The inclusion of civil society, private, and public sectors in the decision-making process of green hydrogen projects, is equally crucial for minimising the risks and securing the benefits for the local population.

- **The additional water requirements for green hydrogen could exacerbate water stress, especially in regions already facing scarcity due to factors like population growth and climate change, although at a global scale the requirement is small compared to other water demands.** Water stress can pose threats to sustainable development and spark conflicts at various levels. Technologies such as seawater desalination and air-to-water generation offer potential solutions to mitigate water scarcity risks associated with green hydrogen production, though some of these technologies are still at an early stage. There are also brine management technologies that reduce concentrated brine and chemical discharge that impact marine environments. Addressing this challenge requires collaborative approaches between the private sector, government, and civil society actors. Governments and regulatory bodies play a pivotal role in managing water resources and promoting sustainable practices to ensure the long-term viability of green hydrogen as a clean energy solution while minimising the impact on water.

- **Large-scale renewable energy projects necessary for green hydrogen production could potentially encroach upon natural habitats and agricultural areas, posing risks to biodiversity and food security.** The renewable energy required for green hydrogen requires considerable amounts of land. Pressures on land use are escalating environmental concerns, particularly in Africa, where competition for arable land and pastures is intensifying. Mitigating these challenges requires inclusive planning processes, effective land-use policies, and stakeholder collaboration to ensure sustainable integration of green hydrogen projects while addressing local concerns and safeguarding land resources. Before committing to establishing a green hydrogen project, it is important to understand the local legal and regulatory framework governing land acquisition and use. The land tenure risks, relations with Indigenous groups, and existing land rights need to be thoroughly understood.

- **Establishing a hydrogen infrastructure in low- and middle-income countries demands substantial upfront investment and has high Weighted Average Cost of Capital, potentially competing with funding for essential initiatives like renewable energy**

deployment, energy efficiency measures, and nature-based solutions that are important for national climate change mitigation and adaptation. While green hydrogen can play a significant role in decarbonising hard-to-abate sectors, such as heavy industry and long-distance transportation, it should complement broader efforts that prioritise renewable energy deployment, energy efficiency, and sustainable land use practices. Ensuring coherence, transparency, and accountability in climate policy decision-making is essential for navigating the transition to a sustainable and resilient low-carbon future.

- **The development of green hydrogen offers a promising solution to reduce greenhouse gas emissions and air pollution, provided that the water and land risks are properly addressed.** Green hydrogen is a versatile energy carrier with the potential to reduce emissions in energy-intensive industries and long-haul transport. This can contribute to national emission reduction targets and improve local air quality. Strategic integration of green hydrogen into broader climate mitigation strategies is essential to maximise its benefits while simultaneously ensuring a balanced and holistic approach to addressing climate change. Continued investment, innovation, and collaboration are essential in realising the full benefits of green hydrogen and accelerating the transition to a cleaner, greener energy landscape.

- **Green hydrogen has the potential to create a sustainable supply of fertilisers, enhance food security, and reduce GHG emissions from fertiliser production.** Green hydrogen can provide a cleaner, more stable, and predictable alternative by replacing fossil fuels in the ammonia synthesis process. Through domestic production, green hydrogen can decouple the price of fertiliser from fossil fuel prices ensuring affordability and sustainability of supply. Through the sustainable production of ammonia from green hydrogen, low- and middle-income countries can improve local food production, enhance their food security, and reduce emissions from fertiliser production. This, however, requires significant investment in scaling up production of green hydrogen and a supportive policy framework to stimulate the sector as well as to ensure that domestic needs are met before considering export.

- **Green hydrogen has the potential to advance universal access to clean energy and clean water in low- and middle-income countries.** Investments in green hydrogen infrastructure, technology transfer, market development, and local capacity building can reduce costs and the complexity of the energy system, facilitating the widespread deployment of renewable energy technologies. Moreover, green hydrogen enhances energy security by reducing reliance on imported fossil fuels, mitigating price volatility, and improving the flexibility and resilience of energy systems. Revenue generated through the export of green hydrogen can also be reinvested to improve energy access in underserved communities. Similarly, promoting green hydrogen production presents an opportunity to adopt integrated management approaches to the energy-water nexus. Technological innovations, such as integrated systems where desalinated water is used for both hydrogen production and other end-uses like irrigation and domestic use, offer promising solutions. By recognising the interconnectedness of energy and water systems, policymakers and stakeholders can develop strategies to optimise resource use and ensure that a green hydrogen economy contributes positively to clean energy and water access.

- **The development of green hydrogen infrastructure and value chains can stimulate economic growth, create employment opportunities, and drive green industrialisation,**

particularly in low- and middle-income countries. Investments in green hydrogen infrastructure and technology not only foster domestic industry growth, but also create opportunities for supply chain development and economic diversification. Strategic industrial policies focused on integrating the hydrogen value chain can increase the local added value, create high-quality jobs, and reduce distribution costs across multiple sectors. There is the need to create local capacity, leverage project Memorandum of Understandings with European countries to set up exchange programmes and other forms of knowledge transfer and identify local demand prior to decision-making.

- **Establishing a green hydrogen economy brings various risks and trade-offs that need thorough attention as well as co-benefits for other development goals.** Key risks include exacerbating water scarcity and intensifying land-related conflicts. There is also the potential risk of hydrogen leakage and the risk of crowding out funding for other climate change mitigation measures. At the same time, green hydrogen offers co-benefits such as improving air quality, improving access to water, enabling green industrialisation including fertiliser production, and creating decent jobs. Strategic integration of green hydrogen into broader climate mitigation strategies is essential to maximise these benefits while simultaneously minimising the risks and ensuring a balanced and holistic approach to addressing climate change. By capitalising on the synergies between green hydrogen and sustainable development goals, African countries could accelerate the transition to a low-carbon economy while fostering inclusive and resilient economic development.

FULL RESULTS

FULL RESULTS

1 Background

The global energy landscape is going through a profound transition towards sustainability, driven by the urgent need to mitigate climate change and reduce reliance on fossil fuels and its associated high energy costs. In this context, hydrogen has emerged as a promising alternative energy carrier.

Hydrogen is categorised into various colours, which refer to the many ways and processes of production. Grey hydrogen, produced through fossil fuel-based reforming or gasification, is the most cost-effective and dominant method, accounting for 80% of current hydrogen production. It comes, however, with high greenhouse gas emissions. Blue hydrogen is also produced from fossil fuels but has an improved environmental impact by incorporating carbon capture, utilisation, and storage (CCUS), capturing up to 90% of CO_2 emissions during production. Green hydrogen, produced via water electrolysis using renewable energy, is by far the cleanest method with zero emissions released during production. As the world seeks to decarbonise numerous sectors, green hydrogen holds great potential to provide a carbon-free energy carrier for a wide range of applications and so to foster economic development.

A few European nations, which have limited land area and relatively low renewable energy potential themselves yet a high energy demand, are showing a growing interest in importing green hydrogen from low- and middle-income countries. There are various studies, plans, and programmes by the European Commission, as well as some European countries like the Netherlands and Germany, already in the pipeline to explore and/or establish a green hydrogen economy in a few countries. The notion of a green hydrogen economy is intertwined with the wider energy sector at several levels, bringing its own opportunities, such as green industrialisation and energy security, as well as challenges and risks, such as pressure on land and water systems I(Signoria and Barlettani 2023; Eljack and Kazi 2021; Bade et al. 2024).

There is an important difference between the priorities of the Global South and North that centres around the question of meeting the growing energy demand for development and mitigating climate change. In the Global South, where many nations are still grappling with basic energy access challenges, the primary focus often lies on addressing energy poverty, accelerating economic development, and adapting to climate change. This involves expanding infrastructure, increasing electricity access, and fostering inclusive industrialisation that helps lift people out of poverty. In the Global North, on the other hand, where energy consumption per capita tends to be several folds higher and infrastructure development tends to be more advanced, there is a greater emphasis on climate change mitigation, energy security, and the transition towards sustainable energy systems.

Bridging the gap between the respective priorities is essential (International Energy Forum 2023). There is an increasing recognition that sustainable development pathways must integrate energy access, climate resilience, and human development goals. Efforts to reconcile these priorities involve fostering international cooperation, technology transfer, and financial support to enable low- and middle-income countries to leapfrog to cleaner and more efficient energy technologies. Ultimately, addressing the priorities of both the Global South and North requires a holistic approach that balances socio-economic development with climate change mitigation and adaptation efforts. Working towards a more sustainable and inclusive future requires leveraging innovation, collaboration, and equitable policies.

The Dutch Ministry of Foreign Affairs is involved in various aspects of the development cooperation with African partners. Green energy, particularly green hydrogen, is a main interest area of collaboration as stated in the Africa Strategy of the Netherlands 2023-2032 (The Ministry of Foreign Affairs 2023). Moreover, the Netherlands Enterprise Agency (RVO) published a ‘Dutch Green Hydrogen proposition for South Africa’ last year, suggesting joint investment and market development opportunities for green hydrogen in South Africa (Becker et al. 2023). There is a drive to make the collaboration on green hydrogen beneficial to all parties involved, including climate change mitigation, energy security, income generation, and local socio-economic development. At the same time, the risks related to land and water systems, environment, and health need to be mitigated and synergies with other development goals should be harnessed.

An earlier PBL report, (Dagnachew et al. 2023), shows the role of green hydrogen in regional and global future energy systems and the role it plays in reducing emissions. While low- and middle-income countries, such as South Africa, Namibia, Mauritania, and Morocco, often face unique challenges in transitioning to sustainable energy systems, they also stand to benefit considerably from their vast renewable energy potentials.

This policy brief explores several social, environmental, and financial risks and trade-offs associated with the green hydrogen economy, as well as its co-benefits for the sustainable development goals in the context of low- and middle-income countries such as Algeria, Egypt, Mauritania, Morocco, Namibia, and South Africa. By understanding these factors, policymakers, financial institutions, and other stakeholders can better navigate the transition towards a more sustainable energy future. The identified risks, trade-offs, and co-benefits will be used as input for discussions of financing from bilateral and multilateral organisations for green hydrogen projects in the Global South. Hence, the objective of this policy brief is threefold. First, to explore some general risks and trade-offs of establishing a hydrogen economy; secondly, to identify co-benefits for other development priorities in low- and middle-income countries; and finally, to present some risk mitigation strategies with case studies of African countries that are front runners in establishing a green hydrogen economy as illustrations.

2 GHG emissions reduction potential of green Hydrogen energy

Climate change is primarily driven by human activities, largely due to the emission of greenhouse gases (GHG) such as carbon dioxide, methane, and nitrous oxide. These emissions trap heat in the Earth's atmosphere and disrupt the planet's natural balance. Climate change has wide-ranging consequences, including rising global temperatures, melting ice caps and glaciers, more frequent and severe weather events, altered ecosystems and habitats, sea level rise, biodiversity loss, and impacts on human health, agriculture, water resources (IPCC 2022).

A rapid and considerable reduction in greenhouse gas emissions is crucial to keep global warming well below 2 °C in line with the Paris Agreement. Green hydrogen, alongside electrification and energy efficiency, plays a role in mitigating climate change by reducing greenhouse gas emissions and supporting the transition to a low-carbon economy. By avoiding carbon emissions entirely during production, green hydrogen can reduce the overall carbon footprint associated with the hydrogen economy, making it a more attractive alternative. The scenario study by Dagnachew et al. (2023) shows such potential of green hydrogen in reducing global emissions related to energy use. According to the study, while neatly complementing energy efficiency and electrification, green hydrogen could play a key role in reducing the risk of delayed emissions reduction as well as facilitating net-zero by 2050 under strict climate change mitigation scenarios.

One of the most important contributions of green hydrogen to emissions reduction is its considerable potential to decarbonise sectors that are difficult to electrify (discussed in more detail in chapter 5). Green hydrogen provides a means of converting renewable electricity into a versatile energy carrier that can be used across various sectors of the economy. As a clean energy carrier, green hydrogen enables the decarbonisation of sectors with high emissions intensity, such as steelmaking, cement production, fertiliser production, and long-haul transportation, thereby contributing to global efforts to mitigate the impacts of climate change. By replacing fossil fuels with green hydrogen in the iron and steel sector, for example, there is a potential to reduce 2.3 gigatonnes of carbon dioxide per year ($GtCO_2$/year) globally (Bhaskar et al. 2020).

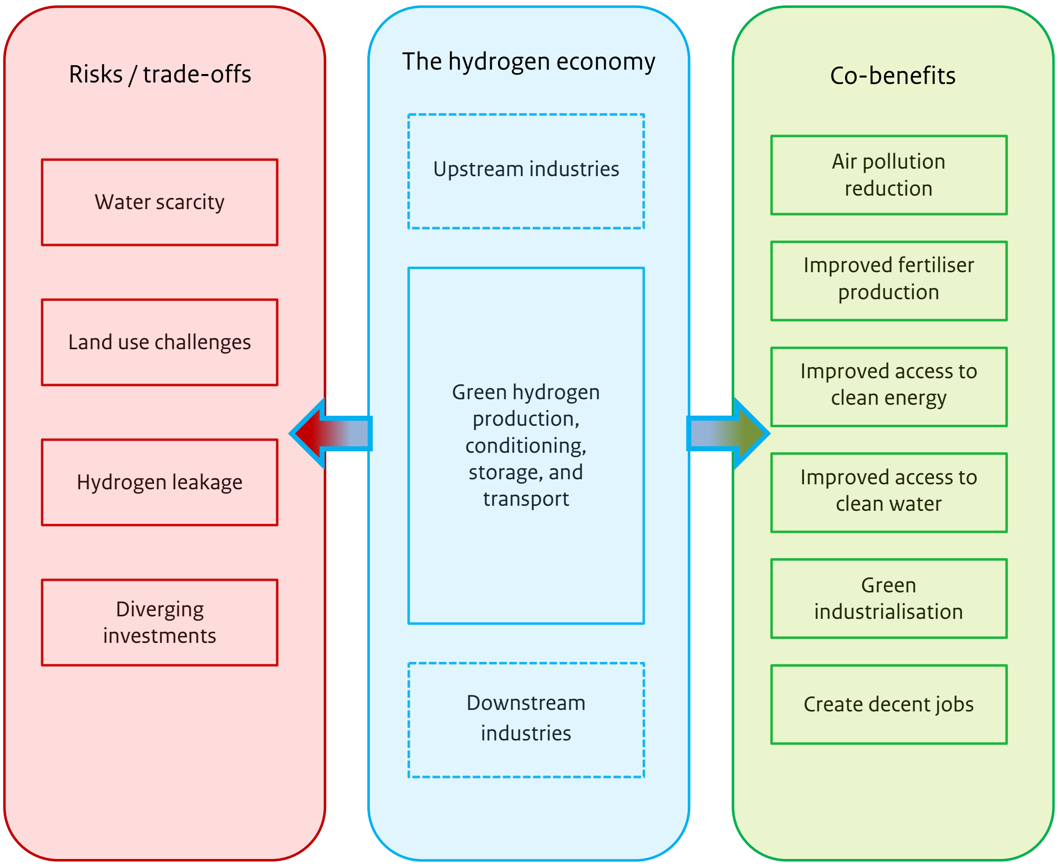
Model results from Ferrada et al. (2023) demonstrate that for countries with a high renewable potential, hydrogen is a cost-effective energy carrier for the reduction of emissions in long-haul transport and serves as an alternative seasonal storage in the electricity sector, contributing to an additional 50% reduction in emissions in these sectors. The authors conclude that in the case of Chile, hydrogen is the most viable solution to effectively decarbonise long-haul transport, for example. Similarly, Yáñez et al. (2022) show the potential of green hydrogen in reducing emissions from oil refineries in Colombia. Zou et al. (2021) investigated the benefits of replacing hydrogen produced from fossil fuels with green hydrogen in order to reduce carbon dioxide emissions in China. The study concludes that, by 2050, green hydrogen could account for 10% of the energy consumption in the country and would reduce about 700 Mt of CO_2 emissions per year. The study by Scolaro and Kittner (2022) demonstrates that an offshore wind farm in the North Sea, which produces hydrogen from excess wind generation rather than curtailing it, offers a large climate change mitigation potential. This is due to the potential of green hydrogen to replace the demand that is currently met by hydrogen produced from fossil fuels. The integration of the offshore wind farm with green hydrogen production also improves the economic viability of a system that suffers from low electricity prices due to high competition in the electricity market (Scolaro and Kittner 2022). These examples all demonstrate the huge potential of a green hydrogen economy.

Furthermore, green hydrogen serves as a valuable seasonal storage solution, allowing excess renewable energy generated during periods of high production to be stored and used when demand is high (Ferrada et al. 2023). This ability enhances the reliability and stability of renewable energy systems, enabling higher levels of renewable energy integration into the grid and reducing the need for backup fossil fuel power plants. By facilitating the integration of renewable energy sources into the grid, green hydrogen helps displace fossil fuel-based electricity generation, thereby ultimately reducing overall emissions from the power sector.

3 Methods

In this policy brief, we build on Dagnachew et al. (2023), which explored the techno-economic opportunities and challenges of establishing a green hydrogen economy in Africa using an integrated assessment model. It also analysed the potential to establish a collaboration on clean hydrogen between Europe and Africa. This policy brief, then, uses that report as a starting point and explores direct risks, trade-offs, and co-benefits that are frequently presented in literature. It is complemented with peer-reviewed literature, for which we used keywords (green hydrogen) AND (the specific risk, trade-off, or co-benefit) AND PUBYEAR > 2014 AND (LIMIT-TO (LANGUAGE, "" English"")). A maximum of five most-cited, relevant articles in each topic are reviewed. Figure 1 below presents the conceptual framework and a set of direct risks, trade-offs, and co-benefits that are covered in this policy brief. The detailed search protocol and the list of the reviewed articles can be found in Table 2 in the Appendix.

Figure 1: The hydrogen economy and associated risks, trade-offs, and co-benefits



4 Risks and trade-offs of a green hydrogen economy and possible mitigation strategies

Hydrogen is increasingly seen as a crucial component in the transition towards a low-carbon energy future. As a clean and versatile energy carrier, hydrogen holds the potential to decarbonise various sectors, including long-haul transportation, (heavy) industry, and heating (see Chapter 2). Among the different methods of hydrogen production, green hydrogen is particularly promising due to its minimal carbon footprint. While it is considered a clean and sustainable alternative to conventional hydrogen production methods, there are several social, environmental, and financial risks that need to be addressed. As it is still an emerging and particularly young technology, its development and market potentials remain uncertain and so do its socio-economic impacts.

Several studies (see list of reviewed literature in the Appendix) have touched upon the risks associated with the green hydrogen economy in local and regional contexts (Alkhalidi et al. 2024; Ajanovic et al. 2024; Akhtar et al. 2023). Additionally, other studies address the relationship between green hydrogen and socio-economic developments, thereby implicitly and explicitly touching upon its impact on employment creation and fostering industrialisation (Beasy et al. 2023; Gronau et al. 2023; Harichandan et al. 2023). This includes the impact on sustainability and the Sustainable Development Goals (Falcone et al. 2021; Cremonese et al. 2023). Finally, other studies also address the risk of explosion and the effects of Substances of Very High Concern (SVHC) on humans and the environment (RIVM 2024b, 2024a). Several mitigation strategies can be implemented to partly abate these risks and trade-offs that include technical, economic, or social components.

4.1 Water stress and water scarcity

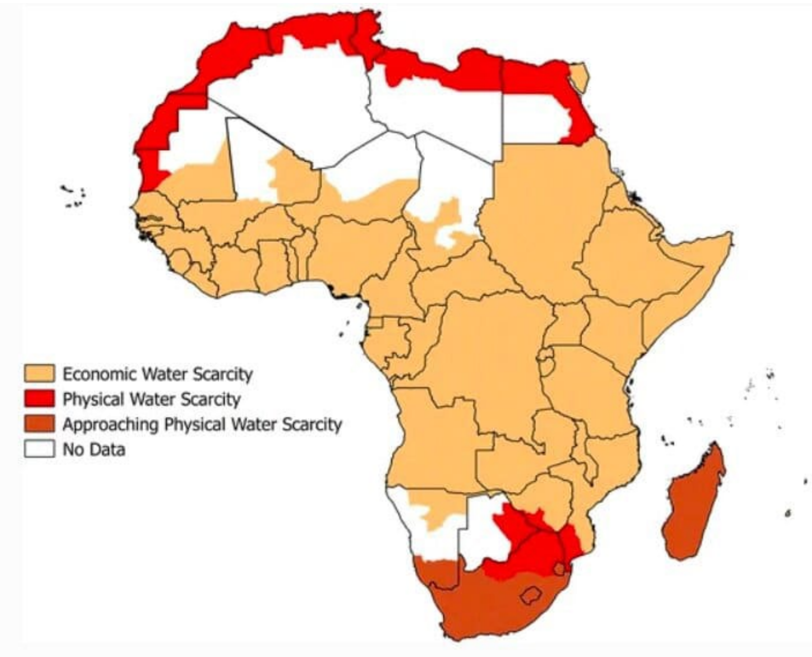
Energy and water systems are very much intertwined. These resources have been vital components of human activity and play a significant role in socio-economic development. The energy sector requires water at various stages of the value chain and accounts for nearly 10% of total global freshwater consumption (Bredariol et al. 2024). Simultaneously, energy is crucial to extract water from various sources, treat it, and deliver it to end users.

In a green hydrogen economy, water is required as input for water purification, electrolysis, and process cooling. As such, the availability and quality of water resources are paramount for the efficient and sustainable production of green hydrogen. Water is, moreover, a vital resource for numerous sectors, including agriculture, industry, and households. Balancing these competing demands is crucial to avoid exacerbating existing water scarcity issues. Regions that are ideal for renewable energy production (high wind and solar resources) may not necessarily have abundant water resources. This geographic misalignment can pose challenges for green hydrogen production in areas where water scarcity is already a concern.

Water scarcity occurs when the demand for water surpasses the available supply, hence reaching or exceeding sustainable thresholds of water resources. Mekonnen and Hoekstra (2016) show that over four billion people experience severe water scarcity at least for parts of the year, while half a billion people face severe water scarcity all year round. For example, numerous countries in Africa face several water-related issues, including limited access to safe drinking water, inadequate sanitation infrastructure, and unsustainable water management practices. Figure 2 shows the economic and physical water scarcity challenges in Africa. Physical scarcity is when there is not enough water available to meet demand due to various reasons including droughts, climate change, variations in weather patterns, and contamination. Economic scarcity, on the other hand, is when water is there but the water infrastructure cannot meet demand due to institutional failings like poor infrastructure, lack of investment, and improper planning (Genesis Water Tech 2023). While water scarcity is a challenge in the continent as a whole, North African countries are facing severe physical water scarcity. Sub-Saharan African countries are suffering more from economic water scarcity. Water scarcity concerns, in Africa and in other parts of the world, are exacerbated by rapid population growth, urbanisation, climate change, and growing demands from the agriculture, industry, and energy sectors.

The water stress concept in general, on the other hand, goes beyond water scarcity, and includes water quality, environmental flows, and the accessibility of water (Alkhalidi et al. 2024). For instance, the water stress ratio in most Middle East and North African (MENA) countries is higher than one, meaning that there is more fresh water being withdrawn than can be renewed (Alkhalidi et al. 2024).The additional water requirements of the hydrogen economy could further aggravate the stress imposed as demand grows driven by increasing population and economic growth.

Figure 2: Economic and physical water scarcity in Africa (Genesis Water Tech 2023)



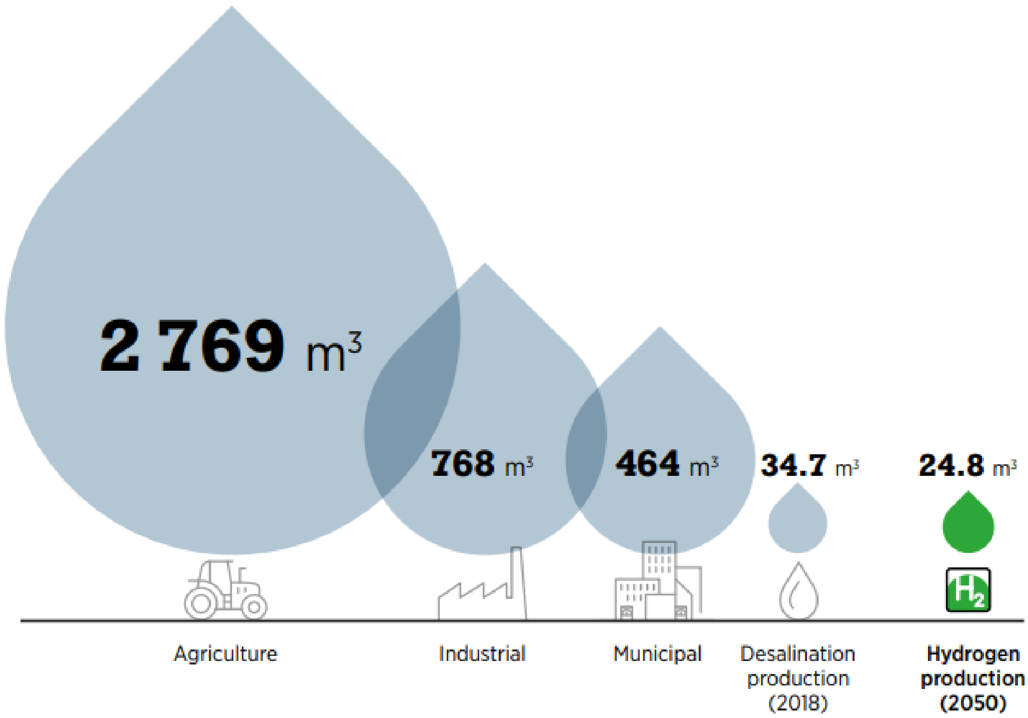
Disclaimer: the map above does not imply the expression of any opinion of PBL or the authors concerning the legal status of any country, territory, city, or area or of its authorities, or concerning the delineation of its frontiers or boundaries.

In theory, 9 kg of water is needed to produce 1 kg of hydrogen excluding water needs for heating, cooling, and general services, but there is still uncertainty due to the nascency of the technology. For example, the water requirements of hydrogen production in Australia vary by the source of electricity. They range from 20 kg water per kg hydrogen when using electricity from wind, to 130 kg of water per kg of hydrogen for electricity from the central grid (Alkhalidi et al. 2024). As reported by Alkhalidi et al. (2024), depending on the choice of technology, green hydrogen could deteriorate the water stress problem in the MENA region as well.

A green hydrogen economy requires a lot of water, but in the context of the current overall global water demand, the increase due to a hydrogen economy is minimal (see Figure 3 below). According to the IRENA (2022b) estimate, the global annual demand for hydrogen under 1.5 °C scenario that describes an energy transition pathway aligned with the ambition to limit global average temperature increase by the end of the century to 1.5°C, relative to pre-industrial level, both for energy and non-energy related purposes (for example as feedstock for the production of fertilisers, iron and steel, chemicals, plastics, and synthetic fuels), reaches 614 Mt by 2050. Under this scenario, two thirds of the global hydrogen supply is green, given its role in climate change mitigation. The production requires 8 – 55 billion kg (0.008 km^3 – 0.055 km^3) of water. To put it into context, this is a fraction of the current global water use of 4600 trillion kg (4600 km^3) a year (Boretti and Rosa 2019).

Although the water demand for a green hydrogen economy does not significantly add to the *global* water demand, there is the need to explore ways to reduce the pressure on *local* freshwater availability. One opportunity lies in research and development in electrolysis technologies that aim to improve efficiency and reduce water consumption. Advanced electrolysis techniques, such as high-temperature electrolysis or membrane technologies, may help mitigate the water scarcity risk associated with green hydrogen production. Green hydrogen can also contribute to the improvement of the supply of water for local communities and businesses, as discussed in more detail in section 5.4.

Figure 3: projected hydrogen water consumption in 2050 relative to current consumption in other demand sectors (IRENA 2022a)



Source: Blanco (2021).
Notes: Figure considers only water consumption, not water withdrawals. Withdrawals cover water that is directly returned to the body of water from which it was taken. Consumption covers any water that is converted into another form or is not returned to the original body. Although most water can be recovered when hydrogen is combusted or used in a fuel cell, it is not generally returned to the original body of water and will be considered to be consumed (Beswick, Oliveira and Yan, 2021).

Note: the water requirement for green hydrogen is based on the projected demand under IRENA's 1.5 °C pathway of 409 million tonnes a year (two thirds of the projected total hydrogen production of 614 Mt). Current hydrogen production is dominated by brown and grey hydrogen that withdraw 2.2 billion m³ of freshwater a year (IRENA and Bluerisk 2023).

There are also technologies to harvest water from the atmosphere as well as purify seawater, industrial wastewater, and municipal wastewater to the required purity level for hydrogen production (Santana et al. 2023). Cattani et al. (2023) proposed an integrated air-to-water generation (AWG) system that could harvest water from the atmosphere for use in electrolysis. The AWG would simply extract potable water from the surrounding air and deliver it to the electrolyser plant. There are various techniques to harvest water from the atmosphere that are at several stages of maturity and development. While integrated AWG systems can vary in scale and complexity, they involve air capture, condensation, collection, and filtration of the condensed water, which is stored or supplied to the electrolyser. AWG offers a sustainable and decentralised approach to water supply for green hydrogen production with only a marginal increase in cost. Moreover, it adds less than 10% to the energy consumption of the electrolyser (Cattani et al. 2023). While the production rates are highly dependent upon the air temperature and the amount of water vapour in the air, the system can harvest water continuously depending on the energy source. The excess water can then be stored or supplied for other uses. While the system requires a considerable amount of energy, recent technological improvements have substantially improved the energy to water ratio of the system, making it a viable option.

Seawater desalination is another way to reduce the pressure on the fresh water supply by utilising abundant saltwater. Desalination is the method of removing salt and other impurities from seawater or brackish water, and so making it suitable for hydrogen production. Varras and Chalaris (2024) present an analysis of a way to address local water scarcity challenges in relation to desalination. Their research addresses the synergies and challenges of three desalination technologies: reverse osmosis, thermal desalination, and membrane desalination. The integration of desalination and green hydrogen production would allow for synergies in energy usage. Excess renewable energy, especially during peak production times, can be utilised for both desalination and hydrogen generation, contributing to the overall efficiency and sustainability of the system. The desalination process, however, requires extra energy input and space. A recent study by Khan et al. (2021) shows that the cost increase due to the extra electricity demand for desalination is 0.1 US dollars per kg H_2, which is a fraction of current green hydrogen production cost of 1.8 – 6.5 US dollars per kg H_2 (Dagnachew et al. 2023). Although, if not coupled with brine treatment facilities, discharging brine water from the desalination plant increases the salinity of the seawater, which can have potential negative effects on the marine ecology (IRENA 2022a).

It is also possible to directly use seawater in electrolysers, but there remain obstacles. The physical and chemical properties of seawater are affected by geographic location and seasonal variations (Gao et al. 2022). Some of the impurity could lead to corrosion, side reactions, and the formation of precipitates on the electrode surface of the electrolyser, thereby limiting its durability (Mohammed-Ibrahim and Moussab 2020).

There are some examples of using wastewater for hydrogen production in arid regions, though mostly still at a pilot phase. The global wastewater production is estimated to be over 380 billion kg (0.38 km^3) and it is projected to increase to 574 billion kg (0.574 km^3) driven by the growing population, improved living standards, and economic growth (Qadir et al. 2020). That is seven times the projected green hydrogen water demand under IRENA's 1.5 °C scenario. Jing et al. (2023) present an innovative hydrogen production process that integrates a water treatment and recovery system that uses wastewater as feedstock. The wastewater mainly comes from residential and industrial sources and could contain organics with high energy potential, precious minerals, acids, bases, and salts (Aydin et al. 2021). Establishing a hydrogen hub adjacent to a wastewater treatment plant improves the energy-water nexus by integrating oxygen and water streams, hence, reduces the environmental impact of the water system in general. The water purification in distilleries and wastewater treatment plants to meet the high purity level required for use in electrolysers does incur additional water, energy, and investment requirements. Direct sea water use, wastewater use, and water harvesting are still at an experimental stage, however, so cost comparison with other established technologies such as desalination is challenging.

Governments and regulatory bodies play a vital role in managing water resources and ensuring sustainable practices in various industries, including green hydrogen production. Well-designed policies can encourage the adoption of water-efficient technologies and responsible water management practices. Sustainable and responsible water management practices are crucial for the long-term viability of green hydrogen as a clean energy solution.

Text box 4.1: The case of Namibia

Namibia is characterised by its arid and semi-arid climates. Water stress and scarcity are particularly prevalent issues as Namibia, with its low and highly irregular rainfall patterns, counts as the driest African country south of the Equator. 65% of the water supply comes from boreholes, while only 35% can be generated from surface water (Mapani et al. 2023). This further strains its water resources. The precipitation patterns and persistent droughts are likely to intensify in the coming decades, as rainfalls are projected to decrease by up to 65% during dry seasons (The World Bank Group 2021), further exacerbating the vulnerability of local communities dependent on agriculture and livestock farming.

Liu and Zhou (2021) have assessed the annual drought patterns in Namibia as of 2010 and have confirmed an increase in their intensity, extent, and duration in 2013, 2015/16, and 2019. Their mapping of the Standard Precipitation Index (SPI), which has been used as an indicator in meteorological drought monitoring, shows a prevalent spreading of drought from north-eastern areas in 2013 towards eastern areas, leading up to the map of 2019 with drought covering nearly the whole country. This further correlates with rapid downward trends in vegetation covers that supply crucial agro-economic and ecological benefits to Namibia.

Despite these challenges, Namibia holds immense potential for green hydrogen production given its abundant land and renewable resources which could provide a significant boost to the country's development ambitions. The current green hydrogen development programme is concentrated in the southwestern part of the country near the coastal city of Lüderitz. There are also other, smaller projects in the north-east or central valley of Namibia that are at a more advanced project stage, such as the Daures Green Hydrogen Village.[1] Namibia's abundant solar and wind resources as well as vast desert landscapes provide ideal conditions for the deployment of renewable energy infrastructure. While the water requirements of hydrogen production are seen as moderate, any scalable production approach would need to follow a sustainable water management strategy. To understand the impact of the green hydrogen economy on water scarcity, however, a more comprehensive analysis of the long-term imbalances between water availability and water demand at local level is required. Moreover, the production of green hydrogen can have a significant impact on the environment in terms of water and air pollution due to its high flammability, as well emissions of hazardous chemicals when impure water is used that generates chlorine gas (Ruppel and Katoole 2023; Perelli and Genna 2022).

To maximise the benefits of establishing a green hydrogen economy while simultaneously addressing water scarcity challenges, a holistic approach to water and energy management is useful. In that respect, Namibia’s potential for green hydrogen production, given its land and renewable energy capacities, needs to be carefully balanced against the lack of water availability and the water demands for decent living and economic development. These different requirements are meant to be regulated by the Namibia Water Corporation Act (NWCA), which aims for sustainable utilisation and protection of water resources. Recent legal analyses of green hydrogen production in Namibia argue that the current water regulations may need to be revised and

[1] https://daures.green/

amended to include new water-related activities for hydrogen, such as extraction, storage, and disposal (Ruppel and Katoole 2023).

Addressing these challenges calls for a collaboration between the government, the private sector, and international partners to promote water conservation measures, invest in water recycling and desalination technologies, and ensure equitable access to water resources for all sectors of society. A major chance to overcome the present water shortage and generate resource-protective green hydrogen is to rely on seawater desalination for water electrolysis. As one of the first green hydrogen projects in Namibia, the HYPHEN project[2] will rely fully on water desalination for its electrolyser and cooling. This project also aims to provide a potable water supply to the towns of Lüderitz and Aus.

Consequently, while seawater desalination seems by far the most viable option for green hydrogen production given the resource constraints, Ruppel and Katoole (2023) discusses the lack of a regulatory framework for seawater extraction in Namibia. Initially this falls under the Water Resources Management Act (WRMA), which allows seawater extraction permits. This has, however, been inactive for several years. Moreover, neither of these two water acts defines how to handle water discharge (brine) from reverse osmosis desalination plants back into the sea. A more positive outlook is given by Namibia's current Green Hydrogen and Derivatives Strategy (Ministry of Mines and Energy Namibia 2022). This strategy outlines an action plan in which enabling legislation for the hydrogen project should be anchored in line with international health, safety, and environmental standards by 2025.

The case of Namibia shows that sustainable water management goes beyond technological fixes and requires legal frameworks to ensure sustainable resource use. Adopting sustainable water management practices and ensuring sustainable practices in industries are key to unlocking the potential of green hydrogen to address the growing energy needs, promote economic growth, and mitigate climate change in Namibia.

4.2 Land use challenges

Large-scale renewable energy projects, such as solar and wind farms, are essential for powering electrolysers to produce green hydrogen. The production of renewable energy and associated infrastructure often requires large amounts of land (Hassan et al. 2023; Lloret et al. 2022). Land is also acquired for the construction of infrastructure, such as pipelines and transportation networks for hydrogen distribution. The land requirements of the green hydrogen economy vary based on the energy generation technology employed. Tonelli et al. (2023) has projected the land requirement necessary to meet an estimated 646 Mt per year of green hydrogen demand in 2050 (5% more than the amount projected under IRENA's 1.5 °C scenario). According to their projections, the land required to meet the demand amounts to 0.6 million km^2 (equivalent to the total size of Ukraine) for solar panel-based production and 13.5 million km^2 (about five times the land area of Argentina), if the electricity is produced with wind turbines. This is the global average land

[2] https://hyphenafrica.com/

requirement. The local land requirement depends on actual climate characteristics, the geology of the location, and technical specifications of the system. The remaining land between turbines and the land area under solar panels can also be used for other functions.

Several countries have allocated large areas of land for green hydrogen production. Morocco, for example, has earmarked one million hectares (10,000 km^2) of land for their green hydrogen project, while Oman has designated five million hectares (50,000 km^2) in the central and southern region of the country for green hydrogen production. Similarly, Namibia, is developing various projects in the 26,000 km^2 area allocated by the government for hydrogen development.

Pressures around land use are becoming increasingly prominent environmental challenges. With the growing demand for land for farming, bioenergy production at scale, and other essential uses, competition for land and its resources and services is set to intensify over the coming decades (King et al. 2023). Though land is abundant in Africa, there is increasing competition for access to arable land and pastures. Conflicts over the rights to land and territories are also becoming more common across the continent (Ugwueze et al. 2022). UNECA (2020) lists climate change, inequitable access to and control of land resources, and the extractive industry as some of the reasons for land-related conflicts in many parts of Africa.

Large projects, such as green hydrogen, could lead to the conversion of natural habitats or agricultural land, which could have negative impacts on biodiversity and food security. Previous renewable energy programmes have shown land seizures without regard for social justice and biodiversity (Swennenhuis et al. 2022), unfair relocations and compensation processes, as well as interference with local landscapes, cultures, and social activities (Cremonese et al. 2023). The resulting deforestation, the use of heavy machinery, and high-density infrastructure during the construction of wind and solar farms could, moreover, lead to enhanced erosion and ecological imbalances (Cremonese et al. 2023; Chigbu and Nweke-Eze 2023). Green hydrogen projects might encroach upon environmentally sensitive or protected areas. Striking a balance between conservation efforts and renewable energy deployment is therefore essential to avoid irreversible environmental damage. It is essential to note that, like water scarcity, these risks are local in nature; thus, while green hydrogen-producing regions are affected, importing countries largely avoid these risks.

Indigenous communities, ethnic minorities, and low-income communities can be disproportionately affected as, for example, dryland areas that offer the best conditions for solar and wind power plants are often used by pastoralists. Implementing large-scale projects can interfere with livestock migration routes and access to pasture, lead to the displacement of communities, disrupt the pastoral land-use system (Whitmee et al. 2024), and it threatens ecologically damaging land use changes by fragmenting desert habitat and using water in arid environments (Turley et al. 2022). This risk is amplified in large parts of Africa where there is a serious lack of formally recognised and secure land tenure (Chigbu and Nweke-Eze 2023) and poor human rights situations.

Conflicts can also emerge when such facilities are proposed in areas designated for urban development or areas with competing land-use priorities, such as residential or commercial zones (Chigbu and Nweke-Eze 2023). Urban peripheries are usually ideal locations for large-scale green energy developments due to their proximity to urban centres and industrial zones. However, urbanisation often involves the expansion of cities, construction of residential and commercial buildings, infrastructure development, and transportation networks, all of which require land. Hence, competing interests may arise between allocating land for renewable energy generation for green hydrogen production and land required for residential and commercial sectors.

To counter these land use risks, it is important to consider the social implications and engage in inclusive planning processes to address the concerns of local communities and avoid negative social impacts. Addressing conflicting land uses in a green hydrogen economy requires careful planning, effective land-use policies, and collaboration between stakeholders, including governments, industries, and local communities. There are examples of multiple land use that combine renewable energy with other land use, especially land which provides economic benefits to farmers and pastoralists (Torma and Aschemann-Witzel 2023; de Ruijter et al. 2023). Combining solar panels with agriculture, for example, creates symbiotic relationships where the shades improve yield and reduce water use. Simultaneously, plants contribute to the cooling of the panels, increasing their efficiency. Adopting sustainable practices, conducting thorough impact assessments, and incorporating community input can contribute to the successful integration of green hydrogen projects while minimising negative consequences on land use. Hence, governments could put in place a framework that allows local communities to both participate in and benefit from large scale green-hydrogen projects.

Text box 4.2: The case of Morocco

In a bid to mitigate climate change and enhance energy security, the European Union has been increasingly investing in renewable energy infrastructure in North Africa. Most of these infrastructure investments are happening in rural areas primarily inhabited by indigenous people (Haag 2022).

Morocco, a country where hydrocarbon imports account for 90% of its energy needs, is striving to become a global leader in renewable energy generation and the fight against climate change (Weko et al. 2023). The National Energy Strategy shows the country's ambition to increase the share of renewable energy in electricity generation to 52% by 2030 (Cantoni and Rignall 2019). This has taken shape in the form of heavy investment in solar and wind power and extended to green hydrogen. Morocco is an ideal candidate for large-scale green hydrogen projects, as it has a proven track record in large renewable energy projects, extensive energy and transport infrastructure, and it is located with proximity of European demand centres (Weko et al. 2023).

The Moroccan government announced the Green Hydrogen Roadmap (GHR) in 2021.This sets the ambition to export 10 TWh (equivalent to 0.25 Mt[3]) and 115 TWh (approximately 3 Mt) of green hydrogen in 2030 and 2050, respectively (Caillard et al. 2023). This roadmap follows previous examples of very rapid advancements in electricity access and renewable energy capacity expansions in wind and solar (Lebrouhi et al. 2024). It expanded its range of hydrogen projects extensively in the last years and just announced additional land resources of up to one million hectares (10,000 km^2) for future green hydrogen projects (Martin 2024), corresponding to 2% of the total land area of the country. The Moroccan government has allocated large areas of land for developers in the Western Sahara, areas which hold the best conditions for green hydrogen production (Weko et al. 2023). Therefore projects in Morocco might be sensitive to land issues, particularly in disputed territories of the Western Sahara (International Alert 2022).

[3] 1EJ hydrogen = 7.1 Mt = 277.78 TWh

A comparison of North African countries based on their technical and socio-economic potentials for green hydrogen production, reveals several existing land conflicts in Morocco (Heinemann et al. 2022). This is partially related to the unresolved occupation of Western Sahara territories by the Moroccan state, which has led to claims of local resources without the consent of the residing communities. Furthermore, the biggest solar project currently active in Morocco, NOOR 1 in Ouarzazate, faced complaints on water and land resources by local groups (Ryser 2019). The project is said to have disrupted social and economic ties within the local community, leading to reports of villagers losing their access to water and collective pastureland because of land appropriation for the project (Weko et al. 2023).

4.3 Climate risk of hydrogen leakage

Hydrogen is an inherently light and reactive gas. Its small molecular size allows it to escape from containment systems more readily than other fuels during production, conversion, storage, transport, or application. In addition to this unintentional leakage, hydrogen can also be intentionally leaked through operational purging and venting. Figure 4 below gives an overview of all potential leakage sources across the hydrogen value chain.

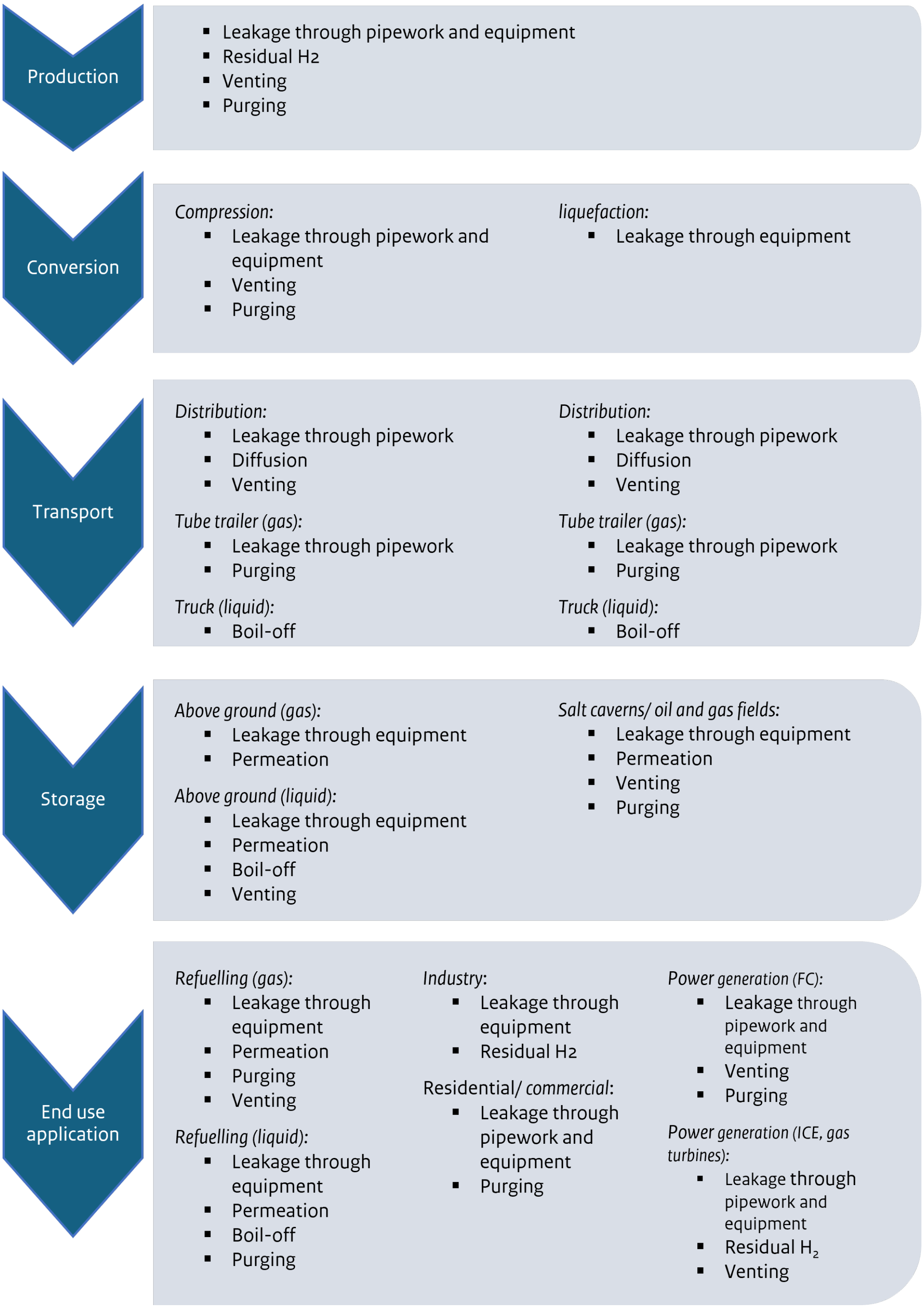
Although hydrogen is non-toxic and disperses rapidly in the atmosphere, its release into the environment can have major climate implications (Warwick et al. 2023; Esquivel-Elizondo et al. 2023). While hydrogen molecules (H_2) do not directly trap heat, they have an indirect global warming effect by extending the lifetime of other GHGs, offsetting greenhouse gas emission reduction gains by switching away from fossil fuels. Using a chemistry-climate model, Warwick et al. (2023) estimate the 100-year indirect Global Warming Potential of hydrogen to be 12±6, which means hydrogen has a warming potency of about 12 times that of CO_2 over 100 years.

Certain GHGs such as methane, ozone, and water vapour are gradually neutralised by reacting with hydroxide radicals (OH) in the atmosphere. When H_2 reaches the atmosphere, however, the H_2 molecule reacts with OH instead, depleting atmospheric OH levels and delaying the neutralisation of the GHGs, which effectively increases the lifetime of these GHGs and continue contributing to the increase of the Earth's temperature in the near-term (Warwick et al. 2023; Esquivel-Elizondo et al. 2023). It also produces tropospheric ozone and serves as a source of water vapour in the stratosphere that increases the potential for global warming (Esquivel-Elizondo et al. 2023; Lakshmanan and Bhati 2024).

The scale of the impact is dependent on the size of the hydrogen economy and the rate of leakage. The overall value-chain leakage of hydrogen is estimated to range between 0.2% and 20% depending on the production process, the transport method, and the end-use application. Given the absence of direct measurements, the total amount of H_2 leakage is estimated based on assumptions, proxies, laboratory experiments, and theory-based models (Esquivel-Elizondo et al. 2023). In general, 70 – 80% of the escaped hydrogen is removed by soils through diffusion and bacteria, while the remaining hydrogen goes into the atmosphere (Lakshmanan and Bhati 2024). A study by Sun et al. (2024) demonstrates that, even at high emission rates from leakage, venting, and purging, green hydrogen is 79 – 88% better in the long-term for the climate than fossil fuel use.

The risk of leakage is not just for hydrogen but its derivatives like ammonia. Leakages in the ammonia value chain could release reactive nitrogen, as attested to by the findings of Bertagni et al. (2023). Reactive nitrogen has detrimental effects for air quality, human health, ecosystems, and climate, and could eventually lead to stratospheric ozone depletion.

Figure 4: Potential sources of H_2 emissions throughout the value chain (Esquivel-Elizondo et al. 2023)



To achieve maximum benefits and mitigate the climate risks associated with hydrogen leakage from green hydrogen projects, several measures can be implemented. First and foremost, robust containment and safety measures must be implemented throughout the hydrogen value chain, from production to end-use applications. This includes the use of high-integrity storage and transportation systems, leak detection technologies, and emergency response protocols to minimise the likelihood of hydrogen release and hence mitigate its consequences. Recent research on reducing leakages in prior gas pipeline infrastructure points to the usage of hydrogen blends (up to 20% volume) instead of pure hydrogen to reduce leakage potential (OECD 2023).

Secondly, comprehensive monitoring and reporting mechanisms are essential to accurately track and quantify hydrogen leakage rates. By identifying and addressing sources of leakage promptly, stakeholders can minimise environmental impacts and optimise the efficiency of green hydrogen production systems. Finally, research and development efforts should focus on advancing hydrogen storage and transportation technologies to enhance containment and minimise fugitive emissions.

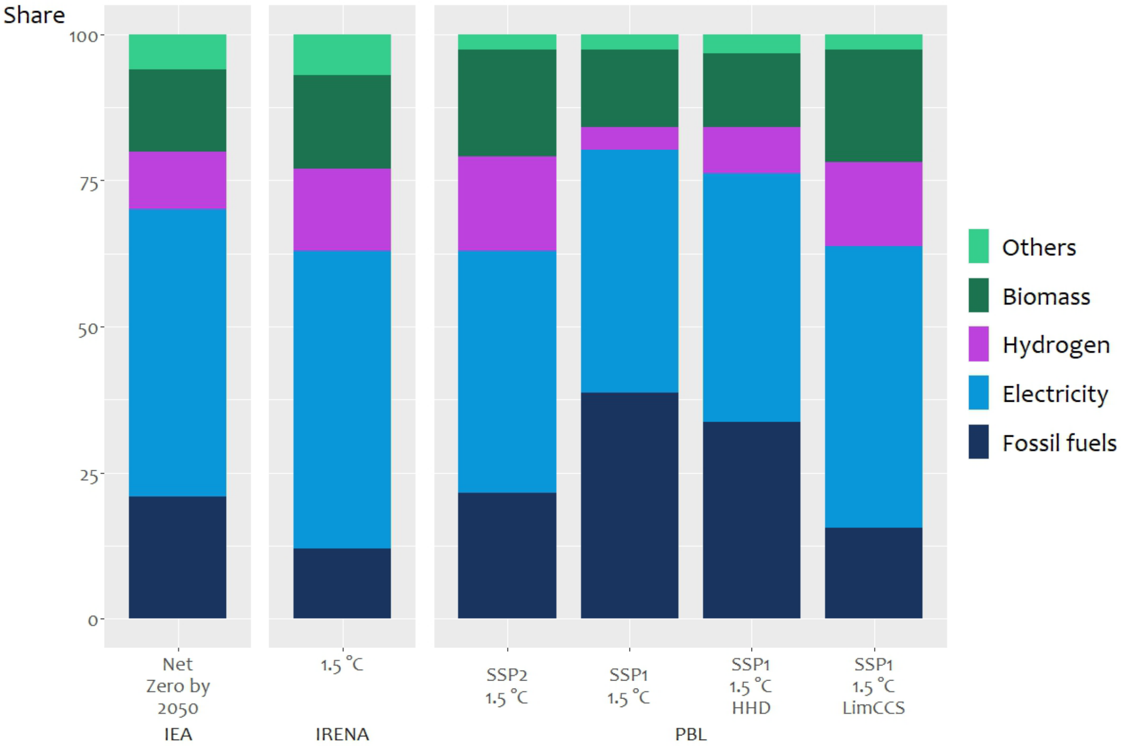
4.4 Diverging investment from other climate mitigation programmes

Effectively tackling climate change requires action across all sectors of the global economy. From energy production and transportation to agriculture, industry, and infrastructure, every facet of economic activity plays a role in contributing to and providing a solution for climate change. While green hydrogen has the potential to play a major role in reducing emissions in hard-to-abate sectors such as heavy industry and long-distance transportation, it should be complementary to efforts that promote large-scale renewable energy deployment, energy efficiency improvements, and sustainable land use practices.

As already indicated, the investment in hydrogen is not only an investment in technology, but a complex investment in an entirely new energy sector. As such, the current investment risk profiles are very insecure and remain subject to large variability, given changing demand projections, technology developments, and geopolitical factors (IEA 2023b). It is likely, therefore, that hydrogen will continue to play a rather limited role in the global energy transition while the focus will be on efficiency and electrification efforts based on renewable energies (see Figure 5). Consequently, the relative importance of hydrogen in overall climate change mitigation should be central to its investment projections.

The rapid growth of green hydrogen projects also raises concerns about the possibility of diverging investment away from other climate mitigation programmes. Establishing a hydrogen infrastructure, including production, storage, transportation, and distribution facilities, requires substantial upfront investment, while low- and middle-income countries also the high weighted average cost of capital (WACC) (Becker et al. 2023). A sole focus on and disproportionate investment allocation for the hydrogen economy could divert already scarce capital from other essential climate mitigation programmes, such as renewable energy for direct electricity access, energy efficiency measures, and nature-based solutions (Ocko and Hamburg 2022; Whitehead et al. 2023; Habib and Ouki 2021). For example, several scenarios that meet the Paris Agreement's goal of keeping global warming to around 1.5 °C above preindustrial temperatures show major energy efficiency improvements and considerable increase in electrification across sectors primarily sourced from renewables, which argues for an allocation of significant resources to programmes other than hydrogen.

Figure 5: Final energy mix, hydrogen has a limited role in decarbonising the energy system (IRENA 2023; IEA 2023c; Dagnachew et al. 2023)



The high upfront investment requirements of green hydrogen could crowd out funding for other climate change mitigation initiatives and, hence, slow down the transition to a net zero economy (Whitehead et al. 2023). North African countries, which are among the European focus areas for green hydrogen production, have a large share of fossil fuels in their power system (Ajanovic et al. 2024). Achieving emission reduction targets in these countries requires primarily decarbonising the electricity system. Producing green hydrogen for export may potentially divert investment from other effective measures that might better serve local needs. Moreover, in addition to dealing with poverty eradication and job creation, low-income countries must also bear the burden of addressing the increased costs associated with combating climate change.

In other words, accepting green hydrogen as the silver-bullet for decarbonisation may overshadow the importance of implementing holistic climate mitigation strategies that address multiple sources of emissions across different sectors. To harness the full potential of green hydrogen while avoiding unintended consequences, policymakers and investors must adopt a balanced and integrated approach to climate action that prioritises a diverse portfolio of mitigation measures. By ensuring coherence, transparency, and accountability in climate policy decision-making, we can navigate the transition towards a sustainable and resilient low-carbon future. There are also examples where this multi-faceted approach is demonstrated, such as the Dutch Green Hydrogen proposition for South Africa (Becker et al. 2023) This set strict standards to ensure that green hydrogen imports from partner countries to the EU are produced from additional renewable energy sources.

Text box 4.3: The case of South Africa

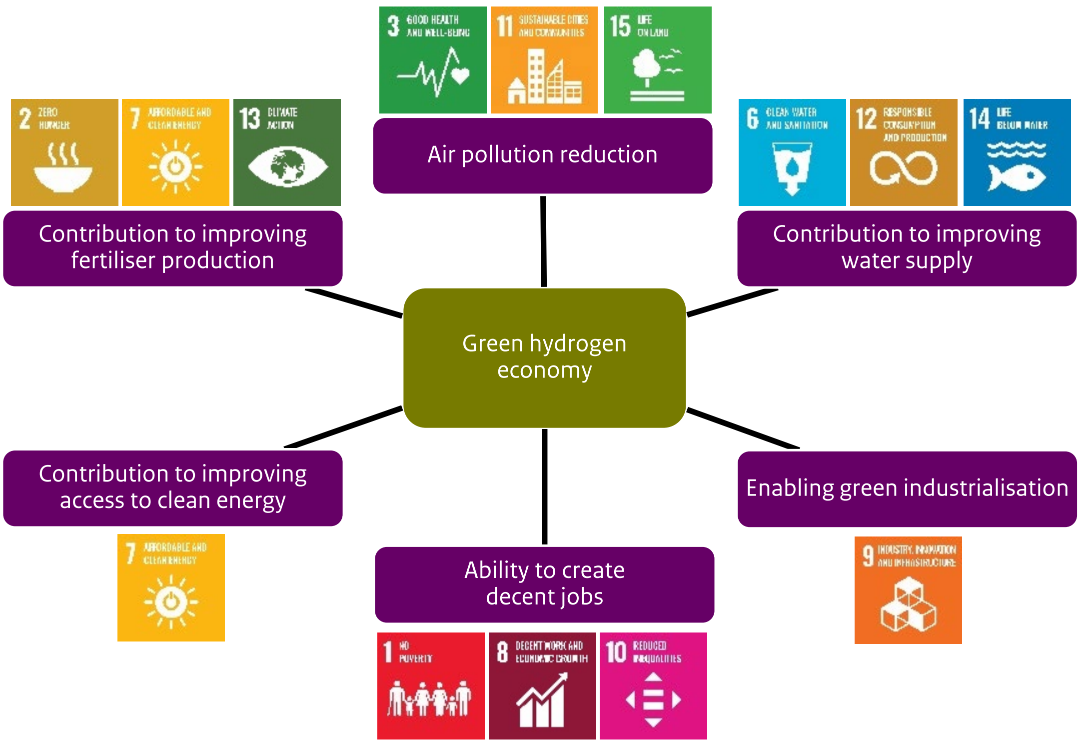
Recent economic developments in terms of GDP growth and investment volumes have been stagnating or even following a downward trend in the Southern Africa region, especially in the Republic of South Africa (Commission and OECD 2023). These conditions have been exacerbated during the COVID-19 pandemic as net capital expenditure by both the public and private sectors in the region decreased by 23%. However, investment flows into renewable energy have been increasing between 2010 and 2020, with a predominant focus on South African projects. In 2020, South Africa accounted for 57% of Africa's installed solar generation capacity (IRENA and AfDB 2022). In stark contrast to this, South Africa's coal-based energy system still largely dominates energy supply and generates electricity blackouts with considerable socio-economic consequences. It maintains long-term purchase agreements between coal companies and the power sector based on traditional labour union and lobby groups. This path dependency on the coal sector is estimated to last up until 2040 (Mirzania et al. 2023).

Given the current attempts to revive its investment climate, South Africa announced extensive green hydrogen investment plans to push its renewable energy expansion. In 2022, a Green Hydrogen Commercialisation Strategy (GHCS) was released, followed by nine investment initiatives and a green hydrogen fund (Naudé 2023). The 'SA-H2 Fund' seeks to generate a total of 1 billion US dollars through public-private partnerships. It also receives support from a Dutch investment company (Development Bank of Southern Africa 2023). But while there is increasing attention on the country's hydrogen potential, investment risks into renewables remain high (Mirzania et al. 2023). Most renewable energy support schemes run through the only national provider, Eskom, which does not generate sufficient competition and scaling opportunities. In addition, current grid availability and stability are not sufficient for renewable energy generation, which is the result of low maintenance of the overall infrastructure (Mirzania et al. 2023). This shows that for a comprehensive renewable energy transition to be possible, including the production of green hydrogen, a more stimulating investment climate in infrastructure and technologies is needed. A sole focus on hydrogen investment as currently announced could potentially diverge investment from other, more crucial energy system improvements.

5 Co-benefits of a green hydrogen economy

As the world faces the urgent challenge of mitigating climate change, the need for clean, sustainable energy solutions, like green hydrogen, has never been greater. Despite the risks and trade-offs associated with green hydrogen as discussed above, an important advantage of the emerging industry is the potential for exploring a wide range of co-benefits that come with the design and development of new infrastructure and entities. The role that green hydrogen can play in achieving the Sustainable Development Goals (SDGs) is considerable; it offers opportunities to harness synergies between goals and address multiple global challenges at the same time. Green hydrogen provides the opportunity to decarbonise hard-to-abate sectors, support over a million jobs, and add billions of dollars to gross domestic product (Lorentz et al. 2023). It also enables the integration of renewable energy into the power system, reduces fuel import dependence, and lowers the carbon footprint of the energy system (Lebrouhi et al. 2022). Figure 6 presents a summary of several such co-benefits of the green hydrogen economy in low- and middle-income countries.

Figure 6: Summary of the co-benefits of green hydrogen economy for SDGs



5.1 Air pollution reduction

Ambient air pollution is contributing to premature deaths including pneumonia, heart disease, stroke, diabetes, chronic lung disease, and lung cancer. It is responsible for over four million deaths each year globally. Air pollution is a major threat to health, human capital, and economic development in low- and middle-income countries (Fisher et al. 2021). Rentschler and Leonova (2023) show the link between poverty and air pollution with over seven hundred million surviving on less than 1.90 US dollars per day living in areas with unsafe levels of air pollution, most of them in Sub-Saharan Africa. For example, acute lower respiratory infection is a major cause of death in children under five in the region (Cai et al. 2021).

Reducing local emissions is crucial for improving local air quality and alleviating negative health impacts. Fossil fuel generates several local pollutants such as nitrogen oxides, fine particulate matter, and sulphur dioxide (Ruf et al. 2018). Green hydrogen can be used as a clean alternative to fossil fuels in various applications, including transportation, industry, and heating. The transport sector, in particular, represents a major source of air pollution that harms human health and the environment, with heavy-duty vehicles responsible for more than 25% of global warming emissions, 45% of NO_x emissions, and nearly 60% of direct PM2.5 emissions from the transportation sector (Union of Concerned Scientists 2022). Hence, the transition of road transport to cleaner fuel technologies has important implications and could significantly improve air quality in urban settlements.

By replacing combustion-based technologies with hydrogen-powered alternatives, green hydrogen helps reduce local air pollution (SDG3, SDG11, SDG15). Hydrogen vehicles have no local emissions while gasoline internal combustion engines emit CO_2, CO, NO_x, CH_4, VOCs, and SO_x. The impact is even bigger when taking the entire life cycle of the vehicles (Walker et al. 2015). Similarly, mixing gasoline with green hydrogen in internal combustion engine vehicles reduces carbon monoxide, unburned hydrocarbons, and nitrogen oxides by 99%, 93%, and 67%, respectively, reducing the risk to human health (Becerra-Ruiz et al. 2019).

India, for example, is home to nine of the ten most polluted cities based on an annual average of PM2.5 concentration (IQAir 2023). Abhyankar et al. (2023) and Vardhan et al. (2022) discuss the role of green hydrogen in reducing emissions in energy-intensive industries. Green hydrogen can significantly contribute to reducing of air pollution, resulting in over 4 million avoided premature deaths in India related to air pollution until 2047 (Abhyankar et al. 2023). With the rapid population growth and urbanisation in Africa, addressing air pollution is a pressing issue. Green hydrogen in (heavy) industry and long-haul and heavy transport could be one amongst a portfolio of solutions that promote human wellbeing and quality of life in urban areas.

5.2 Contribution to improving fertiliser production

A large share of the global hydrogen production is used to produce ammonia, the key ingredient in the production of nitrogen-rich fertilisers alongside urea and ammonium nitrate (Rambhujun et al. 2020). Ammonia plays an important role in the global food system. However, traditional methods of producing hydrogen for ammonia production often rely on natural gas reforming, a process that generates greenhouse gas emissions. The extremely high temperature required in the process also makes it highly energy intensive. By using green hydrogen as a clean and sustainable alternative feedstock instead of hydrogen derived from fossil fuels, fertiliser producers can considerably reduce the carbon footprint of their operations and so contribute to climate change mitigation efforts.

The dependence on fossil fuels has led to a concentration of global ammonia production in a few countries that have low-cost abundant natural gas or coal resources (Osorio-Tejada et al. 2022). Given recent events, such as the COVID pandemic and the Ukraine war, which disrupted global value chains, this has led to supply vulnerability and price volatility that has had a significant impact on food prices in low- and middle-income countries. In this context, locally produced green hydrogen increases the sustainable production of fertilisers and decouples the price of fertiliser from fossil fuel prices.

In India, for example, about fifteen million tonnes of ammonia are used annually in the fertiliser industry. Replacing a fraction of this with green hydrogen would save millions of m^3 natural gas imports and trillions of rupees in annual fertiliser subsidies (Harichandan et al. 2023). Sub-Saharan African countries also import large amounts of fertiliser with high import prices and a vulnerable supply chain. The price of fertilisers in Sub-Saharan Africa has tripled since 2020 and remain volatile, disrupted by war, export taxes, bans, and licensing requirements (Malpass 2022). Yet average fertiliser use in Sub-Saharan Africa is only 15% the global average, and the poorest farmers have no access to mineral fertilisers at all. Improved access to mineral fertiliser could significantly reduce food insecurity among farming households in the region (Falconnier et al. 2023) . Chile, a country with an extraordinary renewable energy potential, is a net importer of ammonia at a cost of hundreds of millions of US dollars (World Bank 2023). According to the National Green Hydrogen Strategy, Chile aims to be a major player in the production of green hydrogen and its derivatives with a potential to produce low cost ammonia from solar and wind by 2030 (Ministry of Energy 2020).

Overall, green hydrogen offers large potential to improve fertiliser production by providing a clean and sustainable source of hydrogen. By transitioning to green hydrogen as a feedstock, fertiliser producers can reduce emissions (SDG13), improve energy efficiency (SDG7), and contribute to a more sustainable and environmentally friendly fertiliser industry. If the green hydrogen is sourced locally, it offers more stable and consistent fertiliser supply and prices and, hence, it could enhance food security (SDG2).

5.3 Contribution to improving access to clean energy

Access to reliable, clean, and modern energy is fundamental for sustainable development and improving the quality of life for people around the world. However, achieving universal access to modern energy remains a challenge, particularly in remote settlements in low-income countries. Off-grid systems are crucial components of the energy access strategy to reach remote locations that have too low levels of electricity consumption or are sparsely populated. Green hydrogen presents a promising opportunity to address both the energy access and sustainability challenges. The renewable energy sources required for green hydrogen production are abundant and can be economically harnessed in large parts of Africa, including those regions with limited access to energy infrastructure. The rapid growth of renewable energy power for green hydrogen production and the lower levelised cost of electricity can enhance the availability of renewable energy solutions for various end users (SDG7) (Climate Analytics 2022).

Green hydrogen-related infrastructure investments, technology transfer, and local capacity building programmes could already lower costs and reduce the complexity of subsequent deployments of renewable energy-only systems (AGHA 2022). Green hydrogen is a dependable and secure energy source, especially for fossil-fuel importing countries (Xiang et al. 2021). Fossil fuel prices can fluctuate, and the supply chain can be interrupted. By reducing the reliance on imported fossil fuel, mitigating price volatility, and hence improving the flexibility and resilience of the energy system, green hydrogen contributes to improving overall energy security and resilience (IRENA 2022a).

Green hydrogen can also be used as a storage medium during periods of peak generation to provide a reliable energy supply, especially for communities in distant locations (Widera 2020). It offers the potential for long-term energy storage (Noussan et al. 2020), allowing excess renewable energy generated during peak seasons to be stored and utilised during periods of low electricity generation. This is particularly relevant and especially valuable for regions with seasonal variations in renewable energy resources, as the share of renewable energy in electricity increases. Oliveira et al. (2021) estimate the global seasonal storage requirement at 14 – 67 PWh annually, which is equivalent to 1.2 Gt of hydrogen.

Significant revenue can be generated by exporting (surplus) green hydrogen and developing the hydrogen value chain for countries with favourable conditions. According to the Hydrogen Council (2022), by capturing just 15% of the projected globally traded hydrogen volume, African countries could earn 15 billion US dollars in 2050. The earnings could be re-invested towards initiatives aimed at improving energy access in underserved communities and enable the faster deployment of renewable power for domestic use at lower costs.

5.4 Contribution to improving water supply

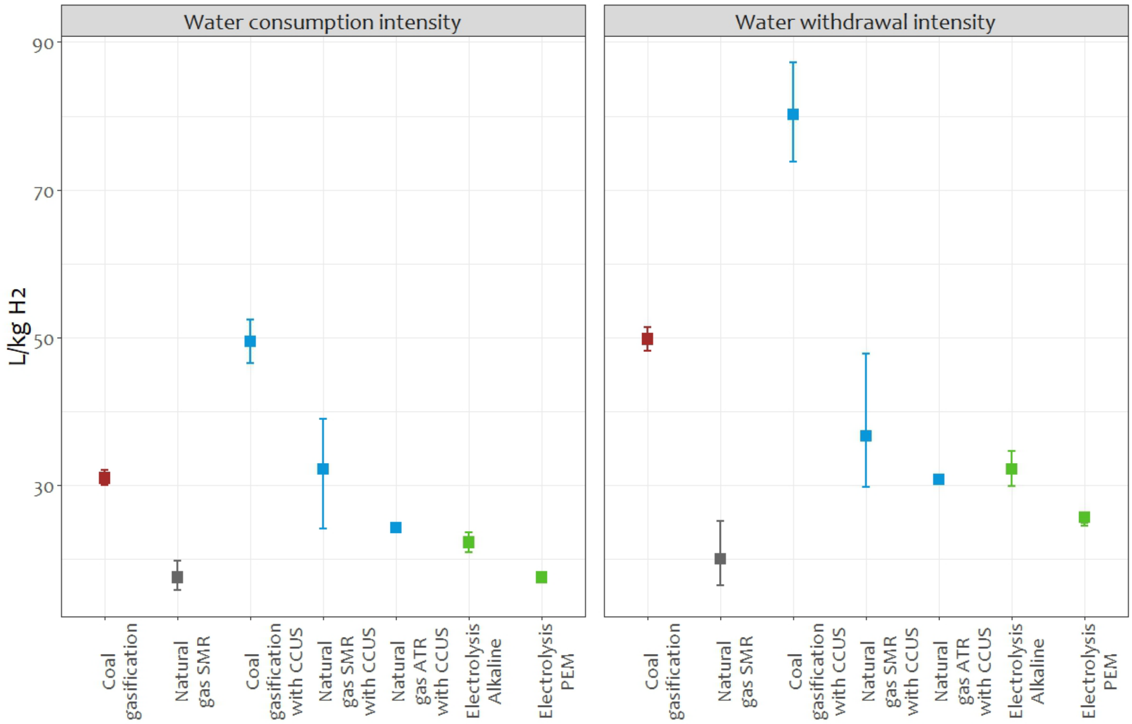
As already discussed in section 4.1, the production of green hydrogen requires considerable amounts of water. As a result, the green hydrogen economy faces challenges as the areas with abundant renewable energy potential are also usually the areas that face water scarcity. The pressure on these areas is further exacerbated by population growth, industrial development, and climate change. The promotion of green hydrogen production can encourage integrated management approaches to the energy-water nexus. By recognising the interdependencies between energy and water systems, policymakers and stakeholders can develop strategies that optimise resource use, minimise environmental impacts, and enhance overall sustainability. Green hydrogen, then, offers an opportunity to align energy production with water conservation goals, fostering synergies between the two sectors.

There are already technologies in concept or pilot phases with an integrated system where the desalinated water is not only used as feedstock for hydrogen production, but also serves as an alternative source of freshwater for other end-use, providing positive spill over benefits. Farhani et al. (2024) describe a system in Tunisia where the water treatment module adopts a low-pressure reverse osmosis approach to supply the electrolyser. The surplus water from the desalination plant is then supplied for irrigation, creating a wider local benefit. The integrated seawater hub, conceptual design described by M.S et al. (2024), consists of a desalination plant that provides water for multiple end-use purposes, including for drinking water supply, for a hydrogen production plant, and for seawater farming. The system uses seawater, brackish, and treated wastewater as input. It proposes a closed loop system that includes the recycling of the waste heat from the reverse osmosis for the desalination process and extraction of minerals (such as sodium chloride, bromine, magnesium, potassium, and lithium) from the brine (SDG12, SDG14).

Desalinated water requires a series of post-treatment steps that might include remineralisation, disinfection, degasification, and corrosion control to make it suitable for drinking or irrigation (Lesimple et al. 2020).

The electrolysis process that is used to produce green hydrogen is powered by renewable energy sources and requires less water than other hydrogen production methods, as shown in Figure 7. By promoting the use of renewable energy, green hydrogen production contributes to reducing the reliance on water-intensive energy sources, such as fossil fuels or nuclear power, which often require a lot of water for cooling and other processes.

Figure 7: Average water withdrawal and consumption across various hydrogen production pathways (IRENA and Bluerisk 2023).



The green hydrogen economy's reliance on renewable energy sources and its potential to promote sustainable energy-water nexus management can contribute to water conservation efforts and support overall water sustainability objectives (SDG6). By integrating green hydrogen production with broader strategies for renewable energy deployment and water management, societies can work towards a more sustainable and resilient future.

5.5 Enabling green industrialisation

Historically, the pursuit of industrialisation often comes with significant energy consumption and high levels of GHG emissions. One promising option for GHG emissions reduction in energy-intensive industries is to switch to renewable electricity and green hydrogen. Given heterogeneity of potentials and costs of renewable electricity across regions, this could lead to a relocation of these industries and a shift in trade patterns (Verpoort et al. 2024). Investments in green hydrogen infrastructure and technology can change the course of development and bring new opportunities for domestic industries, including renewable energy production, electrolyser manufacturing, and hydrogen-related R&D (SDG9). As demand for green hydrogen infrastructure and equipment increases, local suppliers and manufacturers can emerge, creating additional economic opportunities and supporting local economies. Moreover, it could spur investment in complementary sectors, such as transportation, agriculture, and manufacturing. Energy-intensive industries have so far largely relied on fossil fuels, account for a large share of the global GHG emissions and are hard to abate through simple electrification. Green hydrogen is a clean alternative to fossil fuels in various key industrial processes, such as in chemicals, refining, iron and steel, and other industrial uses like glass manufacturing, food products, semiconductors, cooling large stationary electrical generators, and propellant fuel for aerospace vehicles (Agaton et al. 2022).

The growth of green hydrogen industries creates opportunities for supply chain development and diversification, benefiting a wide range of sectors (see Table 1). By replacing carbon-intensive feedstocks and fuels with green hydrogen, industrial emissions can be considerably cut back and dependence on fuel imports can be reduced significantly (Wang et al. 2018). It also offers the opportunity to establish, expand, or relocate downstream industries. By positioning themselves as leaders in the green hydrogen economy, low- and middle-income countries can enhance their global competitiveness and access new markets, driving economic growth and trade expansion, as well as improve their economies by moving from lower to higher value-added activities within the green hydrogen value chain. In this context, pursuing green industrialisation could be particularly important for these countries to foster economic development and create synergies with several other development targets.

Table 1: Upstream, midstream and downstream hydrogen ecosystems (Consilis 2023)

Power generation & distribution	Production	Storage and distribution	Applications
Wind power	Electrolysis	Storage tanks	Iron & steel
Solar power	Compression	Caverns	Petrochemical & chemical industries
Hydropower	Conversion	Pipelines	Manufacturing
Electrical grid		Ships	Power & heat generation, long- and mid-term storage, blending
Battery		Trains	Data centres
		Trucks	Mobility
		Filling stations	

Strategic industrial policies driving integration throughout the value chains could support the relocation or establishment of energy-intensive industries closer to the production locations of green hydrogen (Eicke and De Blasio 2022; IRENA 2022a). Products like ammonia and methanol could be produced near hydrogen sites which would further cut shipping costs (Saygin and Gielen 2021). Similarly, by using a direct hydrogen reduction method, replacing natural gas with hydrogen in steel production could reduce CO_2 emissions during production by up to 84% – 91%, though challenges remain (Wang et al. 2021).

Green hydrogen holds promise for driving green industrialisation. It can help decarbonise industrial processes, spur technological innovation, and create new supply chain opportunities. By embracing green hydrogen, low- and middle-income countries can transition towards more sustainable and resilient industrial economies while limiting the impact on the climate. These countries could find it challenging, however, to compete in value-added segments of the value chains (Eicke and De Blasio 2022) and, hence, require bilateral and multilateral collaborations to avoid geopolitical and market tensions and conflicts.

5.6 Ability to create decent jobs

Green hydrogen holds promise as a clean and versatile energy carrier that can be applied in transportation, industry, and power generation, offering a holistic solution to decarbonise economies. The emergence of green hydrogen as a key player in the global energy transition presents an opportunity to foster economic growth and job creation in low- and medium-income countries (SDG8, SDG10). As nations worldwide pivot towards renewable energy sources, the synergies between the transition to clean energy technologies and decent job creation have become increasingly evident. Given the role that hydrogen is projected to play in reaching climate targets, Lorentz et al. (2023) estimate that the global demand for clean hydrogen will reach 600 Mt by 2050 (2% less than projected under IRENA's 1.5 °C scenario) and the hydrogen economy supports 1.5 million jobs per year between 2030 and 2050 in developing and emerging economies. The employment consists of job transfers from other sectors, but also additional jobs from new economic activities that might also requires education and skills development.

The development of green hydrogen infrastructure and value chains creates employment opportunities across various sectors, from renewable energy generation to manufacturing, transportation, and research and development, thereby contributing to economic development. By fostering innovation, entrepreneurship, and skills development, green hydrogen projects contribute to economic growth and the creation of new opportunities in high-skilled occupations and sustainable livelihoods.

The green hydrogen industry fosters GDP growth and promotes socio-economic and technological developments. A study by Bisognin Garlet et al. (2024) shows that green hydrogen has a positive prospect in creating high added value and specialised jobs in Brazil, for example. Integrating various stages of the green hydrogen value chains provides various advantages, such as lower distribution costs, increased control, and lower dependency, which reduces vulnerability. The resulting relocation or expansion of carbon-intensive industries closer to the hydrogen production location could increase the local added value and create several jobs in low- and middle-income countries (Eicke and De Blasio 2022).

For instance, India already aims to capture the economic potentials of green hydrogen by creating 600,000 jobs in the sector by 2030 Harichandan et al. (2023). The Indian government has announced investment plans for pilot projects in the green hydrogen industry that could create new jobs in the manufacturing, automobiles, and construction sectors. Similarly, van Wijk and Wouters (2021) argue that establishing a renewable-based energy system for local consumption and export in North Africa, has the potential to creates jobs, welfare, and improve living conditions reducing migration. This does require, however, tremendous political and societal will from North African and European countries. Boudghene Stambouli et al. (2024) show that establishing a new green hydrogen economy in Algeria, for example, could support efforts to promote economic development and job creation. The HYPHEN project in Namibia could create some 15,000 jobs during construction that could last four to five years and nearly 3,000 people will be permanently employed once the construction is completed. The ambition of the project is to employ locals for at least 90% of these jobs (Cordonnier and Saygin 2022). What would improve accessibility to these jobs are efforts to improve skills and education, such as by supporting local skill developments, as argued by Agyekum (2024). Namibia's HYPHEN project's Socio-Economic Development (SED) Framework (Hyphen Hydrogen Energy 2023), for example, is committed to education and training to support youth employment opportunities in Namibia. Cremonese et al. (2023) show that the employment opportunities for the NOOR 1 solar thermal power plant in Morocco and the solar parks in Limpopo in South Africa were limited to short-term unskilled and semi-skilled jobs, mostly due to lack of capacity and skill development. Therefore, additional training and study programmes would allow the young population to contribute and benefit from a local hydrogen economy.

The development of green hydrogen infrastructure and value chains stimulates technological innovation and can create employment opportunities across various sectors, including renewable energy generation, hydrogen production, storage, transportation, and utilisation. This has direct benefits to the Sustainable Development Goals that aim to eliminate poverty and hunger, create decent work and economic growth, and stimulate industry, innovation, and infrastructure development.

Text box 5.1: The case of Africa

The green hydrogen economy can provide several benefits for countries in Africa, provided that the socio-economic and environmental risks are properly addressed. Large foreign investments coming to those countries in the forefront of green hydrogen development could enable the expansion of the energy grid, create jobs, reduce emissions, and foster green industrialisation. Average electricity access rates in Namibia and Mauritania are just 55% and 48%, respectively. The expansion of renewable electricity generation as part of the green hydrogen economy can increase domestic electricity access, enabling these countries to achieve energy access targets. Similarly, fossil fuels account for nearly 95% of Egypt's total energy supply, more than 90% of South Africa's total energy supply, almost 90% of Algeria's total final consumption (IEA 2023a). Green hydrogen can be a key strategy to *decarbonise* these countries' energy systems while fostering economic development. Namibia also aims to decarbonise its mining sector with the help of green hydrogen for the heavy-duty trucks involved in the sector. Morocco is importing over 90% of its energy supply. By integrating the green hydrogen plan with energy transition and climate targets could help not only to decarbonise the energy system, but to also improve *energy security* in producing countries.

Average annual PM2.5 concentration in Algeria, Egypt, Mauritania, Morocco, Namibia, and South Africa are 4 – 10 times higher than the World Health Organisation recommended maximum of 5µ g/m^3 (World Health 2021). Expanding the green hydrogen economy could help these countries, especially densely populated cities, cut PM emissions by cutting emissions from industry and heavy transport and reducing health risks associated with poor *air pollution*. In Mauritania, the AMAN (Atchison 2022) green hydrogen project aims to provide 60 hydrogen buses for public use, easing the transport challenges and tackling *air pollution* at the same time.

Nineteen percent of the population in Namibia and South Africa are living under the global poverty line. The overall unemployment rate in these two countries is amongst the highest, standing at 33% and 32.1%, respectively. Green hydrogen could play a key role in creating additional *employment* and accelerate *economic development* to help lift the population out of poverty. Unemployment rates is Algeria, Egypt, Morocco, and Mauritania are far below 10%, and green hydrogen can still create *decent job* opportunities, particularly for those displaced from the fossil fuel industry.

Algeria's economy is dependent on fossil fuel export, making it particularly vulnerable to fluctuations in international markets and the global decarbonisation trends (Boukhatem 2022). Fossil fuel exports and energy-intensive industries, such as the chemical industry and steel industry, play an important role in Egypt's economy. Namibia's economy is dominated by mineral export, while manufacturing accounts for 15% of the GDP (Focus Economics 2024). Industry and agriculture account for 40% of Morocco's GDP and employ 60% of the work force (LLOYDS Bank 2024), and the country is amongst the biggest exporters of fertiliser products (Hmadouch 2023). The share is similar in Mauritania where industry and agriculture account for 60% of the GDP (Hmadouch 2023). Manufacturing, transport and communication, natural resource extraction, and agriculture provide a third of South Africa's GDP (South African Market Insights 2015), but are struggling with unreliable energy supply. The green hydrogen economy provides co-benefits by improving *energy security*, fostering *green industrialisation,* and enabling *economic diversification* with integrated upstream and downstream industries in the value chain.

Water management is a major challenge for most of the countries in Africa with the growing demand for water from various sectors and the consistent spells of drought, both placing greater stresses on the *water supply*. Investments in the green hydrogen economy could be leveraged to support water supply to other end-uses, such as household use and irrigation, at a relatively small increase in the cost of hydrogen production. The AMAN green hydrogen project in Mauritania aims to build a desalination plant with a capacity of 150 million tonnes of water, a third of which is earmarked to support the local water supply system (Atchison 2022). As mentioned in the previous chapter, the HYPHEN project in Namibia will supply drinking water to the towns of Lüderitz and Aus.[4] Algeria already plans to cover 60% of its drinking water demand in 2030 with desalination plants (Magoum 2023), which gives an opportunity to integrate part of this plan into the green hydrogen programme. The desalination plants for the hydrogen economy could be planned not only for the amount required to produce hydrogen but also for various local demands, including drinking water and irrigation.

[4] https://hyphenafrica.com/

References

Abhyankar, Nikit, Priyanka Mohanty, Shruti Deorah, Nihan Karali, Umed Paliwal, Jessica Kersey, and Amol Phadke. 2023. 'India's path towards energy independence and a clean future: Harnessing india's renewable edge for cost-effective energy independence by 2047', *The Electricity Journal*, 36.

Agaton, Casper Boongaling, Kenneth Ian Talosig Batac, and Edgar Medrano Reyes Jr. 2022. 'Prospects and challenges for green hydrogen production and utilization in the Philippines', *International Journal of Hydrogen Energy*, 47: 17859-70.

AGHA. 2022. "Africa's green hydrogen potential."

Agyekum, Ephraim Bonah. 2024. 'Is Africa ready for green hydrogen energy takeoff? – A multi-criteria analysis approach to the opportunities and barriers of hydrogen production on the continent', *International Journal of Hydrogen Energy*, 49: 219-33.

Ajanovic, Amela, Marlene Sayer, and Reinhard Haas. 2024. 'On the future relevance of green hydrogen in Europe', *Applied Energy*, 358.

Akhtar, Malik Sajawal, Hafsa Khan, J. Jay Liu, and Jonggeol Na. 2023. 'Green hydrogen and sustainable development – A social LCA perspective highlighting social hotspots and geopolitical implications of the future hydrogen economy', *Journal of Cleaner Production*, 395.

Alkhalidi, Ammar, Hamza Battikhi, Marah Almanasreh, and Mohamad K. Khawaja. 2024. 'A review of renewable energy status and regulations in the MENA region to explore green hydrogen production – Highlighting the water stress effect', *International Journal of Hydrogen Energy*.

Atchison, Julian. 2022. "Mauritanian mega-project takes next steps." In.: Ammonia Energy Association.

Aydin, M. I., A. E. Karaca, Ammi Qureshy, and I. Dincer. 2021. 'A comparative review on clean hydrogen production from wastewaters', *J Environ Manage*, 279: 111793.

Bade, Shree Om, Olusegun Stanley Tomomewo, Ajan Meenakshisundaram, Patrick Ferron, and Babalola Aisosa Oni. 2024. 'Economic, social, and regulatory challenges of green hydrogen production and utilization in the US: A review', *International Journal of Hydrogen Energy*, 49: 314-35.

Beasy, Kim, Sherridan Emery, Kerrin Pryor, and Tuong Anh Vo. 2023. 'Skilling the green hydrogen economy: A case study from Australia', *International Journal of Hydrogen Energy*, 48: 19811-20.

Becerra-Ruiz, J. D., R. G. Gonzalez-Huerta, J. Gracida, A. Amaro-Reyes, and G. Macias-Bobadilla. 2019. 'Using green-hydrogen and bioethanol fuels in internal combustion engines to reduce emissions', *International Journal of Hydrogen Energy*, 44: 12324-32.

Becker, Sharon, Nienke Homan, Micha Roos, Kim Dutoitova, and Terry Green. 2023. "Dutch Green Hydrogen proposition for South Africa." In. The Hague.

Bertagni, M. B., R. H. Socolow, J. M. P. Martirez, E. A. Carter, C. Greig, Y. Ju, T. Lieuwen, M. E. Mueller, S. Sundaresan, R. Wang, M. A. Zondlo, and A. Porporato. 2023. 'Minimizing the impacts of the ammonia economy on the nitrogen cycle and climate', *Proc Natl Acad Sci U S A*, 120: e2311728120.

Bhaskar, Abhinav, Mohsen Assadi, and Homam Nikpey Somehsaraei. 2020. 'Decarbonization of the Iron and Steel Industry with Direct Reduction of Iron Ore with Green Hydrogen', *Energies*, 13.

Bisognin Garlet, Taís, Fernando de Souza Savian, José Luis Duarte Ribeiro, and Julio Cezar Mairesse Siluk. 2024. 'Unlocking Brazil's green hydrogen potential: Overcoming barriers and formulating strategies to this promising sector', *International Journal of Hydrogen Energy*, 49: 553-70.

Boretti, Alberto, and Lorenzo Rosa. 2019. 'Reassessing the projections of the World Water Development Report', *npj Clean Water*, 2.

Boudghene Stambouli, A., Y. Kitamura, M. T. Benmessaoud, and Noureddine Yassaa. 2024. 'Algeria's journey towards a green hydrogen future: Strategies for renewable energy integration and climate commitments', *International Journal of Hydrogen Energy*, 58: 753-63.

Boukhatem, Imane. 2022. "The challenges of the energy transition in fossil-fuel-exporting countries: The case of Algeria." In.: Transnational Institute.

Bredariol, Tomás de Oliveira, Jinsun Lim, and Leonie Staas. 2024. 'Energy is vital to a well-functioning water sector', Accessed May. https://www.iea.org/commentaries/energy-is-vital-to-a-well-functioning-water-sector.

Cai, Y. S., H. Gibson, R. Ramakrishnan, M. Mamouei, and K. Rahimi. 2021. 'Ambient Air Pollution and Respiratory Health in Sub-Saharan African Children: A Cross-Sectional Analysis', *Int J Environ Res Public Health*, 18.

Caillard, Amandine, Fernando Plazas-Nino, Carla Cannone, Rudolf Yeganyan, and Mark Howells. 2023. 'A critical analysis of Morocco's Green Hydrogen Roadmap: a modelling approach to assess country readiness from the energy trilemma perspective', *Climate*.

Cantoni, Roberto, and Karen Rignall. 2019. 'Kingdom of the Sun: a critical, multiscalar analysis of Morocco's solar energy strategy', *Energy Research & Social Science*, 51: 20-31.

Cattani, Lucia, Paolo Cattani, Anna Magrini, Roberto Figoni, Daniele Dondi, and Dhanalakshmi Vadivel. 2023. 'Suitability and Energy Sustainability of Atmospheric Water Generation Technology for Green Hydrogen Production', *Energies*, 16.

Chigbu, Uchendu Eugene, and Chigozie Nweke-Eze. 2023. 'Green Hydrogen Production and Its Land Tenure Consequences in Africa: An Interpretive Review', *Land*, 12.

Climate Analytics. 2022. "Renewable energy transition in sub-Saharan Africa."

Commission, African Union, and OECD. 2023. *Investing in renewable energies for Southern Africa's sustainable development*.

Consilis. 2023. "Hydrogen Pre-feasibility and Roadmap Study for Combined Transport via the New Silk Roads to (Central) Asia."

Cordonnier, Joseph, and Deger Saygin. 2022. "Green hydrogen opportunities for emerging and developing economies: Identifying success factors for market development and building enabling conditions." In.: OECD.

Cremonese, L., G. K. Mbungu, and R. Quitzow. 2023. 'The sustainability of green hydrogen: An uncertain proposition', *International Journal of Hydrogen Energy*, 48: 19422-36.

Dagnachew, Anteneh G, Stephanie Solf, Samira I. Ibrahim, and Harmen-Sytze de Boer. 2023. "The Opportunities, Challenges and Potentials for Hydrogen in Africa: African-European partnerships for sustainable development." In. The Hague: PBL Netherlands Environmental Assessment Agency.

de Ruijter, Frank , Herman Helsen, Hellen Elissen, and Wilma Eerenstein. 2023. "Producing food and electricity on the same square meter." In.: Wageningen University & Research Renergize Consultancy.

Development Bank of Southern Africa. 2023. "Unveiling the 'SA-H2 Fund': South Africa's Dedicated Green Hydrogen Fund." In. Pretoria.

Eicke, Laima, and Nicola De Blasio. 2022. 'Green hydrogen value chains in the industrial sector—Geopolitical and market implications', *Energy Research & Social Science*, 93.

Eljack, Fadwa, and Monzure-Khoda Kazi. 2021. 'Prospects and Challenges of Green Hydrogen Economy via Multi-Sector Global Symbiosis in Qatar', *Frontiers in Sustainability*, 1.

Esquivel-Elizondo, Sofia, Alejandra Hormaza Mejia, Tianyi Sun, Eriko Shrestha, Steven P. Hamburg, and Ilissa B. Ocko. 2023. 'Wide range in estimates of hydrogen emissions from infrastructure', *Frontiers in Energy Research*, 11.

Falcone, Pasquale Marcello, Michael Hiete, and Alessandro Sapio. 2021. 'Hydrogen economy and sustainable development goals: Review and policy insights', *Current Opinion in Green and Sustainable Chemistry*, 31.

Falconnier, Gatien N., Louise Leroux, Damien Beillouin, Marc Corbeels, Robert J. Hijmans, Camila Bonilla-Cedrez, Mark van Wijk, Katrien Descheemaeker, Shamie Zingore, François Affholder, Santiago Lopez-Ridaura, Eric Malézieux, David Makowski, Jairos Rurinda, Martin K. van Ittersum, Bernard Vanlauwe, Ken E. Giller, Sabine-Karen Lammoglia, and Katharina Waha. 2023. 'Increased mineral fertilizer use on maize can improve both household food security and regional food production in East Africa', *Agricultural Systems*, 205.

Farhani, Slah, El Manaa Barhoumi, Qamar Ul Islam, and Faouzi Becha. 2024. 'Optimal design and economic analysis of a stand-alone integrated solar hydrogen water desalination system case study agriculture farm in Kairouan Tunisia', *International Journal of Hydrogen Energy*, 63: 759-66.

Ferrada, Francisco, Frederic Babonneau, Tito Homem-de-Mello, and Francisca Jalil-Vega. 2023. 'The role of hydrogen for deep decarbonization of energy systems: A Chilean case study', *Energy Policy*, 177.

Fisher, S., D. C. Bellinger, M. L. Cropper, P. Kumar, A. Binagwaho, J. B. Koudenoukpo, Y. Park, G. Taghian, and P. J. Landrigan. 2021. 'Air pollution and development in Africa: impacts on health, the economy, and human capital', *Lancet Planet Health*, 5: e681-e88.

Focus Economics. 2024. "Morocco Economy." In. Barcelona: Focus Economics.

Gao, Fei-Yue, Peng-Cheng Yu, and Min-Rui Gao. 2022. 'Seawater electrolysis technologies for green hydrogen production: challenges and opportunities', *Current Opinion in Chemical Engineering*, 36.

Genesis Water Tech. 2023. 'Top Solutions to Water Scarcity in Africa', Accessed April. https://genesiswatertech.com/blog-post/the-top-solutions-to-water-scarcity-in-africa/#:~:text=Two%20innovative%20primary%20solutions%20to,areas%20and%20brackish%20bore%20wells.

Gronau, Steven, Julian Hoelzen, Tobias Mueller, and Richard Hanke-Rauschenbach. 2023. 'Hydrogen-powered aviation in Germany: A macroeconomic perspective and methodological approach of fuel supply chain integration into an economy-wide dataset', *International Journal of Hydrogen Energy*, 48: 5347-76.

Haag, Leonora. 2022. "Environmental colonialism in the Maghreb? Harnessing green energy on indigenous peoples' land." In.: The Swedish Institute of International Affairs.

Habib, Ali, and Mostefa A. Ouki. 2021. "Egypt's low carbon hydrogen development prospects." In *OIES Paper*. Oxford.

Harichandan, Sidhartha, Sanjay Kumar Kar, and Prashant Kumar Rai. 2023. 'A systematic and critical review of green hydrogen economy in India', *International Journal of Hydrogen Energy*, 48: 31425-42.

Hassan, Qusay, Sameer Algburi, Aws Zuhair Sameen, Hayder M. Salman, and Marek Jaszczur. 2023. 'A review of hybrid renewable energy systems: Solar and wind-powered solutions: Challenges, opportunities, and policy implications', *Results in Engineering*, 20.

Heinemann, Christoph, Roman Mendelevitch, David Ritter, Michael Jakob, Kaya Dünzen, and Susanne Kriege. 2022. "Hydrogen Fact Sheet – North African Countries." In. Freiburg.

Hmadouch, Younes Ait. 2023. "Morocco's Position in Global Fertilizer Market after Russia's Invasion of Ukraine." In.: Morocco World News.

Hydrogen Council. 2022. "Hydrogen Insights 2022."

Hyphen Hydrogen Energy. 2023. "Socio-Economic Development (SED) Framework." In.

IEA. 2023a. "Energy Statistics Data Browser." In. Paris: IEA.

IEA. 2023b. "Lagging policy support and rising cost pressures put investment plans for low-emissions hydrogen at risk." In.

IEA. 2023c. "Net Zero Roadmap A Global Pathway to Keep the 1.5 °C Goal in Reach." In. Paris.

International Alert. 2022. "Fuelling conflict? The impact of the green energy transition on peace and security." In.

International Energy Forum. 2023. "Shaping a Living Roadmap for Energy Transition." In.: International Energy Forum.

IPCC. 2022. "Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change " In, edited by H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem and B. Rama, 3056. Cambridge, UK and New York, NY, USA: Intergovernmental Panel on Climate Change.

IQAir. 2023. "World Air Quality Report: Region & City PM2.5 Ranking."

IRENA. 2022a. "Geopolitics of the Energy Transformation: The Hydrogen Factor." In. Abu Dhabi: International Renewable Energy Agency.

IRENA. 2022b. "Global Hydrogen Trade to Meet the 1.5°C Climate Goal Part III - Green Hydrogen Cost and Potential." In. Abu Dhabi: International Renewable Energy Agency.

IRENA. 2023. "World Energy Transitions Outlook 2023: 1.5° C Pathway." In. Abu Dhabi.

IRENA, and AfDB. 2022. "Renewable Energy Market Analysis: Africa and Its Regions." In. Abu Dhabi and Abidjan: International Renewable Energy Agency and African Development Bank.

IRENA, and Bluerisk. 2023. "Water for hydrogen production." In. Abu Dhabi, United Arab Emirates: International Renewable Energy Agency, Bluerisk,.

Jing, Dongmei, Abdulrazak Abdulsalam Mohammed, Ammar Kadi, Samariddin Elmirzaev, Mohsin O. Al-Khafaji, and Mohammad Marefati. 2023. 'Wastewater treatment to improve energy and water nexus with hydrogen fuel production option: Techno-economic and process analysis', *Process Safety and Environmental Protection*, 172: 437-50.

Khan, M. A., Tareq Al-Attas, Soumyabrata Roy, Muhammad M. Rahman, Noreddine Ghaffour, Venkataraman Thangadurai, Stephen Larter, Jinguang Hu, Pulickel M. Ajayan, and Md Golam Kibria. 2021. 'Seawater electrolysis for hydrogen production: a solution looking for a problem?', *Energy & Environmental Science*, 14: 4831-39.

King, Richard, Tim G. Benton, Antony Froggatt, Helen Harwatt, Daniel Quiggin, and Laura Wellesley. 2023. "The emerging global crisis of land use: How rising competition for land threatens international and environmental stability, and how the risks can be mitigated." In.

Lakshmanan, Sandhiya, and Madhulika Bhati. 2024. 'Unravelling the atmospheric and climate implications of hydrogen leakage', *International Journal of Hydrogen Energy*, 53: 807-15.

Lebrouhi, B. E., J. J. Djoupo, B. Lamrani, K. Benabdelaziz, and T. Kousksou. 2022. 'Global hydrogen development - A technological and geopolitical overview', *International Journal of Hydrogen Energy*, 47: 7016-48.

Lebrouhi, B. E., B. Lamrani, Y. Zeraouli, and T. Kousksou. 2024. 'Key challenges to ensure Morocco's sustainable transition to a green hydrogen economy', *International Journal of Hydrogen Energy*, 49: 488-508.

Lesimple, Alain, Farah Ejaz Ahmed, and Nidal Hilal. 2020. 'Remineralization of desalinated water: Methods and environmental impact', *Desalination*, 496.

Liu, Xuan, and Jie Zhou. 2021. 'Assessment of the Continuous Extreme Drought Events in Namibia during the Last Decade', *Water*, 13.

Lloret, J., A. Turiel, J. Sole, E. Berdalet, A. Sabates, A. Olivares, J. M. Gili, J. Vila-Subiros, and R. Sarda. 2022. 'Unravelling the ecological impacts of large-scale offshore wind farms in the Mediterranean Sea', *Sci Total Environ*, 824: 153803.

LLOYDS Bank. 2024. "Morocco: Economic and Political Overview."

Lorentz, Bernhard, Johannes Trüby, Felix Chr. Matthes, Pradeep Philip, Sébastien Douguet, Behrang Shirizadeh, Emmanuel Bovari, Aurélien Ailleret, and Augustin Guillon. 2023. "Green hydrogen: Energizing the path to net zero." In.: Deloitte.

M.S, Sajna, Tasneem Elmakki, Kira Schipper, Seungwon Ihm, Youngwook Yoo, Byungsung Park, Hyunwoong Park, Ho Kyong Shon, and Dong Suk Han. 2024. 'Integrated seawater hub: A nexus of sustainable water, energy, and resource generation', *Desalination*, 571.

Magoum, Inès. 2023. "ALGERIA: the use of containerised seawater desalination plants." In *Afrik21*.

Malpass, David. 2022. "A transformed fertilizer market is needed in response to the food crisis in Africa." In *World Bank Blogs*.

Mapani, Benjamin S., Rosemary N. Shikangalah, and Asteria L. Mwetulundila. 2023. 'A review on water security and management under climate change conditions, Windhoek, Namibia', *Journal of African Earth Sciences*, 197.

Martin, Polly. 2024. "Morocco promises a million hectares of land for green hydrogen project development."

Mekonnen, Mesfin M., and Arjen Y. Hoekstra. 2016. 'Four billion people facing severe water scarcity', *Science Advances*, 2: e1500323.

Ministry of Energy. 2020. "National Green Hydrogen Strategy: Chile, a clean energy provider for a carbon neutral planet." In. Santiago, Chile: Ministry of Energy, Government of Chile.

Ministry of Mines and Energy Namibia. 2022. "Namibia Green Hydrogen & Derivatives Strategy." In. Windhoek, Namibia.

Mirzania, Pegah, Joel A. Gordon, Nazmiye Balta-Ozkan, Ramazan Caner Sayan, and Lochner Marais. 2023. 'Barriers to powering past coal: Implications for a just energy transition in South Africa', *Energy Research & Social Science*, 101.

Mohammed-Ibrahim, Jamesh, and Harb Moussab. 2020. 'Recent advances on hydrogen production through seawater electrolysis', *Materials Science for Energy Technologies*, 3: 780-807.

Naudé, Wim. 2023. "South Africa's gamble on green hydrogen."

Noussan, Michel, Pier Paolo Raimondi, Rossana Scita, and Manfred Hafner. 2020. 'The Role of Green and Blue Hydrogen in the Energy Transition—A Technological and Geopolitical Perspective', *Sustainability*, 13.

Ocko, Ilissa B., and Steven P. Hamburg. 2022. 'Climate consequences of hydrogen emissions', *Atmospheric Chemistry and Physics*, 22: 9349-68.

OECD. 2023. *Pipeline transport: leakage from high pressure pipeline*.

Oliveira, Alexandra M., Rebecca R. Beswick, and Yushan Yan. 2021. 'A green hydrogen economy for a renewable energy society', *Current Opinion in Chemical Engineering*, 33.

Osorio-Tejada, J., N. N. Tran, and V. Hessel. 2022. 'Techno-environmental assessment of small-scale Haber-Bosch and plasma-assisted ammonia supply chains', *Sci Total Environ*, 826: 154162.

Perelli, S., and G. Genna. 2022. 'azards Identification and Risk Management of Hydrogen Production and Storage Installations', *Chemical Engineering Transactions*, 96: 6.

Qadir, Manzoor, Pay Drechsel, Blanca Jiménez Cisneros, Younggy Kim, Amit Pramanik, Praem Mehta, and Oluwabusola Olaniyan. 2020. 'Global and regional potential of wastewater as a water, nutrient and energy source', *Natural Resources Forum*, 44: 40-51.

Rambhujun, N., M. S. Salman, T. Wang, C. Pratthana, P. Sapkota, M. Costalin, Q. Lai, and K. F. Aguey-Zinsou. 2020. 'Renewable hydrogen for the chemical industry', *MRS Energy Sustain*, 7: 33.

Rentschler, J., and N. Leonova. 2023. 'Global air pollution exposure and poverty', *Nat Commun*, 14: 4432.

RIVM. 2024a. "Effecten van waterstofexplosies." In, edited by M. van der Linden and A.G. Wolting. Rijksinstituut voor Volksgezondheid en Milieu (RIVM).

RIVM. 2024b. "Liquid hydrogen carriers: an overview of technical aspects and SVHC properties." In, edited by M. Marinković and J. Ng-A-Tham. National Institute for Public Health and the Environment (RIVM).

Ruf, Yvonne, Simon Lange, Johannes Pfister, and Claudia Droege. 2018. "Fuel Cells and Hydrogen for Green Energy in European Cities and Regions." In. Munich: Roland Berger GmbH.

Ruppel, Oliver C. , and Magano Katoole. 2023. "A regulatory green hydrogen framework for Namibia." In *Graz Law Working Paper*.

Ryser, Sarah. 2019. 'The Anti-Politics Machine of Green Energy Development: The Moroccan Solar Project in Ouarzazate and Its Impact on Gendered Local Communities', *Land*, 8.

Santana, Leonardo O. S., Artur S. Bispo, Gustavo S. Santos, Chrislaine B. Marinho, Ewerton E. S. Calixto, José L. G. Almeida, and Fernando L. P. Pessoa. 2023. 'Water sources evaluation for green hydrogen production: a case study in Brazil.' in Antonios C. Kokossis, Michael C. Georgiadis and Efstratios Pistikopoulos (eds.), *Computer Aided Chemical Engineering* (Elsevier).

Saygin, Deger, and Dolf Gielen. 2021. 'Zero-Emission Pathway for the Global Chemical and Petrochemical Sector', *Energies*, 14.

Scolaro, Michele, and Noah Kittner. 2022. 'Optimizing hybrid offshore wind farms for cost-competitive hydrogen production in Germany', *International Journal of Hydrogen Energy*, 47: 6478-93.

Signoria, C., and M. Barlettani. 2023. "Environmental, Health, Safety, and Social Management of Green Hydrogen in Latin America and the Caribbean." In.: IADB: Inter-American Development Bank. United States of America.

South African Market Insights. 2015. "South Africa's Economic Structure." In.

Sun, T., E. Shrestha, S. P. Hamburg, R. Kupers, and I. B. Ocko. 2024. 'Climate Impacts of Hydrogen and Methane Emissions Can Considerably Reduce the Climate Benefits across Key Hydrogen Use Cases and Time Scales', *Environ Sci Technol*, 58: 5299-309.

Swennenhuis, Floris, Vincent de Gooyert, and Heleen de Coninck. 2022. 'Towards a CO2-neutral steel industry: Justice aspects of CO2 capture and storage, biomass- and green hydrogen-based emission reductions', *Energy Research & Social Science*, 88.

The Ministry of Foreign Affairs. 2023. "The Africa Strategy of the Netherlands 2023-2032." In. The Hague: The Ministry of Foreign Affairs.

The World Bank Group. 2021. " Climate Risk Profile: Namibia."

Tonelli, D., L. Rosa, P. Gabrielli, K. Caldeira, A. Parente, and F. Contino. 2023. 'Global land and water limits to electrolytic hydrogen production using wind and solar resources', *Nat Commun*, 14: 5532.

Torma, Gabriele, and Jessica Aschemann-Witzel. 2023. 'Social acceptance of dual land use approaches: Stakeholders' perceptions of the drivers and barriers confronting agrivoltaics diffusion', *Journal of Rural Studies*, 97: 610-25.

Turley, Bethani, Alida Cantor, Kate Berry, Sarah Knuth, Dustin Mulvaney, and Noel Vineyard. 2022. 'Emergent landscapes of renewable energy storage: Considering just transitions in the Western United States', *Energy Research & Social Science*, 90.

Ugwueze, Michael I., J. Tochukwu Omenma, and Felicia O. Okwueze. 2022. 'Land-Related Conflicts and the Nature of Government Responses in Africa: The Case of Farmer-Herder Crises in Nigeria', *Society*, 59: 240-53.

UNECA. 2020. "Synthesis Report Land, Ethnicity and Conflict in Africa: Implications for African Land Policy Initiatives." In. Addis Ababa, Ethiopia: Economic Commission for Africa.

Union of Concerned Scientists. 2022. "How to Eliminate Pollution from Heavy-Duty Vehicles." In.

van Wijk, Ad , and Frank Wouters. 2021. 'Hydrogen–The Bridge Between Africa

and Europe.' in Margot P. C. Weijnen, Zofia Lukszo and Samira Farahani (eds.), *Shaping an Inclusive Energy Transition* (Springer Nature Switzerland AG: Cham, Switzerland).

Vardhan, R. V., R. Mahalakshmi, R. Anand, and A. Mohanty. 2022. "A Review on Green Hydrogen: Future of Green Hydrogen in India." In *2022 6th International Conference on Devices, Circuits and Systems (ICDCS)*, 303-09.

Varras, G., and M. Chalaris. 2024. 'Critical Review of Hydrogen Production via Seawater Electrolysis and Desalination: Evaluating Current Practices', *Journal of Electrochemical Energy Conversion and Storage*, 21.

Verpoort, Philipp C., Lukas Gast, Anke Hofmann, and Falko Ueckerdt. 2024. 'Impact of global heterogeneity of renewable energy supply on heavy industrial production and green value chains', *Nature Energy*.

Walker, Sean B., Michael Fowler, and Leila Ahmadi. 2015. 'Comparative life cycle assessment of power-to-gas generation of hydrogen with a dynamic emissions factor for fuel cell vehicles', *Journal of Energy Storage*, 4: 62-73.

Wang, Bing, Zhifu Mi, Ioan Nistor, and Xiao-Chen Yuan. 2018. 'How does hydrogen-based renewable energy change with economic development? Empirical evidence from 32 countries', *International Journal of Hydrogen Energy*, 43: 11629-38.

Wang, R. R., Y. Q. Zhao, A. Babich, D. Senk, and X. Y. Fan. 2021. 'Hydrogen direct reduction (H-DR) in steel industry—An overview of challenges and opportunities', *Journal of Cleaner Production*, 329.

Warwick, Nicola J., Alex T. Archibald, Paul T. Griffiths, James Keeble, Fiona M. O'Connor, John A. Pyle, and Keith P. Shine. 2023. 'Atmospheric composition and climate impacts of a future hydrogen economy', *Atmospheric Chemistry and Physics*, 23: 13451-67.

Weko, Silvia, Andrew Farrand, Dina Fakoussa, and Rainer Quitzow. 2023. "The Politics of Green Hydrogen Cooperation: Emerging Dynamics in Morocco, Algeria and Mauritania." In.: Research Institute for Sustainability (RIFS).

Whitehead, Jake, Peter Newman, Jessica Whitehead, and Kai Li Lim. 2023. 'Striking the right balance: understanding the strategic applications of hydrogen in transitioning to a net zero emissions economy', *Sustainable Earth Reviews*, 6.

Whitmee, S., R. Green, K. Belesova, S. Hassan, S. Cuevas, P. Murage, R. Picetti, R. Clercq-Roques, K. Murray, J. Falconer, B. Anton, T. Reynolds, H. Sharma Waddington, R. C. Hughes, J. Spadaro, A. Aguilar Jaber, Y. Saheb, D. Campbell-Lendrum, M. Cortes-Puch, K. Ebi, R. Huxley, M. Mazzucato, T. Oni, N. de Paula, G. Peng, A. Revi, J. Rockstrom, L. Srivastava, L. Whitmarsh, R. Zougmore, J. Phumaphi, H. Clark, and A. Haines. 2024. 'Pathways to a healthy net-zero future: report of the Lancet Pathfinder Commission', *Lancet*, 403: 67-110.

Widera, Barbara. 2020. 'Renewable hydrogen implementations for combined energy storage, transportation and stationary applications', *Thermal Science and Engineering Progress*, 16.

World Bank. 2023. "Chile to Accelerate its Green Hydrogen Industry with World Bank Support." In. Washington, D.C.

World Health, Organization. 2021. *WHO global air quality guidelines: particulate matter (PM2.5 and PM10), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide* (World Health Organization: Geneva).

Xiang, Huang, Paramaiah Ch, Muhammad Atif Nawaz, Supat Chupradit, Arooj Fatima, and Muhammad Sadiq. 2021. 'Integration and economic viability of fueling the future with green hydrogen: An integration of its determinants from renewable economics', *International Journal of Hydrogen Energy*, 46: 38145-62.

Yáñez, Édgar, Hans Meerman, Andrea Ramírez, Édgar Castillo, and Andre Faaij. 2022. 'Fully integrated CO2 mitigation strategy for an existing refinery: A case study in Colombia', *Applied Energy*, 313.

Zou, Caineng, Bo Xiong, Huaqing Xue, Dewen Zheng, Zhixin Ge, Ying Wang, Luyang Jiang, Songqi Pan, and Songtao Wu. 2021. 'The role of new energy in carbon neutral', *Petroleum Exploration and Development*, 48: 480-91.

Appendices

Appendix List of reviewed articles

Table 2: Selection criteria for and list of reviewed articles

Key word	Year range	Reviewed articles
Water scarcity AND green hydrogen	2015-2024 Search conducted on 5 March 2024	Alkhalidi, Battikhi et al. (2024) Boretti and Rosa (2019) Santana, Bispo et al. (2023) Cattani, Cattani et al. (2023) Jing, Mohammed et al. (2023)
Land use AND conflict AND green hydrogen	2015-2024 Search conducted on 10 March 2024	Turley, Cantor et al. (2022) Chigbu and Nweke-Eze (2023) Cremonese, Mbungu and Quitzow (2023) de Ruijter, Helsen et al. (2023) Torma and Aschemann-Witzel (2023)
"Hydrogen leakage" AND "climate"	2015-2024 Search conducted on 15 March 2024	Esquivel-Elizondo, Hormaza Mejia et al. (2023) Warwick, Archibald et al. (2023) Lakshmanan and Bhati (2024) Sun, Shrestha et al. (2024)
Green hydrogen AND (finance OR investment) AND risk	2015-2024 Search conducted on 15 March 2024	Habib and Ouki (2021) Ocko and Hamburg (2022) Whitehead, Newman et al. (2023) Ajanovic, Sayer and Haas (2024)
Green hydrogen AND Sustainable development goals	2015-2024 Search conducted on 20 March 2024	Bhaskar, Assadi and Nikpey Somehsaraei (2020) Ferrada, Babonneau et al. (2023) Yáñez, Meerman et al. (2022) Zou, Xiong et al. (2021) Scolaro and Kittner (2022)
Green hydrogen AND Air pollution	2015-2024 Search conducted on 25 March 2024	Ruf, Lange et al. (2018) Walker, Fowler and Ahmadi (2015) Becerra-Ruiz, Gonzalez-Huerta et al. (2019) Abhyankar, Mohanty et al. (2023)

Key word	Year range	Reviewed articles
		Vardhan, Mahalakshmi et al. (2022)
Green hydrogen AND Job creation OR employment	2015-2024 Search conducted on 29 March 2024	Bisognin Garlet, de Souza Savian et al. (2024) Eicke and De Blasio (2022) Harichandan, Kar and Rai (2023) van Wijk and Wouters (2021) Boudghene Stambouli, Kitamura et al. (2024)
Green hydrogen AND (fertiliser OR food OR agriculture)	2015-2024 Search conducted on 2 April 2024	Rambhujun, Salman et al. (2020) Osorio-Tejada, Tran and Hessel (2022) Harichandan, Kar and Rai (2023)
Green hydrogen AND water AND supply AND (synergy OR synergies)	2015-2024 Search conducted on 4 April 2024	Farhani, Barhoumi et al. (2024) M.S, Elmakki et al. (2024) Newborough and Cooley (2021)
Green hydrogen AND (energy security OR energy access)	2015-2024 Search conducted on 5 April 2024	Xiang, Ch et al. (2021) Widera (2020) Noussan, Raimondi et al. (2020) Oliveira, Beswick and Yan (2021)
Green hydrogen AND industrialisation	2015-2024 Search conducted on 8 April 2024	Agaton, Batac and Reyes Jr (2022) Wang, Mi et al. (2018) Eicke and De Blasio (2022) Saygin and Gielen (2021) Wang, Zhao et al. (2021)