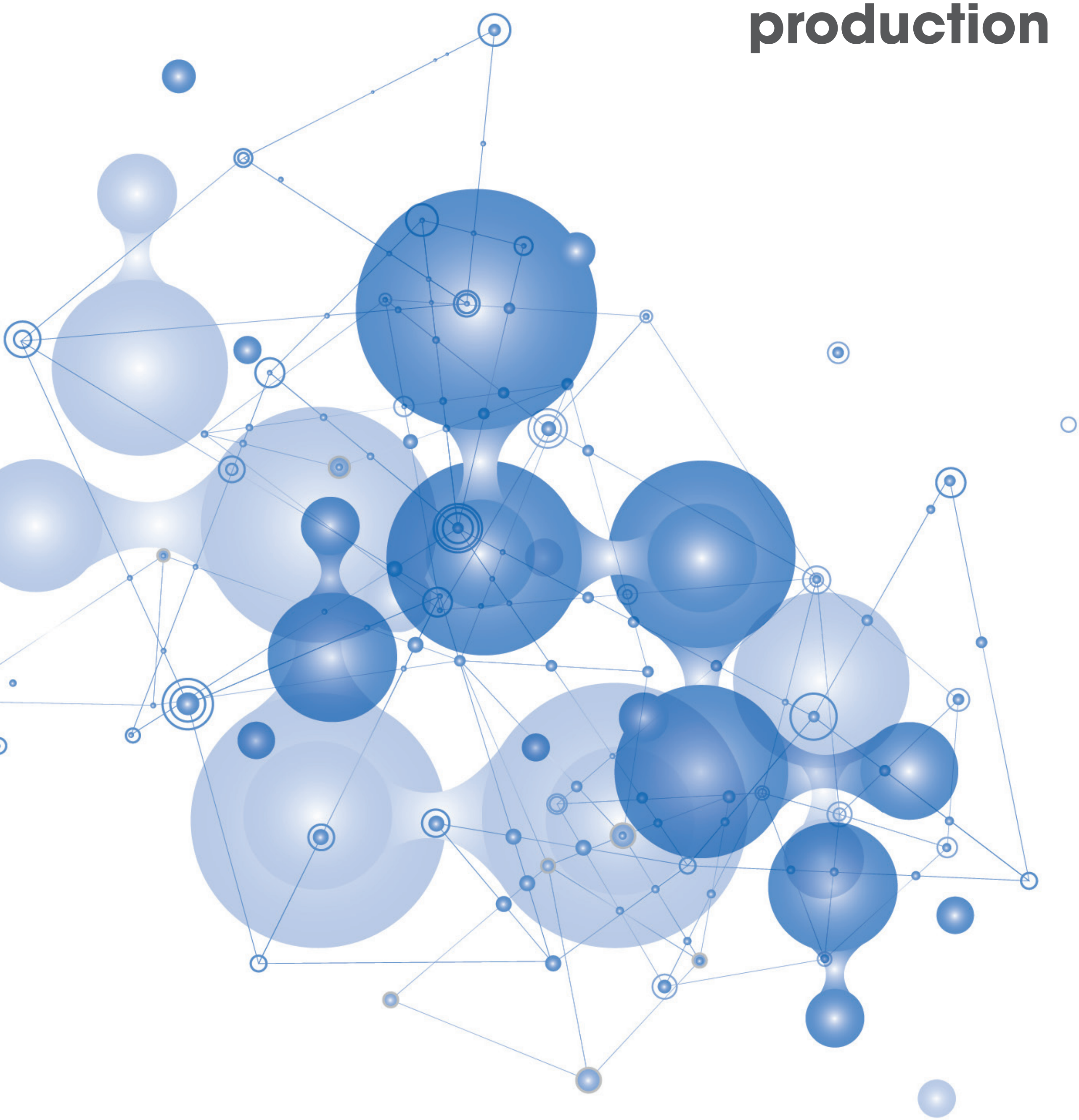
IRENA
International Renewable Energy Agency

Water for hydrogen production



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ABOUT IRENA

The International Renewable Energy Agency (IRENA) is an intergovernmental organisation that supports countries in their transition to a sustainable energy future and serves as the principal platform for international co-operation, a centre of excellence, and a repository of policy, technology, resource and financial knowledge on renewable energy. IRENA promotes the widespread adoption and sustainable use of all forms of renewable energy, including bioenergy, geothermal, hydropower, ocean, solar and wind energy, in the pursuit of sustainable development, energy access, energy security and low-carbon economic growth and prosperity.

www.irena.org

ABOUT BLUERISK

Bluerisk is a water strategy and data analytics consultancy focused on enhancing resilience and reducing risk in the face of emerging water challenges.

Bluerisk

www.blueriskintel.com

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For further information or to provide feedback: **publications@irena.org**

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Abbreviations

AEM	anion exchange membrane
ATR	auto-thermal reforming
CCS	carbon capture and storage
CCUS	carbon capture, utilisation and storage
GCC	Gulf Cooperation Council
GHG	greenhouse gases
H_2	hydrogen
PEM	proton exchange membrane
PV	photovoltaic
SDG	Sustainable Development Goals
SMR	steam methane reforming
SOEC	solid oxide electrolyser cells

Units of measure

GW	gigawatt
kg	kilogram
kt	kilotonne
L	litre
m^3	cubic metre
Mt	megatonne

Glossary

Blowdown water: Water drained intentionally from cooling systems to prevent mineral build-up.

Cycle of concentration: A measure of the build-up of dissolved minerals in cooling systems. The cycle is calculated by comparing the concentration of a particular dissolved solid in the water coming out of a cooling system to its concentration in the water flowing into the system.

Deionised water: A type of highly purified water that does not contain any atoms, ions or molecules. Deionisation removes dissolved substances like sodium chloride, minerals, carbon dioxide, organic pollutants and various other contaminants from water.

Makeup water: The water added back into a cooling system to replace water lost due to evaporation, leaks, *etc.*

Permeate rate: In membrane-based water treatment systems, the ratio of the volume of water passing through the membrane to the total quantity of raw water.

Water withdrawal: Measured by the quantity of water withdrawn from a source *(e.g.* river, lake, groundwater) for use.

Water withdrawal/consumption intensity: The quantity of water withdrawn for or consumed in the generation of a unit of a product *(e.g.* a megawatt hour of energy, a megatonne of hydrogen).

Water consumption: The portion of withdrawn water that is not returned to the source.

Water stress: Measured using the ratio of the total water withdrawal to the available renewable freshwater supply. It should be calculated at a watershed scale. Water stress poses significant risks to human and environmental well-being and is a proxy for water competition among sectors and uses.

Executive summary

The energy sector is the largest water user of all industrial sectors. Water is required in many of its processes, from fuel extraction to electricity generation. As seen in the recent nuclear power plant shutdowns in Europe in 2022, water shortages can significantly disrupt the sector. And the disruptions are likely to continue and to become even more frequent, especially as extreme weather events intensify amid a changing climate. To address the rising climate risks, the energy sector is already establishing good practices for integrating water considerations into planning. The sector can mitigate its water risks by transitioning to renewable energy sources, which consume less water than traditional fossil fuels.

Clean hydrogen has emerged as a viable alternative in the fight against climate change. Hydrogen is a game changer, especially for "hard to abate", such as steelmaking, chemical production, aviation, shipping and truck transport. Assessing the water use implications of hydrogen production, especially in water-stressed areas, is essential in managing potential disruptions to production.

All hydrogen production technologies require water as an input. Water is needed not only in production but also for cooling. The withdrawal and consumption of water for clean hydrogen production have been debated, yet too often the discussions are not informed by in-depth knowledge of these still-nascent technologies.

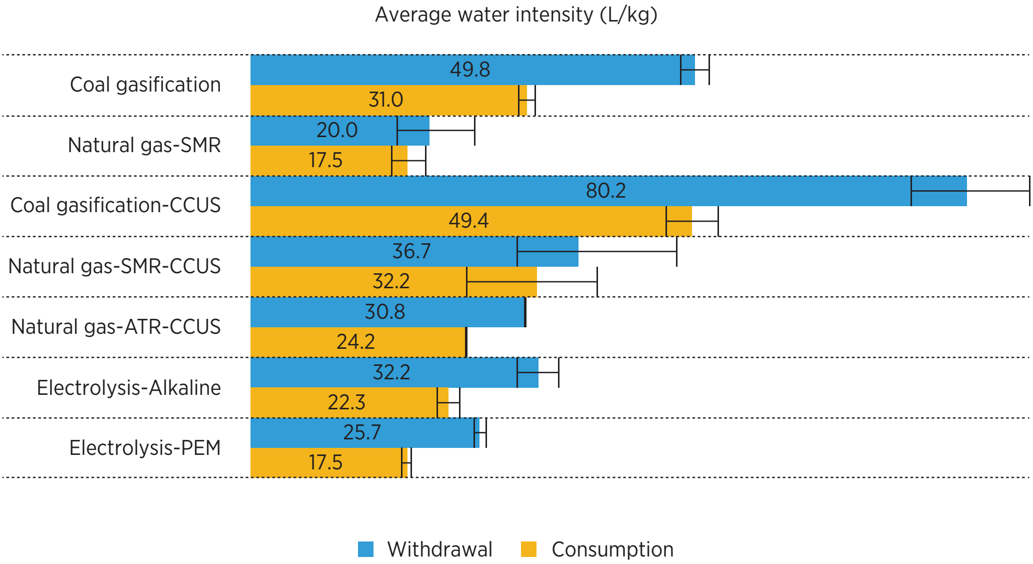
This report, compiled by the International Renewable Energy Agency (IRENA) and Bluerisk, seeks to answer some of these questions.

How much water does a hydrogen plant actually consume?

This report reviews the water withdrawal and consumption requirements of various hydrogen production technologies in detail. Data have been sourced from interviews with industry experts and a review of existing literature, shedding light on the water implications of scaling up clean hydrogen production. Average water withdrawal and consumption intensity and ranges are visualised in Figure S1.

Green hydrogen is the most water efficient of all clean hydrogen types. It is found that on average, proton exchange membrane (PEM) electrolysis has the lowest water consumption intensity at about 17.5 litres per kilogramme of hydrogen (L/kg). Alkaline electrolysis follows PEM electrolysis, with a water consumption intensity of 22.3 L/kg. These may be compared with steam methane reforming–carbon capture, utilisation and storage (SMR-CCUS), at 32.2 L/kg, and autothermal reforming (ATR)-CCUS at 24.2 L/kg.

FIGURE S1 A comparison of average water withdrawal and consumption intensities by hydrogen production technology



Note: Tap water (or sources with similar water quality) is (are) used or assumed to be the water source(s) behind these data points. For blue hydrogen, the cooling requirements for CCUS systems are included. For PEM and ATR, available data points are limited since these technologies are relatively new – thus the much smaller ranges of values. ATR = autothermal reforming; CCUS = carbon capture, utilisation and storage; kg = kilogramme; L = litre; PEM = proton exchange membrane; SMR = steam methane reforming.

Coal gasification is by far the most water intensive of available technologies; it would be about 60% more intensive if equipped with CCUS. Coal gasification has a water withdrawal requirement of about 50 L/kg and consumes 31 L/kg, on average – roughly twice PEM's water withdrawal and consumption requirements. Equipped with CCUS, coal gasification's withdrawal as well as consumption requirements could further increase to 80.2 and 49.4 L/kg, respectively. A coal gasification hydrogen plant producing 237 kilotonnes (kt) of hydrogen per year and equipped with CCUS would withdraw about 19 million cubic metres (m^3) of water annually; this volume of water could support half the water demand of the city of London for an entire year.

Water is required as an input for production and as a cooling medium for all types of hydrogen production. Depending on the technology, the share of withdrawal for cooling can range from 14% to 92%. The share of water withdrawal for cooling is the lowest for grey hydrogen production, at about 14%. Green and brown hydrogen's shares are 56% and 52%, respectively. Blue hydrogen production requires more water for cooling, due to the significant water requirements of CCUS systems for heat transfer. Cooling can account for up to 92% of the total withdrawal requirement of blue hydrogen, according to data from the National Energy Technology Laboratory in the United States. However, more evidence is needed before a general production-cooling ratio can be determined without dispute.

For every 1 percentage point increase in electrolysis efficiency, the water withdrawal as well as consumption requirements of green hydrogen production lessen by about 2%. This is primarily because, for the same type of hydrogen production technology, the more energy efficient the system is, the less waste heat needs to be transferred; this means less water is required for cooling.

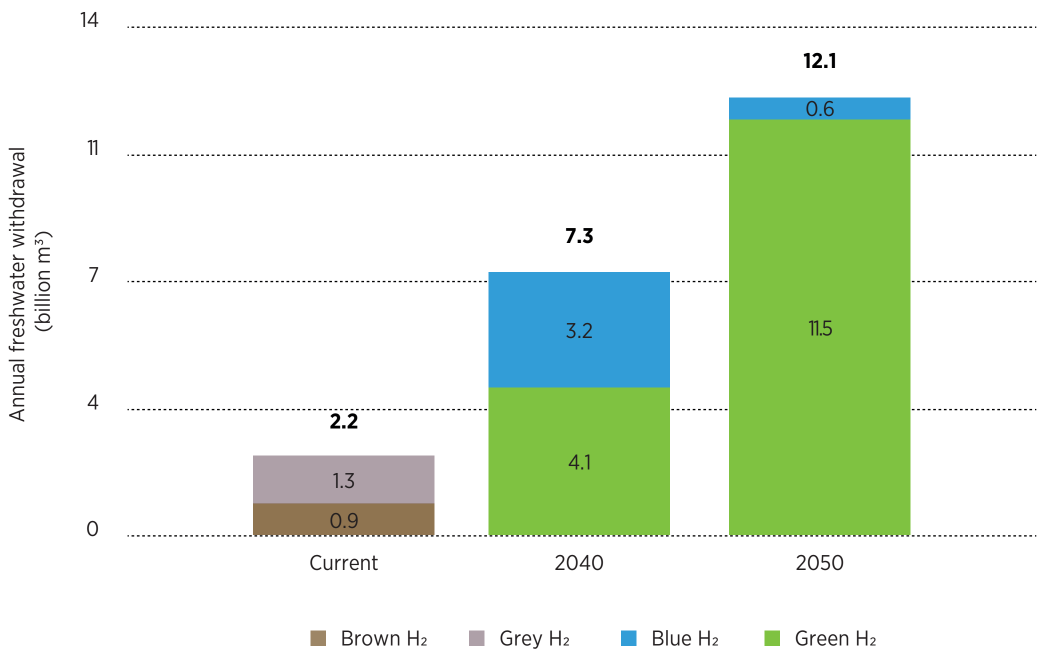
What will be the global impact of clean hydrogen?

This report presents a comprehensive analysis of the water footprint and risks associated with current and projected future global hydrogen production. The analysis is based on IRENA's 1.5°C Scenario, which projects substantial growth in hydrogen production by 2050.

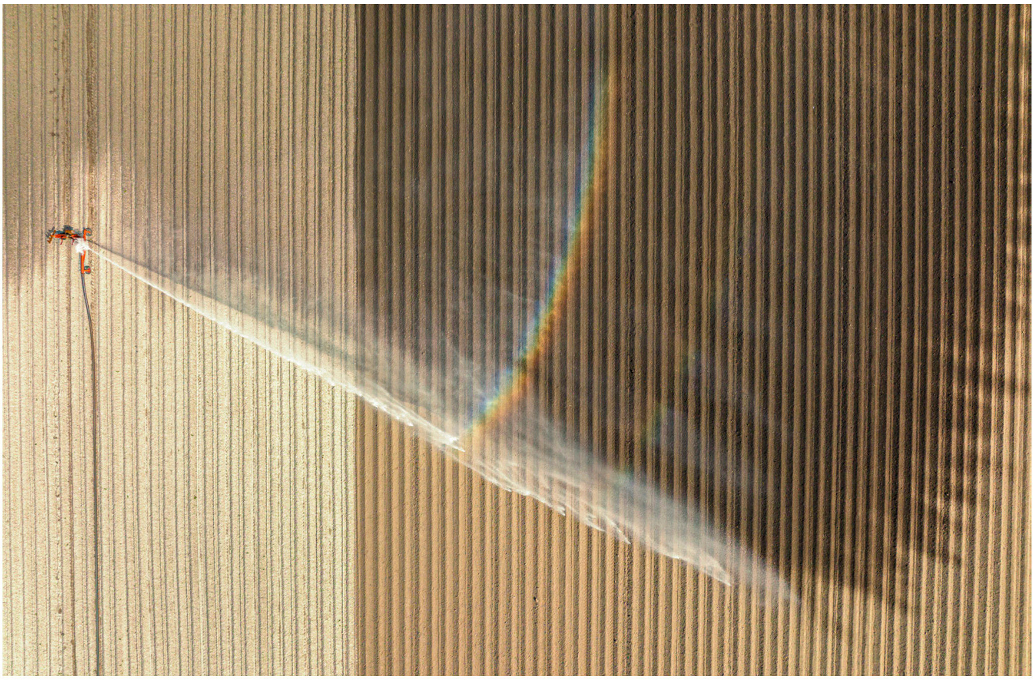
Today, about 2.2 billion m³ of freshwater is withdrawn for global hydrogen production every year; this accounts for 0.6% of the energy sector's total freshwater withdrawal. As illustrated in Figure S2, grey hydrogen production accounts for about 59% of the global freshwater withdrawal for hydrogen production, brown hydrogen 40%, and the rest is from green and blue hydrogen.

Freshwater withdrawals for global hydrogen production could more than triple by 2040 and increase six-fold by 2050, compared with today. Driven by the significant expansion of global demand for hydrogen, the total freshwater withdrawal required by global hydrogen production is projected to be about 7.3 billion m³ by 2040 and 12.1 billion m³ by 2050, factoring in technology advancements. Hydrogen production's share of total freshwater withdrawn for the energy sector could rise from 0.6% today to 2.4% by 2040.

FIGURE S2 Current and projected freshwater withdrawal for global hydrogen production, by pathway



Note: Tap water (or water sources with similar water quality) is (are) assumed to be the water source(s). Projected desalination-based and seawater-cooled hydrogen production (*e.g.* in the GCC countries) is excluded. Blue H_2 includes SMR-CCUS, ATR-CCUS and coal-CCUS, with the share of ATR-CCUS assumed to gradually increase to 75% by 2050. Cooling in blue H_2 production includes the cooling demand due to CCUS systems. Green H_2 includes both alkaline and PEM electrolysis with the share of PEM electrolysis assumed to gradually increase to 75% by 2050. Moderate gradual increases in electrolysis efficiency (7.5 percentage points for alkaline electrolysis and 4.5 percentage points for PEM-electrolysis over the coming three decades) are assumed. For calculation purposes, the cooling and production shares of blue H_2 in Case 2 from Lewis *et al.* (2022) are applied. ATR = autothermal reforming; CCUS = carbon capture, utilisation and storage; H_2 = hydrogen; PEM = proton exchange membrane; SMR = steam methane reforming.



And the local impact?

Although the water consumed for hydrogen production will not have a significant impact globally, the importance of considering local water contexts when planning hydrogen development cannot be overstated, especially chronic water risks such as water stress.

More than 35% of the global green and blue hydrogen production capacity (in operation and planned) is located in highly water-stressed regions. Using the Aqueduct Water Risk Atlas, this report assesses water stress conditions in locations where global green and blue hydrogen projects are already operating or being planned. Key regional findings reveal that India is likely to have 99% of its hydrogen capacity in extremely water-stressed areas by 2040, while China and the EU-27 also face significant water stress challenges. The United States and other Group of Twenty (G20) countries are exposed to water stress to varying degrees. Hydrogen production under water stress conditions would face frequent disruption, besides being exposed to the risk of uncertainties surrounding environmental regulations.

The report presents in-depth analyses of the water challenges faced by the hydrogen production industry in Northern China, the Gulf Cooperation Council (GCC) countries and Europe.

Northern China

Coal chemical plants in northern China contribute significantly to the country's current hydrogen production, but they require large amounts of freshwater to operate. For example, freshwater withdrawals for hydrogen production in the province of Shanxi are estimated to account for over 30% of the province's overall industrial water withdrawal. Most of these coal-fired chemical plants are located in the Yellow River Basin, a region where water is extremely scarce. Over 70% of these plants operate in areas under severe water stress, making them vulnerable to fluctuations in water availability and changing regulations.

Continuous expansion of the hydrogen industry is projected to drive up water demand significantly by 2030 if coal-based production continues to dominate. This would bring the region's water resources under even more stress. A transition to alternative technologies such as alkaline electrolysis becomes crucial to sustainably address these challenges since these technologies can help meet future demand for hydrogen, while reducing freshwater withdrawal and consumption to levels even below those seen today. Alternative technologies are thus promising solutions to water-related concerns.

Gulf Cooperation Council

In the GCC countries, the pursuit of hydrogen production presents unique challenges and opportunities. These countries are major producers of grey hydrogen from natural gas and offer scope for a transition to green hydrogen production. However, water scarcity is a significant issue in the GCC countries, which rely heavily on desalinated water for hydrogen production and employ once-through cooling systems, raising both environmental and economic concerns, including thermal and brine pollution and high energy costs.

As the region aims to produce more hydrogen by 2040, a tripling of seawater withdrawal is projected. This underlines an urgent need for sustainable water management practices. A transition to alternative production technologies such as alkaline and PEM electrolysis can effectively reduce seawater withdrawal and the demand for desalinated water, addressing these challenges while making the hydrogen production industry more sustainable and responsible.

Europe

The pursuit of green hydrogen in Europe is pivotal to the region's ambitious emission mitigation goals. However, Europe faces unique challenges, notably increased occurrences of droughts, which impact energy production and exacerbate water stress. Even though Europe's hydrogen consumption is relatively low today, the region has a rapidly growing hydrogen industry, which has projects located across the continent, many near coastlines and major rivers. Importantly, over 23% of Europe's green hydrogen projects and 14% of its blue hydrogen projects are likely to be in areas under high or extremely high water stress by 2040, potentially increasing the competition for local water use.

As Europe shifts its hydrogen production mix, the water demand is expected to increase significantly by 2040. This will place new pressures on water resources in water-stressed regions. To ensure a sustainable and environmentally responsible hydrogen industry, Europe must integrate water considerations into its energy planning and development decision making. It must carefully manage water competition and promote water-efficient technologies such as PEM-based electrolysis.

So, what should we do?

The report ends with a set of recommendations, based on the results of the analysis. These recommendations are designed to reduce the exposure of future clean hydrogen projects to water-shortage-related risks.

→ Green hydrogen projects should be prioritised for future hydrogen development.

→ Water-related impacts and potential risks need to be carefully evaluated in hydrogen production development plans, particularly in water-stressed regions where stringent water use regulations must be established for the sector, and enforced.

→ Retiring fossil-fuel-based hydrogen plants and replacing them with green hydrogen should be prioritised in hydrogen development plans, particularly in areas where water is already scarce.

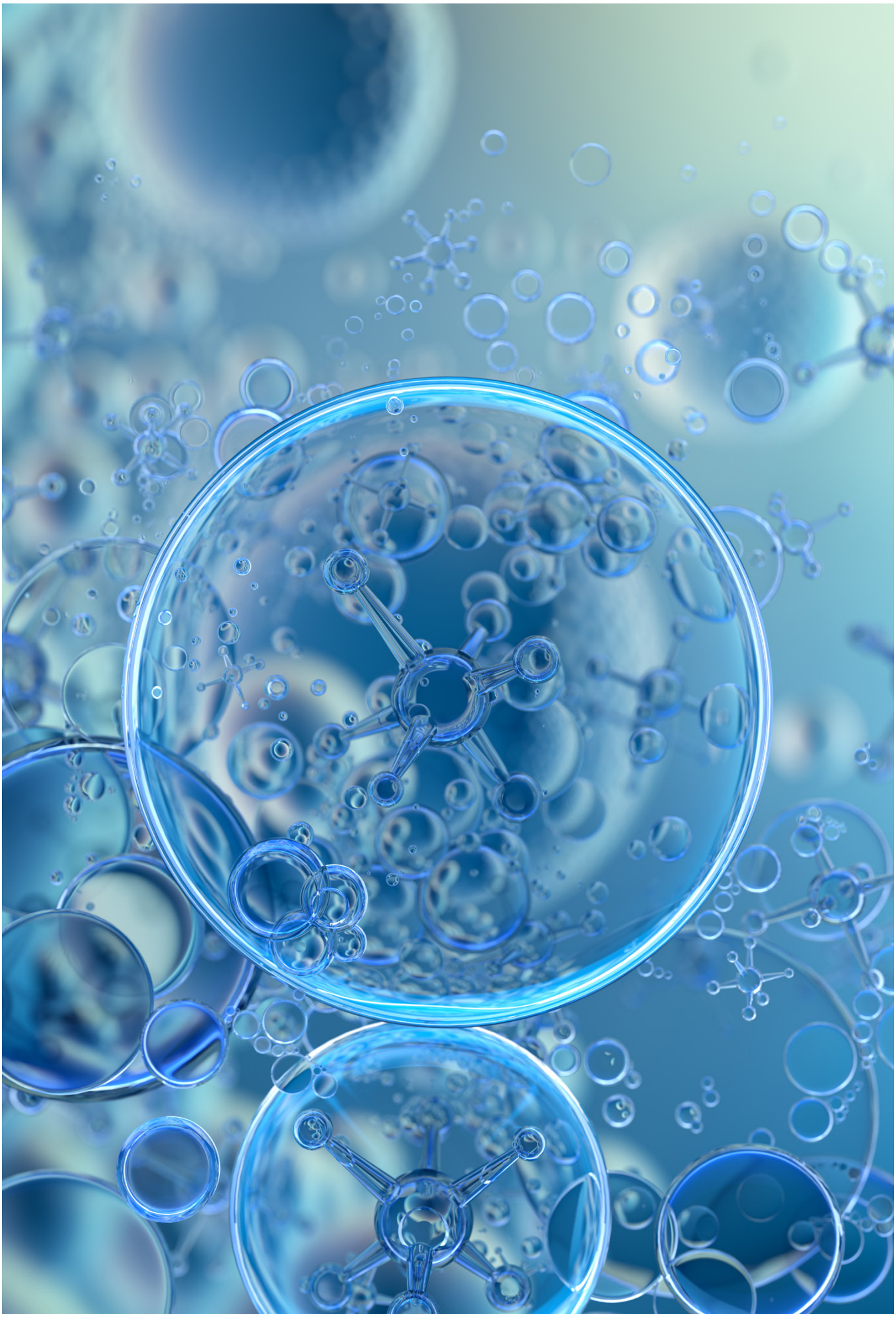
→ Water withdrawal and consumption should be considered as performance indicators of hydrogen production projects for pre-operational evaluation purposes and be metered and monitored during operation.

→ Regulations and financial incentives should favour projects demonstrating higher efficiency in energy conversion and water consumption.

→ More investment and research are required to improve the efficiency of commercial-scale electrolysers and reduce the consumption of freshwater for cooling.

→ Hydrogen production projects in regions where water is already scarce should be incentivised to use water-efficient cooling technologies such as air cooling.

→ In present and future freshwater-stressed coastal areas, utilising seawater for hydrogen production and cooling processes should be incentivised, even as regulations for thermal pollution and brine management are enforced.



Chapter 1: Introduction to the hydrogen-water nexus

In 2015, parties to the Paris Agreement concurred that urgent action to decarbonise their national economies is necessary to mitigate the harmful effects of climate change. Later, in 2018, the Intergovernmental Panel on Climate Change released the report “Global Warming of 1.5°C”, which called for policy makers to intensify and accelerate efforts to mitigate greenhouse gas (GHG) emissions, limit the global temperature rise and address the climate crisis (IPCC, 2018).

According to the report, there is a narrow window of opportunity to enact meaningful measures to prevent further temperature increase and address the climate crisis. Policy makers must therefore strengthen efforts to reduce GHG emissions from all economic activities as much as possible. Solutions that reduce only a small portion of emissions are inadequate; it is now critical to prioritise options that can provide significant emission reductions.

Meanwhile, certain industry and transport subsectors are particularly difficult to decarbonise, from both a technical and economic perspective, and corresponding solutions are limited in number. These sectors, known as “hard-to-abate” sectors, include steelmaking, basic chemical production, long-haul aviation, shipping and truck transport.

Enter hydrogen, the most abundant chemical in the universe. Around 95 megatonnes (Mt) of hydrogen were produced from fossil fuels in 2022 – for refineries, the production of basic chemicals and a few other uses (IEA, 2023).

Hydrogen can be used as a feedstock - to produce steel, ammonia, methanol, fertilisers and synthetic fuel, and to power vehicles - or stored, for times when renewables are at a seasonal low. The International Renewable Energy Agency (IRENA) estimates that under a Scenario where the average global temperature rise is successfully limited to 1.5°C, 523 Mt of hydrogen will be produced by 2050 (IRENA, 2023a). Of course, this production must come through climate-aware pathways. The good news is that these pathways do exist.

Hydrogen colour coding

It is common (even if the practice is disputed) to use colour coding to represent the hydrogen produced via different pathways. This report will follow the same practice. For those unaware of the colours' meaning, here is a brief vocabulary:

→ **Brown hydrogen** is produced via coal gasification.

→ **Grey hydrogen** is produced from methane via steam methane reforming (SMR).

→ **Blue hydrogen** production follows the brown and grey hydrogen pathways, but coupling with carbon capture, utilisation and storage (CCUS) limits GHG emissions. Further, autothermal reforming (ATR) is gaining attention for the production of blue hydrogen using CCUS. However, to be on a 1.5°C-consistent pathway, high carbon capture rates and the complete prevention of methane leakage are critical.

→ **Green hydrogen** is produced via renewable-fuelled water electrolysis.

Brown or grey hydrogen production releases substantial GHG emissions, rendering these technologies unsuitable on a net-zero emissions pathway. Other pathways, and other colours, may exist, although technologies other than SMR with biogas and nuclear-powered electrolysis (*e.g.* chemical looping cycles or photochemical and photo-electrochemical routes) have not yet reached commercial maturity, and are thus not foreseen to play a significant role in the near future (and are not included in this report).

As a somewhat new technology, green hydrogen is also under a lot of scrutiny, and rightly so. Many aspects of its production are unclear or untested, including, for example, land use, actual GHG emissions and the possibility of extending the life of fossil fuel power plants.

Also critical is the dimension of water. Carefully assessing and managing water use requires distinguishing withdrawal from consumption (detailed definitions in the glossary).

The water dimension

The Sustainable Development Goals (SDGs) underscore water's critical role in sustaining life and promoting development. Specifically, SDG 6 seeks to ensure the availability and sustainable management of water and sanitation for all. This goal highlights the elemental role played by water not only as a vital resource for life but also as an enabler of societal and economic development.

Unfortunately, access to clean and safe water remains an elusive quest for many communities around the world. Today, 27% of the world's population still lack access to any safely managed drinking water services, and 43% lack access to clean sanitation. The challenges surrounding access to water are not just about its availability but are tightly interwoven with the aspects of quality, reliability and affordability. These challenges, coupled with the impacts of climate change, further exacerbate water scarcity, disrupting ecosystems and straining livelihoods, especially in marginalised and vulnerable communities.

The energy sector relies heavily on water across the supply chain, from fuel production to electricity generation. Insufficient access to water has disrupted the sector severely across locations, from nuclear power plants in France to coal-fired power plants in India. Disruptions due to water shortages have become increasingly frequent as extreme weather events intensify.

At a national level, the energy sector accounts for a significant share of water withdrawals and consumption. In the United States, for instance, thermal power plants requiring water for cooling accounted for more than 40% of total water withdrawals in 2015. In China, the power sector accounts for over 10% of total water withdrawals, second only to agriculture (EIA, 2020; IRENA and China Water Risk, 2016).

The competition for limited freshwater resources intensifies as demand for water grows across end-use sectors and climate impacts further compound supply constraints.

A warming climate is already limiting the availability of ambient-temperature water for cooling in thermal and nuclear power plants, besides inducing variability in hydropower generation in many power systems (Bloomberg, 2023; Peter, 2019; Wang *et al.,* 2022).

There is growing recognition of the need to effectively integrate water perspectives into energy sector planning to address trade-offs and mitigate physical climate risks to the water sector that could jeopardise energy security. One mitigation solution is to reduce the water dependency of energy production. Many countries have adopted power sector regulations facilitating a transition from open-loop systems to closed-loop or even air-cooling technologies. Closed-loop systems reduce the water dependency, and in turn the exposure to physical climate risks related to water shortage. Further, the transition to certain renewable energy technologies, including solar photovoltaics (PV) and wind, which require significantly less water for generation than thermal technologies, would reduce both the water and carbon intensity of power generation (IRENA, 2015).

For instance, IRENA analysis of China's and India's Nationally Determined Contributions finds that scaling up renewable power, especially solar PV and wind, along with improved cooling technologies could reduce the water withdrawal intensity of electricity generation by 42% and 84% by 2030, respectively, compared with current levels. In the Gulf Cooperation Council (GCC) region, achieving renewable energy deployment targets and plans by 2030 can reduce water withdrawal for power production and associated fuel extraction by 11.5 trillion litres, a 17% decrease (IRENA, 2019; IRENA and China Water Risk, 2016; IRENA and WRI, 2018).

Given the focus on green hydrogen as a solution to facilitate the energy transition in hard-to-abate sectors and the ambition of national and regional targets and programmes, the water implications of hydrogen production must be assessed.[1] Specifically, correlating the location of announced projects with existing water stress[2] indicators could highlight potential competition during the operational phase and inform policy making to manage it.

Location-specific considerations

Grey and brown hydrogen can cost as little as USD 1-2/kilogramme (kg). However, coupling grey hydrogen plants with carbon capture and storage (CCS) for blue hydrogen production raises the capital expenditure (CAPEX) by up to 50%, resulting in blue hydrogen costs of USD 1.5-3.0/kg. By contrast, green hydrogen can cost USD 4-6/kg and is getting close to competitive only in regions where all favourable conditions are in place. For example, in Patagonia, wind energy could have a capacity factor of almost 50%, with the electricity costing USD 25-30/megawatt hour (MWh). This would be sufficient to achieve a cost of about USD 2.5/kg for the green hydrogen produced (IRENA, 2020).

1 *While the water implications of hydrogen conversion, transport, re-conversion and usage are worthy of further study, they are beyond the scope of this report.*

2 *According to the World Resources Institute, water stress is defined as the ratio of the total water withdrawals and available renewable freshwater supply, and it should be calculated at a watershed level. Water stress deteriorates freshwater resources' quantity (e.g. aquifer overexploitation and dry rivers) and quality (e.g. eutrophication, organic matter pollution and saline intrusion), poses significant risks to human and environmental well-being, and is a proxy measure for local water competition between sectors.*

The cost of green hydrogen (often referred to as the levelised cost of hydrogen, in USD/kg) depends mainly on four factors:

- The CAPEX component, which relies on the cost of land and electrolysers, and all initial investments;
- The weighted average cost of capital;
- The cost of the electricity to fuel hydrogen production; and
- The capacity factor – the longer an electrolyser is in use, the more widely the CAPEX component is distributed.

To reduce the cost of the electricity to fuel hydrogen production and maximise capacity factors, many green hydrogen investors have targeted locations with the best solar PV (the energy source for most planned green hydrogen projects) and wind resources. However, the sunniest locations also tend to be the driest. A significant share of the planned electrolyser capacity will be in water-stressed regions, in countries such as Australia, Chile, Mauritania, Morocco, Oman, Saudi Arabia and Spain (Chapter 3).

In the absence of adequate freshwater resources, planned green hydrogen projects may have to rely on desalination for water. The process of desalinising seawater would add USD 0.02-0.05 to the cost of a kilogramme of hydrogen (Caldera and Breyer, 2017; Delpisheh *et al.,* 2021).

Importantly, green hydrogen could then provide an opportunity to tackle instead of aggravate the water stress challenge. Water supply systems designed specifically for hydrogen production could be modified (extended) so as to also meet other users' water needs and provide cross-sector benefits, for example, clean drinking water and sanitation, with minimal additional costs for hydrogen production. The extended systems could help reduce water-related expenses if they achieve economies of scale (IRENA, 2022).

However, there is a significant lack of comprehensive and reliable data concerning the water required for clean hydrogen production. The information available is both insufficient and of inadequate quality, given the relatively small number of studies investigating this topic. This is partly because research in clean hydrogen production and its water use is still in its early stages. Furthermore, initial studies primarily focused on small-scale hydrogen production, in a laboratory, which did not consider water use in crucial processes like cooling, which is essential for commercial-scale production.

The water stress question is thus an important one, but has no answers yet. Indeed, lack of information surrounding water stress forecasts has had present-day consequences. For example, in 2021, Kallis Energy Investments announced the 6 gigawatt (GW) Moolawatana plant, which was meant to produce hydrogen for export to the Republic of Korea and Japan by utilising the solar and wind resources of the northern desert area of the state of South Australia. Plans were shelved after a feasibility study identified unacceptable environmental and permitting risks related to water supply and desalination (Peacock, 2022).

Announcements of new hydrogen plants often precede detailed water supply analyses, which are often conducted during the feasibility study phase. Developers must identify major issues as early in a project as possible, so that if necessary, they can scrap plans and focus instead on more promising projects.

About this study

This study reviews the water quantity requirements of hydrogen production and assesses the water risks facing major hydrogen production regions. Although water quality is also an important aspect, the study focuses on water quantity during hydrogen production as the first step towards identifying and addressing the water implications of and risks facing the hydrogen value chain.

Chapter 2 reviews the water requirements of all types of mainstream hydrogen production technologies, which include electrolysis *(e.g.* alkaline, proton exchange membrane [PEM]), SMR, ATR and coal gasification. For each technology, the water footprint is assessed for each water-related process, including water pre-treatment, hydrogen production, cooling and hydrogen purification, providing a breakdown of the water withdrawal and consumption requirements for each of these processes.

Chapter 3 estimates the current and future water demand of global hydrogen production, by region. It also assesses how much of that water demand will be met in water-stressed areas.

Chapter 4 presents deep-dive analyses of three regions – Europe, the GCC countries and northern China – where the hydrogen production potential is high and water, scarce.

Chapter 5 summarises key findings and provides recommendations on hydrogen production planning and development for policy makers.

Chapter 2: A review of water quantity requirements in commercial-scale hydrogen production

This chapter provides a detailed review of the water withdrawal and consumption requirements for hydrogen production technologies. To ensure effective capture of these requirements, hydrogen producers and water service providers from the industry were interviewed. This process was complemented by a literature review. For each technology, water withdrawal and consumption intensities for production at scale are provided in a table and analysed. Water-dependent processes in green, grey and brown hydrogen production are illustrated in schematics and explained.

All hydrogen production technologies require water. It is used not only during production (electrolysis, fossil fuel reforming, gasification) but also for cooling. In some cases, water at low temperatures (*e.g.* 7°C) is used for hydrogen purification. Further, water is required in CCUS systems for absorption/adsorption, separation and also cooling.

However, as mentioned earlier, data on the water requirements of clean hydrogen production are insufficient as well as of inadequate quality. This is because studies examining hydrogen production and its water use are relatively limited in number, considering the nascent stage of research in this field. Further, initial studies in this area focused primarily on small-scale hydrogen production, in a laboratory. The data reported in these studies do not consider the water needed in processes such as cooling, which is critical for commercial-scale production. Existing studies may thus be underestimating the projected water demand if global hydrogen production is scaled up to align with the

announced ambitions and climate scenarios. This chapter aims to enhance understanding of the water implications of scaling up commercial hydrogen production, and of the water consumption and withdrawal intensities of various production processes.

To ensure effective capture of all water requirements for commercial-scale hydrogen production, hydrogen producers and water service providers from the industry were interviewed. This activity was complemented by a review of existing literature on the water required for cooling. A significant portion of the source data points are based on industry models rather than from metering, which is not yet a common practice among hydrogen producers.

This review has not included solid oxide electrolyser cells (SOEC) and anion exchange membrane (AEM) electrolysis since these technologies are still experimental, with no commercial-scale project data available. For coal gasification, the coal-water slurry gasification technology is considered since it accounts for almost all coal-based hydrogen production. For the sake of simplicity, coal-water slurry gasification is most often referred to as coal gasification.

Water use in hydrogen production

Figure 2.1 illustrates – for typical green, grey, blue and brown hydrogen technologies – where and how much water is withdrawn and discharged throughout the production process. The actual quantities of water withdrawn and consumed are site specific and could vary based on factors including, for example, the source water type and its quality, specific hydrogen production technology, the adoption and type of carbon capture, and cooling technology. The water requirements presented in Figure 2.2 are estimated based on the commonly used production assumptions recommended by the industry and mentioned in the figure's note.

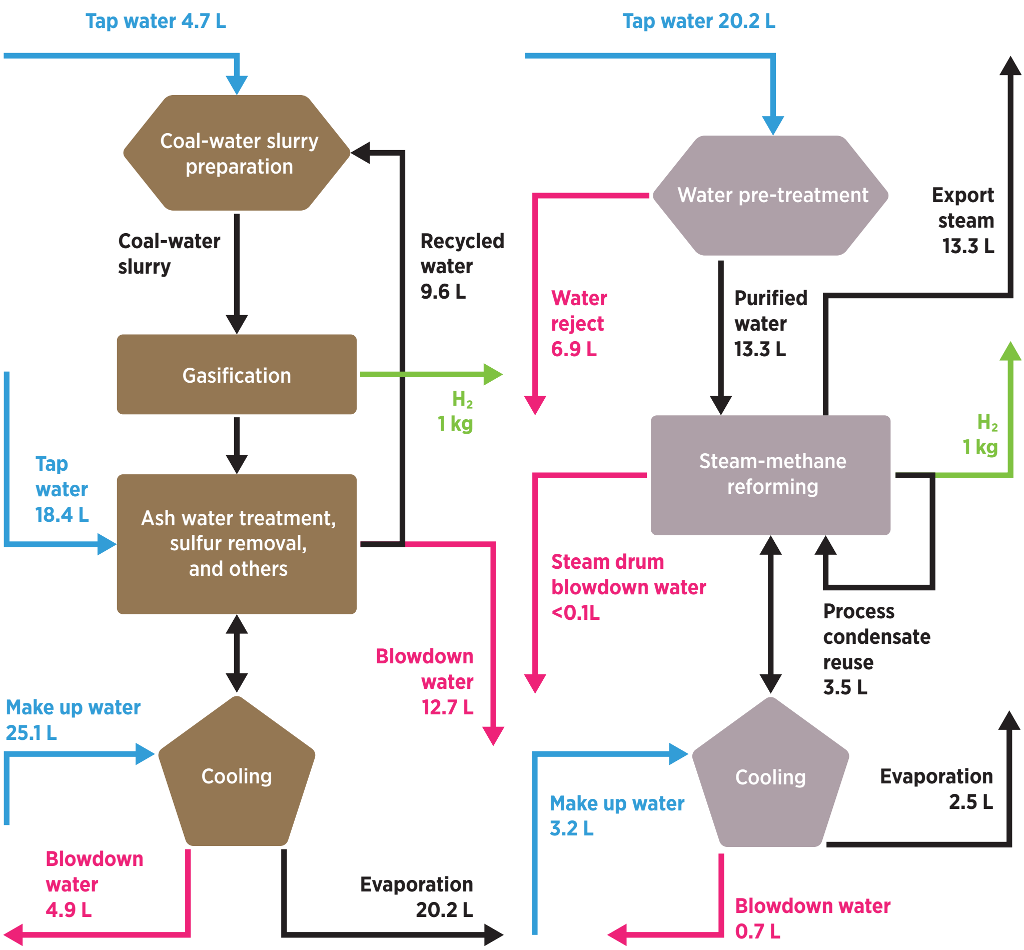
FIGURE 2.1 Schematics of process-specific water withdrawal and consumption in litres for typical hydrogen technologies to generate 1 kilogramme of hydrogen

Brown hydrogen

Volume requirements for alternative water sources
River: 26.1 L
Groundwater: 26.1 L
Seawater: 43.5 L

Grey hydrogen

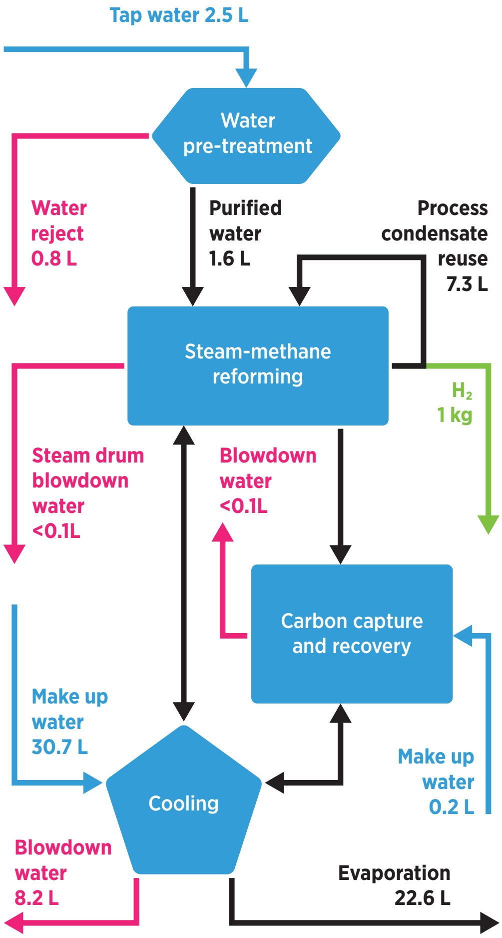
Volume requirements for alternative water sources
River: 22.9 L
Groundwater: 22.9 L
Seawater: 38.0 L



Note: The blue and pink arrows represent water withdrawal and discharge, respectively. Water volumes are estimates for the four hydrogen production approaches, represented by examples of their most common technologies today (*e.g.* alkaline electrolysis as green, SMR as grey, SMR+CCUS as blue, and coal-water slurry gasification as brown). The data on the green and brown examples are based on engineering design models obtained from the industry. For the grey and blue examples, the data and processes are obtained from Cases 1 and 2 in NETL 2022, which have the most efficient designs among all the systems reviewed in this report. "Export steam" is the excess steam generated as a byproduct during the SMR process, and is utilised by other applications in a refinery for enhancing the overall energy efficiency.

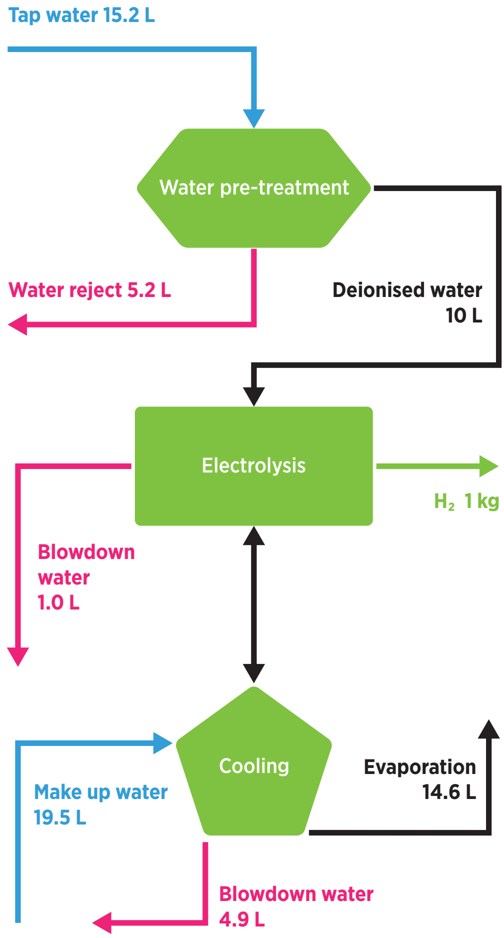
Blue hydrogen

Volume requirements for alternative water sources
River: 2.8 L
Groundwater: 2.8 L
Seawater: 4.7 L



Green hydrogen

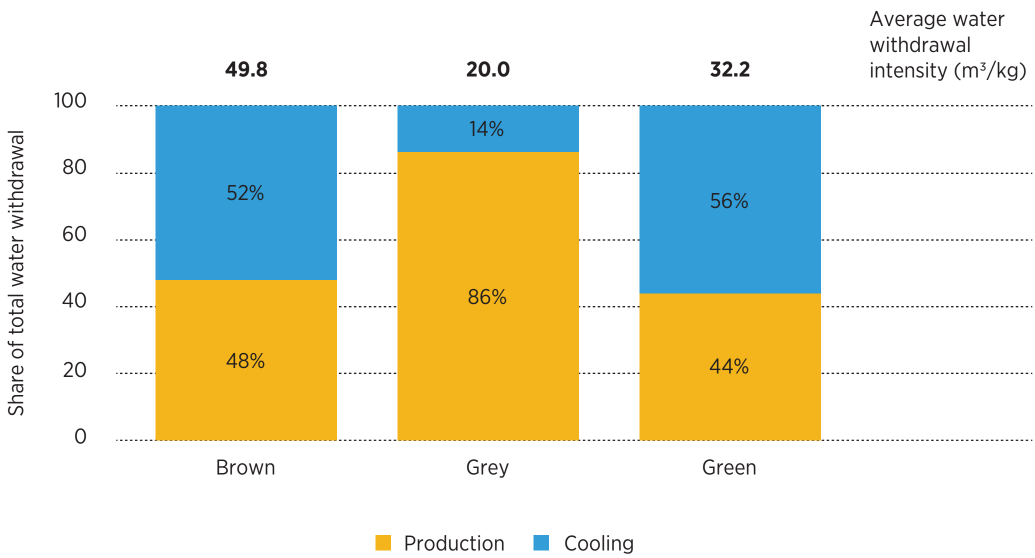
Volume requirements for alternative water sources
River: 17.2 L
Groundwater: 17.2 L
Seawater: 28.6 L



Water use is estimated based on the following assumptions: (1) tap water is used as the source water, with a pre-treatment permeate rate of 66% for green, grey and blue production; (2) the energy efficiency for green, grey and blue production is 70%, 76% and 71%, respectively; and (3) evaporative cooling is assumed for all the cooling processes, with and a cycle of concentration of 6 for green and brown production. Estimates for specific plants will vary depending on location, climate, specific technology adopted, plants' age, local regulations and management. CCUS = carbon capture, utilisation and storage; H_2 = hydrogen; kg = kilogramme; L = litre; SMR = steam methane reforming.

As shown in Figure 2.2, cooling make up water represents about 56% and 52%, respectively, of the total water withdrawal of green and brown hydrogen facilities. It thus represents the largest source of water demand in hydrogen production. On the other hand, cooling represents only about 14% of the total withdrawal of grey hydrogen facilities. For blue hydrogen, given the insufficient literature and the lack of real-life project cases, specific water requirements for production and cooling require more evidence before a general ratio can be determined without dispute.

FIGURE 2.2 Share of the water withdrawal needs of production and cooling in the overall water demand of hydrogen production examples



Note: These shares are estimates for the Three hydrogen production approaches, represented by examples of their most common technologies today *(e.g.* alkaline electrolysis as green, steam methane reforming as grey and coal-water slurry gasification as brown). The data on the green and brown examples are based on engineering design models obtained from the industry. For the grey hydrogen, the data and processes are obtained from Case 1 in Lewis *et al.* (2022), which has the most efficient designs among all the studies reviewed by the authors. These data indicate the general magnitude of the water shares for cooling and production. Water share data for specific plants will vary depending on location, climate, specific technology adopted, plants' age and management. kg = kilogramme; m^3 = cubic metre.

However, it can be concluded that blue hydrogen production will have a significantly larger share of cooling water demand than grey, since CCUS systems require sufficient cooling during carbon capture and compression (Rosa *et al.*, 2021), besides the cooling needed for SMR. Further, a past study has shown that cooling can account for as much as 98% of the total water withdrawal of a highly efficient SMR-CCUS system, since large volumes of the water used in production will be recycled (Lewis *et al.*, 2022).

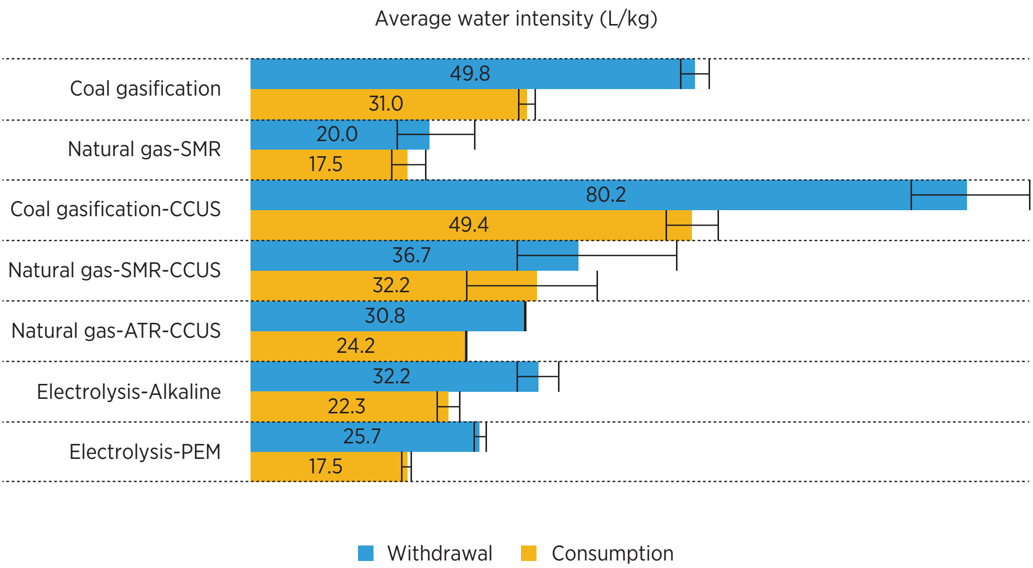
The cycle of concentration of evaporative cooling systems typically ranges from 4 to 6 in hydrogen production. This means that about 70%-85% of the water withdrawn for cooling evaporates (or is consumed). Increasing the cycle of concentration could somewhat reduce the water withdrawal for cooling, but it would not affect consumption. In general, the more energy efficient a process is, the less heat that is released, and the less cooling water is consumed. Further, although air cooling is technically feasible and commonly observed in the power generation sector, information from industry interviews indicates that no existing hydrogen facility has yet utilised this technology, given its higher capital and operational costs.

For green and grey hydrogen production, water needs to be treated (illustrated as water pre-treatment in Figure 2.1) for high purity before it can be used for electrolysis and SMR. For green hydrogen production, high purity or high water quality means low conductivity and minimal organic carbon. Improving water's purity can reduce its electrical resistance, in turn increasing energy efficiency. Water impurities can adversely impact many elements of electrolysers: for example, circulation of low-quality water has been observed to cause higher levels of degradation, affecting plant's lifetime (IRENA, 2020).

The lower the quality of the water withdrawn from a source, the more it needs to be withdrawn and treated to produce the same quantity of hydrogen. The source water's quality, especially salt content, could cause significant variations in the permeate rate for water pre-treatment, which ranges from 66% for typical tap water, to 58% for river or groundwater, to 35% for seawater, based on data shared by the industry. It is worth noting that water quality can vary even within the same category of sources, across geography and time of year, and before and after extreme weather events such as droughts and floods.

Hydrogen production already includes water recycling and reuse practices, which help to reduce water withdrawal. For example, as illustrated in Figure 2.1, process condensate water is generally reused for methane reforming, and the water discharge used for ash treatment and sulphur removal is recycled and reused for preparing coal-water slurry. While recycling and reuse reduce water withdrawal, they do not reduce water consumption. In other words, unless we switch to technologies that rely less on water, water consumption will only increase as production increases.

FIGURE 2.3 A comparison of average water withdrawal and consumption intensities by hydrogen production technology



Note: Tap water (or sources with similar water quality) is (are) used or assumed to be the water source(s) behind these data points. For blue hydrogen, the cooling requirements for CCUS systems are included. For PEM and ATR, available data points are limited since these technologies are relatively new – thus the much smaller ranges of values. ATR = autothermal reforming; CCUS = carbon capture, utilisation and storage; kg = kilogramme of hydrogen; L = litre; PEM = proton exchange membrane; SMR = steam methane reforming.

Water withdrawal and consumption intensities

Figure 2.3 compares average water withdrawal and consumption intensities by hydrogen production technology. The intensities are summarised with additional statistics in Table 2.1. Table A.1 (in the Appendix) presents the source data from our interviews and literature review.

As illustrated in Figure 2.3, on average, water consumption intensity is the lowest for PEM – about 17.5 L/kg – while SMR requires withdrawing the least quantity of water – about 20 litres – per kilogramme of hydrogen produced. Coal-based hydrogen production has the highest water withdrawal and consumption. Natural gas SMR has the least water withdrawal intensity among all the alternatives. Coal gasification without CCUS requires withdrawing about 50 Litres and consuming 31 Litres of water to generate 1kg of hydrogen. This is higher than any of the non-coal-based technologies' withdrawal and consumption intensities. To put this into perspective, a 1 GW equivalent coal gasification

TABLE 2.1 A summary of water withdrawal and consumption intensities by hydrogen production technology

Type		Water withdrawal intensity (L/kg)			Water consumption intensity (L/kg)		
		Average	Max	Min	Average	Max	Min
Brown	Coal gasification	49.78	51.41	48.14	31.00	32.02	29.98
Grey	Natural gas-SMR	20.01	25.16	16.40	17.54	19.80	15.80
Blue	Coal gasification-CCUS	80.23	87.21	73.85	49.44	52.47	46.53
	Natural gas-SMR-CCUS	36.69	47.79	29.81	32.18	38.96	24.15
	Natural gas-ATR-CCUS	30.76	30.76	30.76	24.22	24.22	24.22
Green	Electrolysis-Alkaline	32.24	34.61	29.88	22.28	23.59	20.96
	Electrolysis-PEM	25.70	26.46	24.94	17.52	18.04	17.00

Note: ATR = autothermal reforming; CCUS = carbon capture, utilisation and storage; L/kg = litre per kilogramme; PEM = proton exchange membrane; SMR = steam methane reforming.

hydrogen plant would withdraw about 36 million L of water every day – sufficient to meet the basic domestic water needs, including drinking, dishwashing and showering, of roughly 400 000 people.[3]

Integrating CCUS with fossil-fuel-based hydrogen production also means higher water since CCUS systems often require substantial cooling, make production less efficient and need water for the sorbent intensity (Rosa *et al.*, 2021). With CCUS integrated, coal gasification requires withdrawing as much as 80 L of water to produce 1 kilogram of hydrogen – 61% more than coal gasification without CCUS. This is about 2.5 times as much as the water withdrawal requirement of alkaline electrolysis and 2.2 times that of SMR-CCUS – two of the most common green and blue hydrogen production technologies on the market today.

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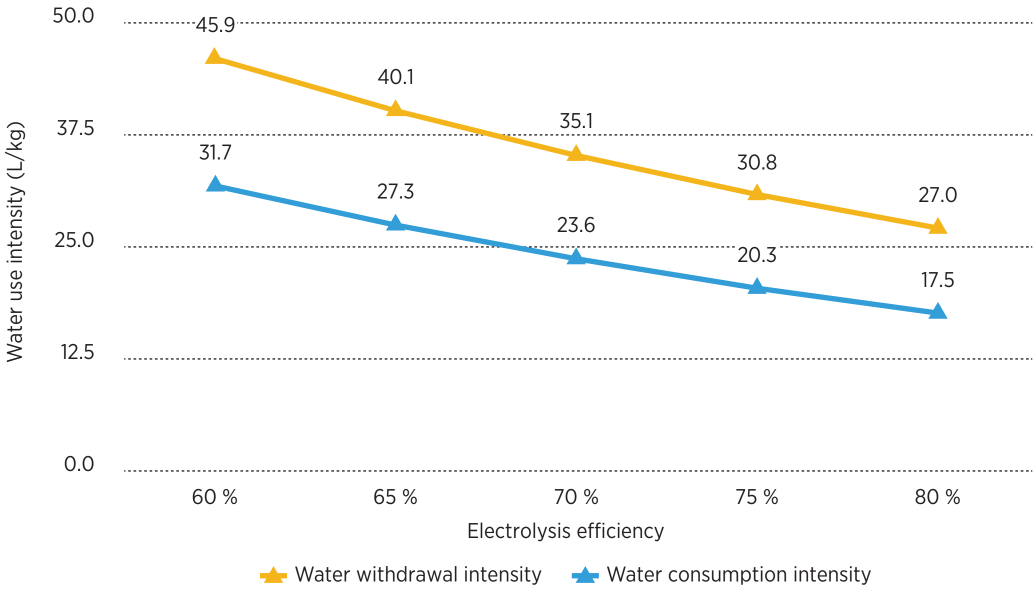
3 It should be noted that this value does not consider upstream water withdrawal and consumption – i.e. the water needs for producing the electricity or fossil fuels consumed in hydrogen facilities. This is explained by two factors, which have to be considered. Operational water consumption/withdrawal for variable renewable energy plants is close to 0 and would not change the estimation notably (IRENA, 2015). At the same time, natural gas and coal can be produced at a distance from grey and brown hydrogen facilities, while this report focuses more on local water impacts.

FIGURE 2.4 Relations between hydrogen conversion efficiency and water withdrawal and consumption intensities of a typical electrolysis project

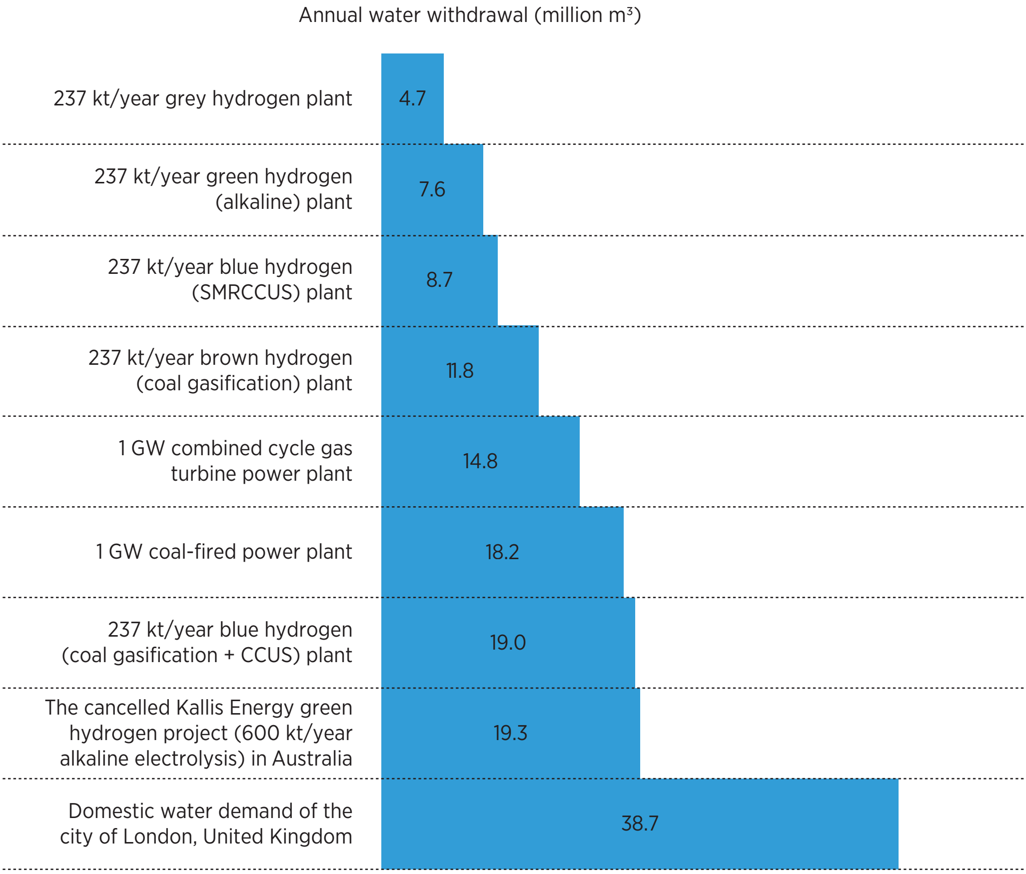


Note: The curves are estimated based on water balance modelling for a typical green hydrogen project with all system variables kept constant except efficiency. The system assumptions are the same as mentioned in the note of Figure 2.1. kg = kilogramme; L = litre.

ATR is the CCUS-integrated technology with the least water withdrawal requirement, even though its water consumption intensity is still higher than any of the green hydrogen technologies.

A hydrogen production technology is more energy efficient the less water intensive it is. As shown in Table 2.1, PEM on average requires 20.3% less water withdrawal and 21.4% less water consumption than alkaline electrolysis. According to the water balance model used for green hydrogen production, this is primarily because PEM converts electricity to hydrogen more efficiently than alkaline electrolysis. This means less energy is wasted as heat, which reduces the water requirement for cooling. Figure 2.4 shows how water use intensities decrease alongside an increase in electrolysers' energy efficiency. For every 1 percentage point increase in electrolysis efficiency, the intensity of water withdrawal and consumption for green hydrogen production falls by about 2%.

FIGURE 2.5 Annual water withdrawal of typical hydrogen production projects, thermal power plants and municipalities



Based on: Macknick *et al.,* 2011; Greater London Authority.

Note: The water estimates are calculated using the average factors from Table 2.1, and for power plants, recirculating cooling was assumed. CCUS = carbon capture, utilisation and storage; GW = gigawatt; kt = kilotonne; SMR = steam methane reforming.

Water withdrawal for hydrogen production can be significant at a local scale. Proposed commercial projects can produce a few kilotonnes (kt) up to 2 000 kt or so of hydrogen annually. As illustrated in Figure 2.5, a 237 kt hydrogen production plant requires withdrawing anywhere between 4.7 and 19.0 million m^3 of water annually, which is about 26%-104% of the annual requirement of a typical 1 GW coal-fired power plant[4] with recirculating cooling. It is worth noting that thermal power generation is by far the largest water user among key industries (US EPA, 2017).

4 *A 1 GW coal-fired power plant operating at 90% capacity can generate about 7.9 terawatt hours of electricity per year. This is the same amount of energy that can be generated from 236.5 kt of hydrogen.*

Chapter 3: Water footprint and risks of global hydrogen production

This chapter provides a comprehensive analysis of water use in the hydrogen sector, considering both quantitative and qualitative aspects. IRENA's 1.5°C Scenario (see Box 3.1) up to 2050 yields insights into the scale and trajectory of water consumption associated with hydrogen production. Quantifying current and projected future freshwater consumption and withdrawal for hydrogen production enables a better assessment of the magnitude of water use and its potential impact on freshwater resources.

Further, this chapter aims to highlight the specific risks associated with water-intensive practices in hydrogen production. It highlights, for example, issues related to water scarcity, water stress and potential conflicts over water resources. The chapter also highlights the relationship between global water stress and the geographic distribution of the hydrogen project pipeline. This analysis helps identify areas where future high water stress and hydrogen production coincide. Such insights can contribute to the sustainable and responsible development of the hydrogen sector by informing decision-making processes such as project planning, technology selection and water resource management strategies.

BOX 3.1 Hydrogen in the World Energy Transitions Outlook

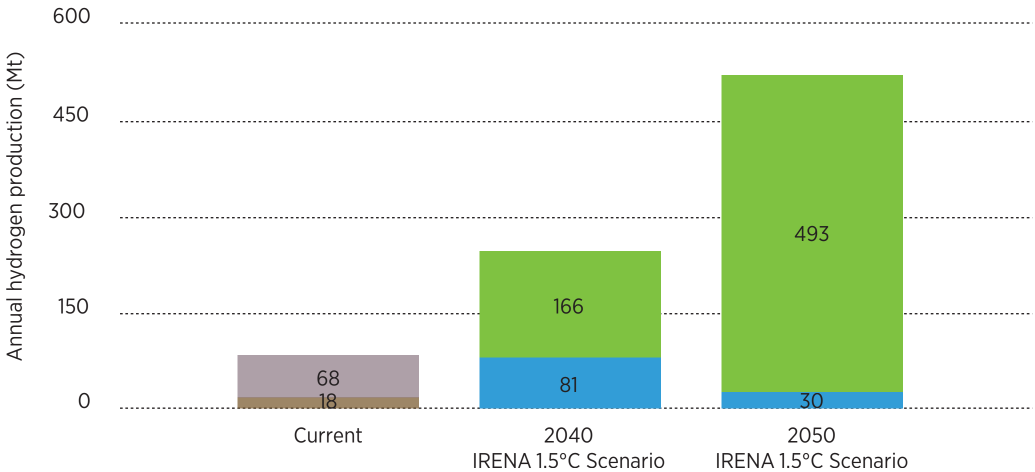
The latest edition of IRENA's flagship report, the *World Energy Transitions Outlook 2023,* presents a vision for transforming the global energy landscape in line with the objectives of the Paris Agreement. The report outlines a pathway to limit the rise in global temperature to 1.5°C and achieve net-zero CO_2 emissions by mid-century. The 1.5°C Scenario described in the report focuses on an energy transition approach that aligns with the goal of limiting temperature increase to 1.5°C compared with pre-industrial levels. This Scenario prioritises the adoption of readily available technology solutions that can be scaled up to meet the 1.5°C target.

Under the 1.5°C Scenario, the production of clean hydrogen for direct use and as a feedstock for derivative fuels is projected to increase significantly from negligible levels in 2020 to reach 523 by 2050. Hydrogen and its related compounds, such as ammonia, methanol and kerosene, would account for 14% of the final energy consumption by 2050. Early investments in the green hydrogen supply chain are crucial for the widespread adoption of hydrogen applications in various sectors and for reaching decarbonisation goals. Key steps include developing electrolysis technologies, fuel cells, transport pipelines and storage facilities. The importance of green hydrogen becomes especially pronounced in hard-to-decarbonise sectors like air, marine and heavy-duty transportation, as well as certain industrial processes. IRENA anticipates that by 2030, 125 Mt of clean hydrogen will be required, and 523 Mt by 2050 (of which 94% would be green under the 1.5°C Scenario).

The water footprint of global hydrogen production

It is estimated that 2021 hydrogen production reached 86 Mt globally. Of that, 68 Mt was grey hydrogen and 18 Mt was brown hydrogen. As shown in Figure 3.1, under IRENA's 1.5°C Scenario, by 2040, 247 Mt of hydrogen would have to be produced globally every year, 166 Mt being green hydrogen and 81 Mt, blue. By 2050, annual global hydrogen production would reach 523 Mt, green hydrogen accounting for almost 94% (IRENA, 2023a).

FIGURE 3.1 Current and projected future global hydrogen production under the 1.5°C Scenario

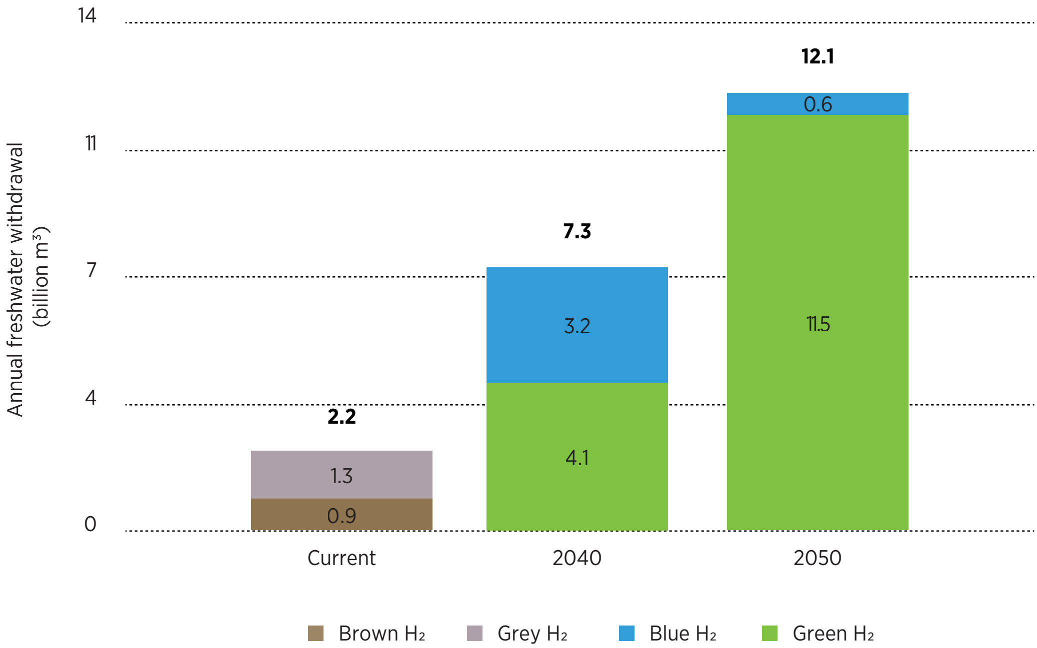


Source: IRENA, 2023a.

Currently, global hydrogen production withdraws about 2.2 billion m^3 of freshwater annually (Figure 3.2). This volume is relatively small in the broad context of the entire energy sector and accounts for about 0.6% of the sector's global water withdrawal, which is estimated to have been 369 billion m^3 in 2021 (IEA, n.d.).

However, expanding hydrogen production means growing water demand. As illustrated in Figure 3.3, the hydrogen production sector could withdraw over three times as much freshwater by 2040, 7.3 billion m^3, and withdrawal could increase almost six-fold to 12.1 billion m^3 by 2050. These estimates are, however, conservative since tap water (or water sources with similar water quality) is (are) assumed to be the water source(s); they could be much higher if lower-quality water is used. By 2040, about 61% (or 4.5 billion m^3) of the total water withdrawal will be required for cooling, 26% for green hydrogen and 36% for blue hydrogen, where cooling is needed for hydrogen production and CCUS systems. By 2050, the water withdrawal share required for cooling could decrease to 45%, thanks to progress in green hydrogen production and electrolysis efficiency.

FIGURE 3.2 Current and projected freshwater withdrawal for global hydrogen production, by hydrogen production pathway



Note: Tap water (or water sources with similar water quality) is (are) assumed to be the water source(s). Projected desalination-based and seawater-cooled hydrogen production (*e.g.* in the GCC countries) is excluded. Blue H_2 includes SMR-CCUS, ATR-CCUS and coal-CCUS, with the share of ATR-CCUS assumed to gradually increase to 75% by 2050. Cooling in blue H_2 production includes the cooling demand due to CCUS systems. Green H_2 includes both alkaline and PEM electrolysis with the share of PEM electrolysis assumed to gradually increase to 75% by 2050. Moderate gradual increases in electrolysis efficiency (7.5 percentage points for alkaline electrolysis and 4.5 for PEM- electrolysis over the coming three decades) are assumed. For calculation purposes, the cooling and production shares of blue H_2 in Case 2 from Lewis *et al.* (2022) are applied. ATR = autothermal reforming; CCUS = carbon capture, utilisation and storage; H_2 = hydrogen; PEM = proton exchange membrane; SMR = steam methane reforming.

It is likely that the water withdrawal and consumption requirements of hydrogen production will continue increasing till 2040, falling thereafter (below current levels) as of 2050. As shown in Figure 3.3a, between now and 2040, the freshwater withdrawal intensity will grow from 26.4 L/kg to 31.8 L/kg, and consumption intensity will grow from 20.4 L/kg to 22.8 L/kg. This is because SMR – the hydrogen production technology with the lowest water withdrawal and consumption intensities – accounts for about 80% of the global hydrogen production today, and blue hydrogen is projected to account for 33% of the total market by 2040. The remaining portion would be green hydrogen. Green as well as blue hydrogen production would still have higher overall withdrawal and consumption intensities than SMR by 2040, considering the increasing shares of ATR-CCUS (50%) and PEM (50%) in the mix.

However, by 2050, overall water withdrawal intensity would likely decrease to 24.9 L/

kg – even below the current level (26.4 L/kg) – and consumption would likely decrease to 17.1 L/kg (from 20.4 L/kg currently). This is because green hydrogen is projected to dominate the global hydrogen market by 2050, and PEM (the most water-efficient clean hydrogen technology) is likely to represent the majority of green hydrogen production. Further, as explained in Figure 3.3, electrolysis efficiency is expected to continue increasing for both alkaline and PEM electrolysis. This reduces energy wasted as heat, in turn reducing the demand for cooling, and making green hydrogen even more water efficient.

Further, as shown in Figure 3.3b and Table 3.1, the share of water withdrawal used for cooling is about 29% today, although the transition from SMR (with a low cooling requirement) to green and blue hydrogen (with a high cooling requirement) is likely to drive it up to 62% by 2040. However, since green hydrogen is projected to capture a larger share of the production market from blue hydrogen (which has very high cooling requirements due to CCUS) by 2050, the cooling-specific share of total water withdrawal could decrease to 46% for the global hydrogen production market.

The consumptive portion of the overall water withdrawal would also decrease gradually, meaning less water consumption per unit of water withdrawn for producing hydrogen. The decrease between now and 2040 is primarily because SMR has a very high consumptive use ratio since most of its withdrawal is consumed in the reforming processes, whereas for green and blue hydrogen production, the withdrawal is used more for cooling, which has a lower consumptive ratio than SMR's production water withdrawal. The decrease between 2040 and 2050 can be mostly explained by the increase in overall fuel-to-hydrogen efficiency.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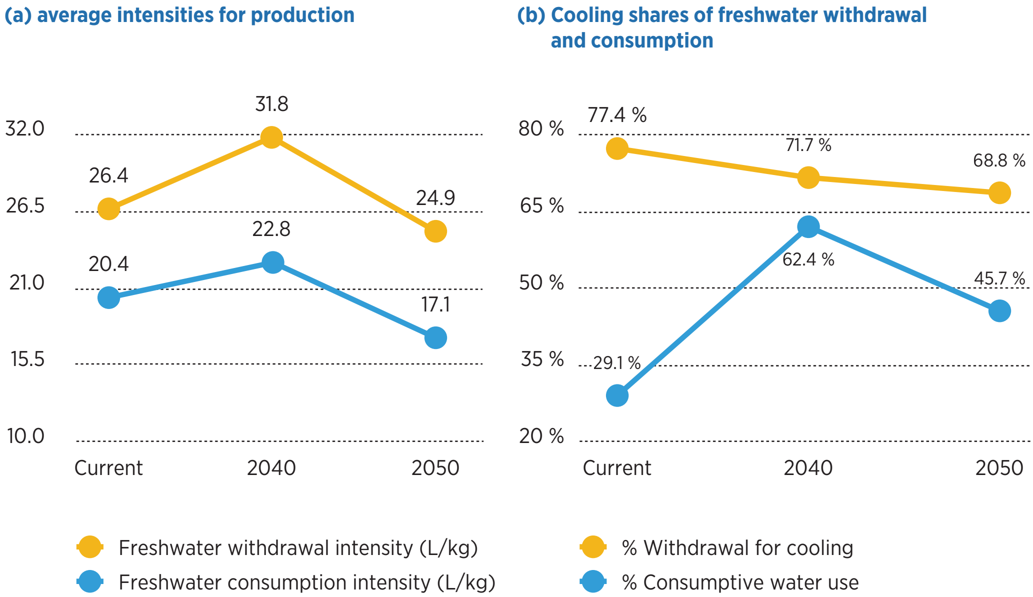
Even though hydrogen production represents only a fraction of the total water demand of all industries globally, as discussed in Chapter 2, it can create significant water demand locally (Figure 2.5.) It is thus important to understand and consider the local context when discussing the sector's water demands. While acknowledging that acute water risks such as drought can pose a significant threat to hydrogen production and potentially disrupt operations, the report focuses on analysing chronic water risks such as water stress, aiming to inform long-term planning, policy making and investment decisions.

FIGURE 3.3 Freshwater for hydrogen production and cooling, today to 2050



Note: Same assumptions of Figure 3.2

TABLE 3.1 Current and projected freshwater withdrawal and consumption for global hydrogen production (billion m^3), today to 2050

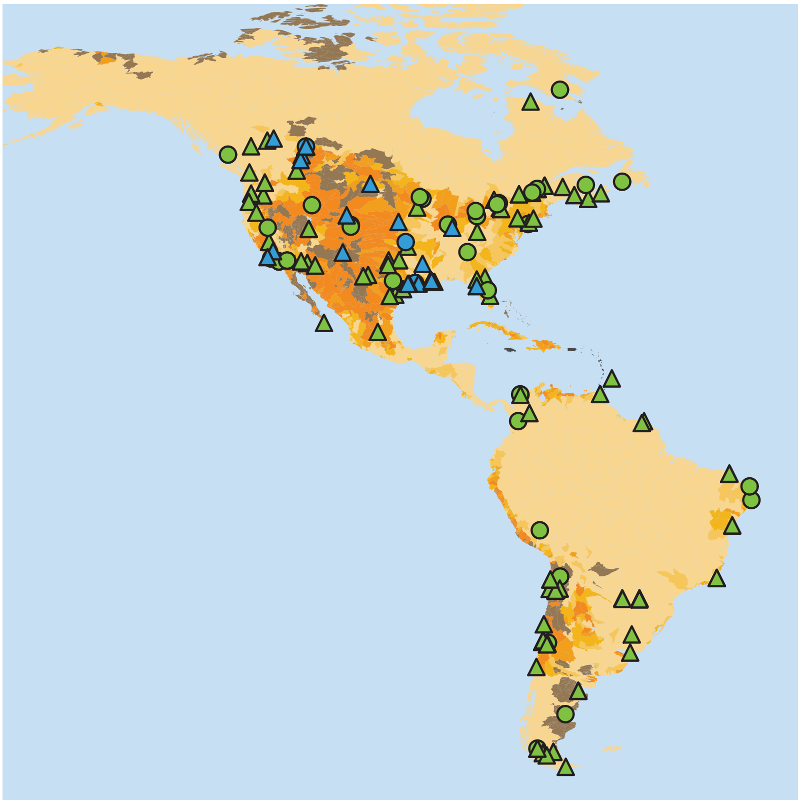
	Current	2040	2050
Total water withdrawal	2.23	7.27	12.09
For cooling	0.65	4.54	5.52
For production	1.58	2.73	6.57
Total water consumption	1.72	5.21	8.32
For cooling	0.49	3.56	4.35
For production	1.23	1.65	3.97

Note: The assumptions are the same as mentioned in the note of Figure 3.2.

FIGURE 3.4
Global water stress conditions and green and blue hydrogen project locations for 2040

Hydrogen production projects
- Blue - Operational
- Blue - Planned
- Green - Operational
- Green - Planned

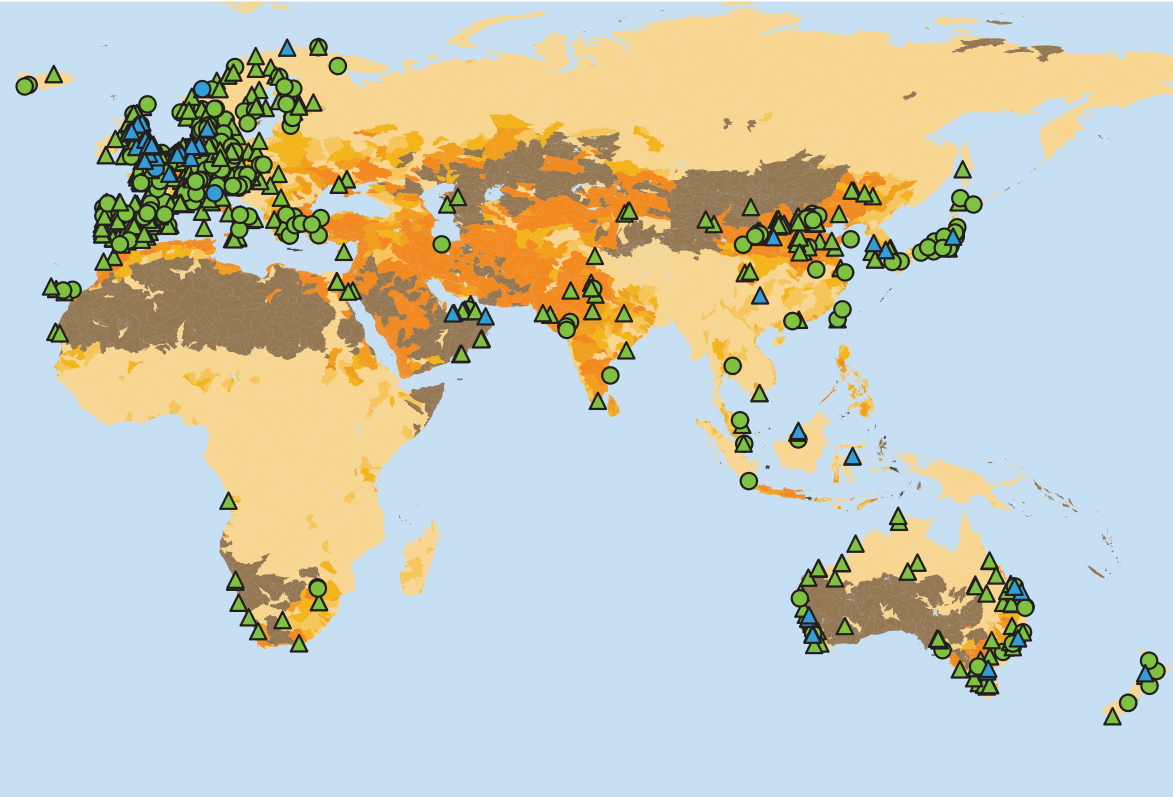
Water stress conditions in 2040
- Low (<10%)
- Low to medium (10-20%)
- Medium to high (20-40%)
- High (40-80%)
- Extremely high (>80%)
- Arid and low water use
- No data



Hydrogen water stress mapping

Data on global green and blue hydrogen production projects are collected, including their capacity and status, production technology, fuel type and location. The Aqueduct Water Risk Atlas 3.0, developed by the World Resources Institute, is used to assess current and future local water stress (explained in Box 3.2) conditions for all project locations. Figure 3.4 illustrates the spatial distribution of either operational or planned global green and blue hydrogen projects against the projected water stress conditions in 2040 as a visual example.

Globally, the total annual capacity of existing operational green and blue hydrogen plants is about 1.7 Mt; of this, roughly 12.3% is in highly water-stressed areas, as shown in Figure 3.5. In comparison, the current planned projects are exposed to much higher water stress. About 35.7% of the planned capacity (a global total of 56.3 Mt annually) is in areas experiencing high water stress. About 35% of the combined 58 Mt annual production capacity of the current operational and planned green and blue hydrogen projects is also in such areas. By 2040, the increased water demand across sectors and reduced water availability due to climate change could cause water stress in areas not experiencing it today. Consequently, 39% of the 58 Mt combined capacity could be operating in highly stressed areas in 2040 and be exposed to higher disruption risks and uncertainties regarding environmental regulations.



Source: Project data compiled by authors based on European Hydrogen Observatory (2023) and IEA (2022); 2040 projected water stress obtained data from WRI (2023).

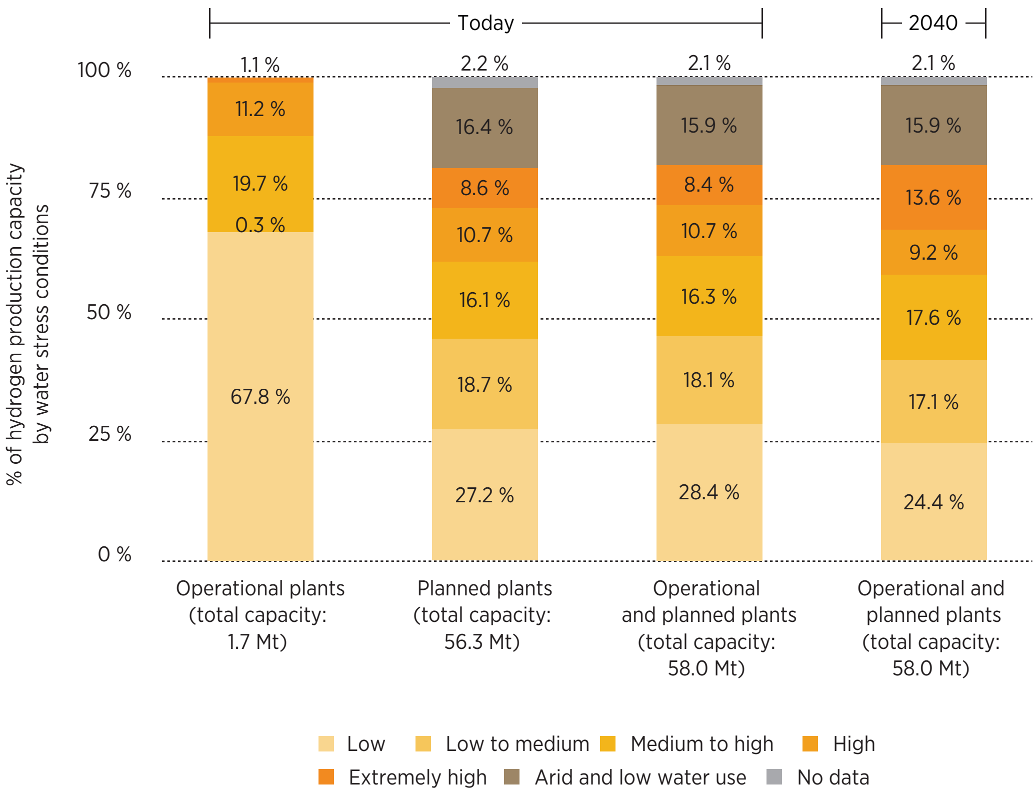
Note: The green and blue hydrogen production projects mapped include those operational as well as planned. These include projects that have been announced, projects awaiting a final investment decision and projects under construction. The 2040 water stress conditions are projected under the Representative Concentration Pathway (RCP8.5) and Shared Socio-economic Pathway (SSP2) scenarios.

Disclaimer: This map is provided for illustration purposes only. Boundaries and names shown on this map do not imply the expression of any opinion on the part of IRENA concerning the status of any region, country, territory, city or area or of its authorities, or concerning the delimitation of frontiers or boundaries.

BOX 3.2 What is water stress?

Water stress is defined as the ratio of total water withdrawals to available renewable surface and groundwater supplies. It is measured at a local watershed level. Water withdrawals encompass consumptive and non-consumptive uses of water for domestic and industrial purposes, for irrigation and for livestock. Available renewable water supplies include mainly local precipitation, and water discharged from upstream and local groundwater resources. Higher water stress values indicate more competition among users. A ratio over 40% indicates high water stress, which is unsustainable.

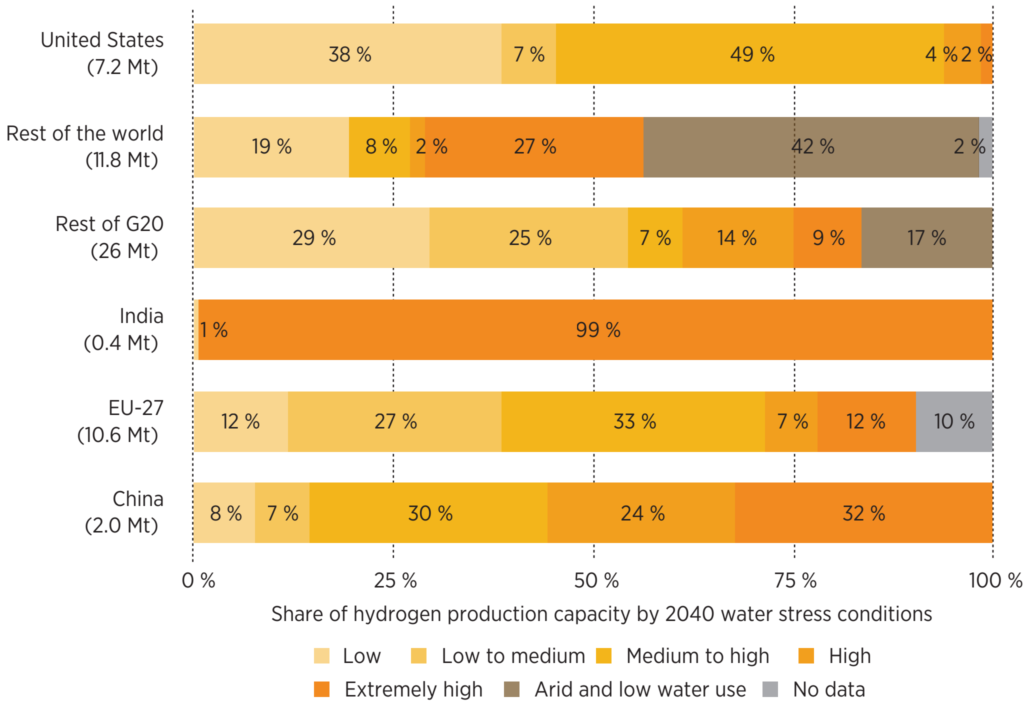
FIGURE 3.5 Distribution of global operational and planned green and blue hydrogen production capacities by water stress level, today and in 2040



Note: Areas under high or extremely high water stress or with arid conditions are commonly classified as "highly water-stressed areas". Mt = megatonne.

Water stress conditions have a non-uniform spatial distribution. Certain markets have more highly water-stressed areas than others due to climate-related and socio-economic reasons. As illustrated in Figure 3.6, by 2040, 99% of India's current operational and planned green and blue hydrogen capacity is likely to be in areas under extreme water stress. China and the EU-27 have 56% and 19%, respectively, of their operational and planned capacities in highly water-stressed areas.

FIGURE 3.6 Distribution of global operational and planned green and blue hydrogen production capacities by water stress level and region in 2040



Note: G20 = Group of Twenty; Mt = megatonne.

The green and blue hydrogen projects in the United States have minor exposure to water stress conditions. For the remaining G20 countries – and for 71% for the rest of the world – over 40% of operational and planned capacities are in high-water-stress areas.

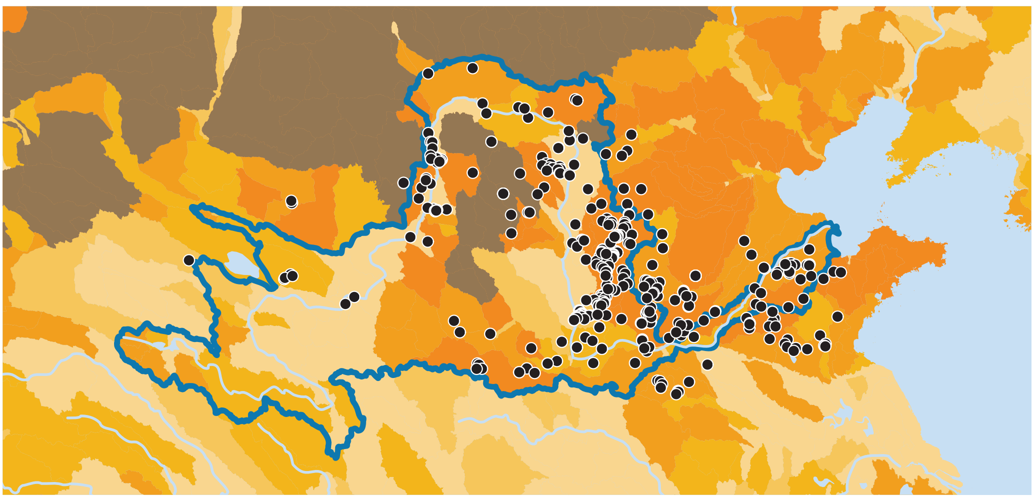
Chapter 4: Deep-dive analyses of northern China, the Gulf and Europe

In this chapter, we consider the water challenges of hydrogen production in three regions: northern China, the GCC countries and Europe.

Northern China

Clean hydrogen could go far in advancing China's energy transition. The country's hydrogen industry is expected to be worth CNY 1 trillion (USD 134 billion) by 2025 (Nikkei, 2022). About 63% of the hydrogen produced today is from carbon- and water-intensive coal chemical plants (IEA and ACCA21, 2022). Over 80% of China's coal chemical industry is concentrated in the water-stressed Yellow River Basin (MEE, 2022), home to the majority of the country's coal reserves.

FIGURE 4.1 Hydrogen-producing coal chemical plants and levels of water stress in the Yellow River Basin



Coal chemical plants

Yellow River Basin

Major rivers and lakes

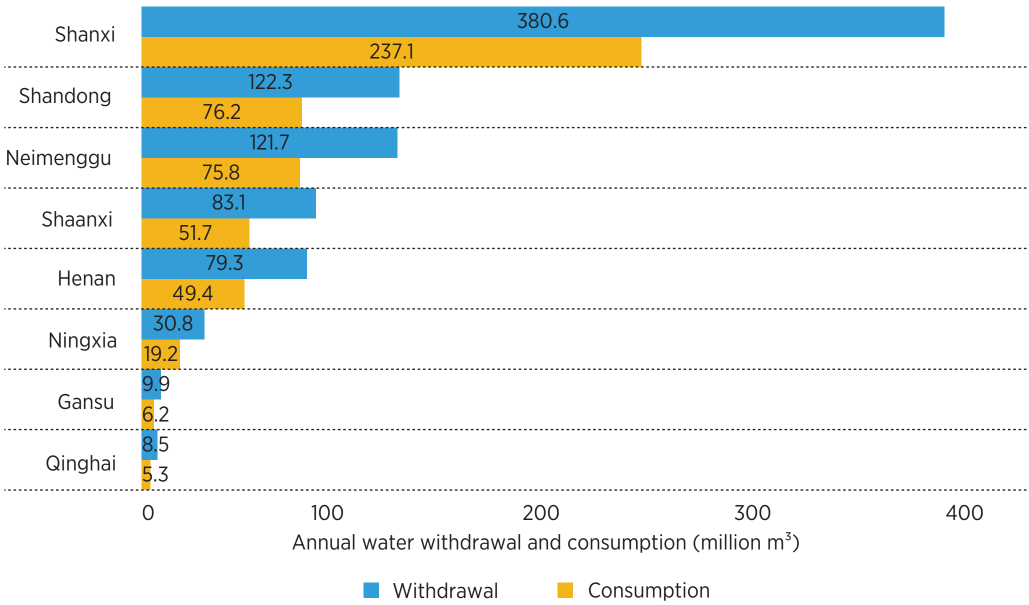
Water stress conditions in 2040

- Low (<10%)
- Low to medium (10-20%)
- Medium to high (20-40%)
- High (40-80%)
- Extremely high (>80%)
- Arid and low water use
- No data

Based on: WRI, 2023; Xia *et al.,* 2023

Disclaimer: This map is provided for illustration purposes only. Boundaries and names shown on this map do not imply the expression of any opinion on the part of IRENA concerning the status of any region, country, territory, city or area or of its authorities, or concerning the delimitation of frontiers or boundaries.

FIGURE 4.2 Annual water withdrawal and consumption due to coal-based hydrogen production in the Yellow River Basin, by province

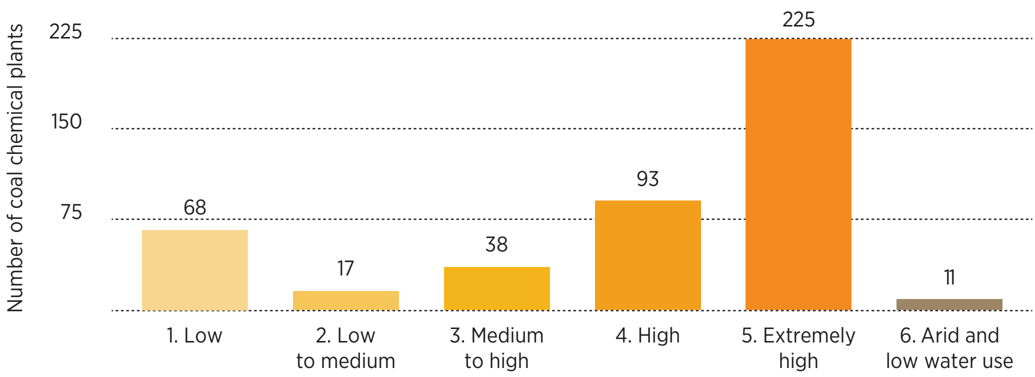


Note: m^3 = cubic metre.

The Yellow River, the largest river in northern China, flows eastward through nine provinces, holding significant economic, environmental, cultural and spiritual value. To safeguard this value, the Yellow River Protection Law, effective since 1 April 2023, mandates environmental protection and restoration, water resources management and pollution control.

The significant water challenges facing the Yellow River Basin are difficult to address. The region relies heavily on water-intensive, coal-based industries, such as mining, power generation and coal-to-chemicals, and, to a lesser extent, agriculture. As depicted in Figure 4.1, clusters of coal-based chemical plants produce coke oven gases, methanol and fertilisers. While most such plants are concentrated in the middle and lower reaches of the Basin, a few are in Qinghai and Gansu provinces, upstream areas where source watershed protection is prioritised over industrial development. The province of Shanxi accounts for more than 45% of all brown hydrogen produced in the Yellow River Basin, demanding 381 million m^3 of water in withdrawal and 237 million m^3 in consumption annually, as shown in Figure 4.2. That withdrawal accounted for 31% of Shanxi's total industrial water withdrawal in 2020, which stood at 1.24 billion m^3 (NBS, 2023).

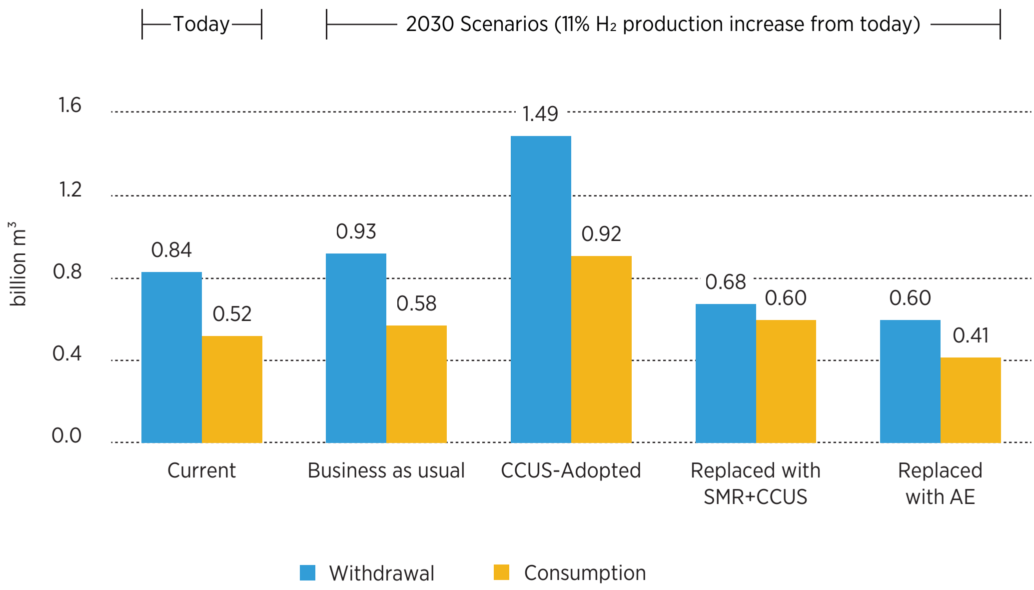
FIGURE 4.3 Distribution of hydrogen-producing coal chemical plants in the Yellow River Basin by current water stress level



Tensions and disputes among water users in the basin, especially those in mining and agriculture, have attracted significant media and public attention nationwide (Global Times, 2023). As Figure 4.3 highlights, 318 or over 70% of all coal chemical plants in the Yellow River Basin are located in areas with high or extremely high levels of water stress. This makes them particularly susceptible to fluctuations in water availability and changes in regulations regarding water use limits, pricing and rights.

The China Hydrogen Alliance estimates that fossil-based hydrogen production in the country will grow 11% by 2030 (IEA and ACCA21, 2022). Assuming that the geographic distribution of hydrogen production remains the same, coal-based hydrogen production in the Yellow River Basin would require 930 million m^3 in annual water withdrawal and 580 million m^3 in consumption. This amounts to an increase of 90 million m^3 in withdrawal and 6 million m^3 in consumption, compared with 2020 levels. These estimates constitute the "business as usual" case illustrated in Figure 4.4, which also forecasts the water use of three zero-emission hydrogen production scenarios in the Yellow River Basin by 2030. Utilising CCUS for all current production capacity would require an additional 560 million m^3 of water withdrawal each year (beyond the 90 million m^3 mentioned). This raises the total annual water withdrawal to almost 1.5 billion m,^{3} or 77% more than in 2020.

FIGURE 4.4 Annual water withdrawal and consumption requirements of coal-based hydrogen production in the Yellow River Basin under four scenarios



Note: AE = alkaline electrolysis; CCUS = carbon capture, utilisation and storage; H_2 = hydrogen; m^3 = cubic metre; SMR = steam methane reforming.

Hydrogen development in the Yellow River Basin can be supported without consuming more water. If coal-based hydrogen production were to be replaced with SMR+CCUS, alkaline electrolysis or a mixture of both, the Yellow River Basin would be able to produce more hydrogen with less water withdrawal in 2030 than in 2020. As seen in Figure 4.4, switching from coal to SMR+CCUS would produce 11% more hydrogen while cutting the total water withdrawal by 18% – but water consumption would rise by 15%. Or, by switching from coal to alkaline electrolysis, hydrogen production in the Yellow River Basin could grow by 11%, and at the same time involve 28% less withdrawal and 20% less consumption.

On a pathway to decarbonising hydrogen production in the Yellow River Basin, the water-related implications of various approaches need to be considered. Water use in the Basin is already unsustainable. The coal + CCUS approach would require the most water, about 893 million m^3 per year more withdrawal – equivalent to the annual demand of 13.8 million people in China – and 505 million m^3 more in consumption, relative to alkaline electrolysis, the least-water-demanding clean hydrogen production technology.

The Gulf Cooperation Council countries

The GCC countries – that include Bahrain, Kuwait, Oman, Qatar, Saudi Arabia and the United Arab Emirates – produce and use large quantities of grey hydrogen based on natural gas, 7.8 Mt/year, or close to 9% of the world total. Qatar, Kuwait and Saudi Arabia collectively account for more than 82% of the GCC's total production. Most hydrogen units are part of refineries, steel factories and petrochemical facilities. Some of this production may be suitable for retrofitting with CCUS (IRENA, 2023b).

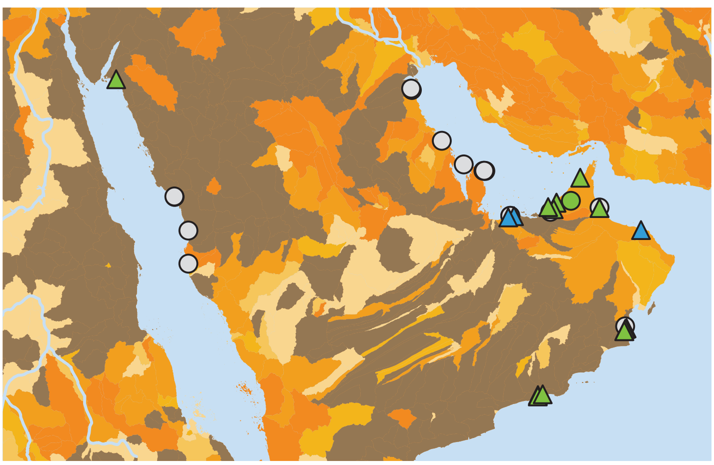
However, the GCC countries have significant potential to become green hydrogen producers and exporters, due to their ample low-cost land, existing industrial capacity, excellent solar resources, financial availability and geographical proximity to growth markets. Saudi Arabia, Oman and the United Arab Emirates, in particular, have announced or kick-started large-scale projects for the production of green hydrogen. These countries' ambitious plans to export hydrogen and derivatives could have significant implications for water demand in the local context.

Freshwater is extremely scarce in the GCC countries; as illustrated in Figure 4.5, almost all areas in the region are either arid or under high water stress. The GCC countries collectively have the largest share of global desalination capacity (34.8 billion m^3 per year), with capacity in Saudi Arabia (15.5%) and the United Arab Emirates (10.1%) being the world's largest and third-largest, respectively (Jones *et al.*, 2019) such as desalinated water, are expected to play a key role in narrowing the water demand-supply gap. Our synthesis of desalination data suggests that there are 15,906 operational desalination plants producing around 95 million m^3/day of desalinated water for human use, of which 48% is produced in the Middle East and North Africa region. A major challenge associated with desalination technologies is the production of a typically hypersaline concentrate (termed 'brine'). All the hydrogen plants in operation in the region are SMR facilities, located on the coasts of the Persian Gulf and the Red Sea (Figure 4.5). Desalinated water is required for the SMR but not all processes.

FIGURE 4.5 Hydrogen plants in the Gulf Cooperation Council countries and the region's current water stress conditions

Hydrogen production projects
- Grey - Operational
- Blue - Operational
- Blue - Planned
- Green - Operational
- Green - Planned

Water stress conditions in 2040
- Arid and low water use
- No data
- Low (<10%)
- Low to medium (10-20%)
- Medium to high (20-40%)
- High (40-80%)
- Extremely high (>80%)



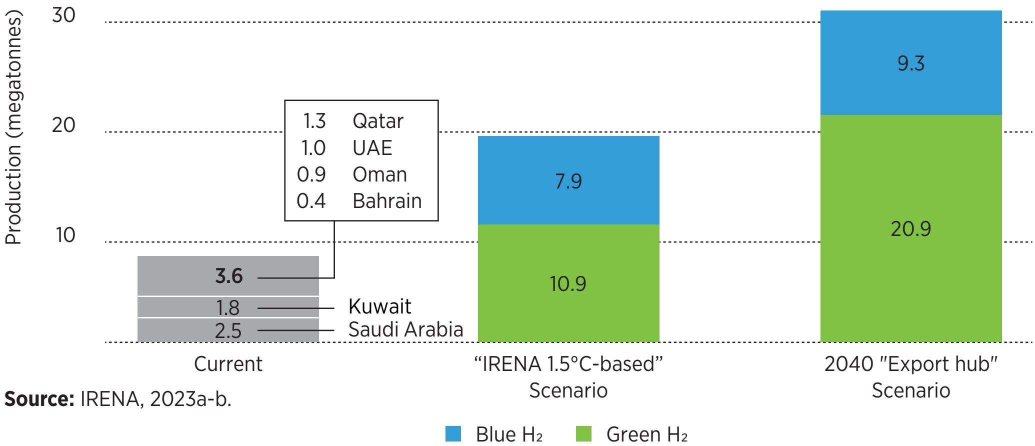
Based on: Qamar Energy, 2020; WRI, 2023

Disclaimer: This map is provided for illustration purposes only. Boundaries and names shown on this map do not imply the expression of any opinion on the part of IRENA concerning the status of any region, country, territory, city or area or of its authorities, or concerning the delimitation of frontiers or boundaries.

Once-through cooling systems take in seawater directly and discharge it back to the sea immediately after running it through the unit and removing the heat, and do not require desalinated water.

As shown in Figure 4.6, the GCC countries are projected to produce 18.8 Mt (a 138% increase from their current level of 7.9 Mt) of hydrogen per year by 2040, under the "IRENA 1.5°C-based" Scenario. Electrolysis will account for 62% of the GCC countries' total hydrogen production by 2040, whereas natural gas with CCS for 38% by 2040. Additionally, an "export hub" Scenario for the year 2040 is included, which assumes an annual hydrogen production of 30.2 Mt, 9.3 Mt from natural-gas-based blue hydrogen and 20.9 Mt from electrolysis.

FIGURE 4.6 Current and projected future hydrogen production of the Gulf Cooperation Council countries

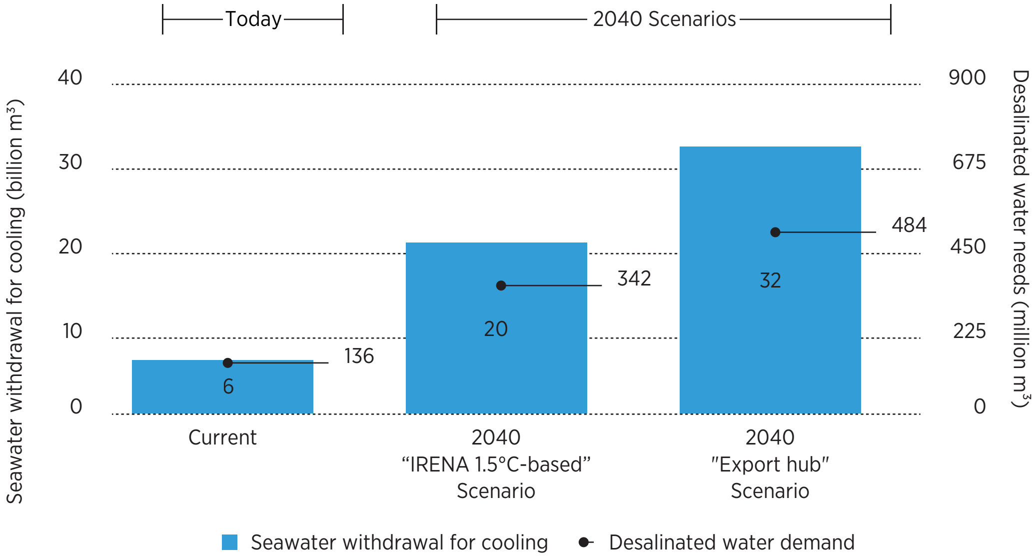


Source: IRENA, 2023a-b.

The utilisation of seawater is critical in arid regions, particularly the GCC countries. However, seawater utilisation must be carefully managed, as it has implications for both the environment and economy. The main environmental concerns surrounding desalination plants and once-through seawater cooling systems include brine and thermal pollution, both of which can disrupt aquatic ecosystems. Also, seawater desalination is an energy-intensive process and expensive both in terms of construction and operation. Figure 4.7 estimates seawater withdrawal for cooling and the desalinated water needed for electrolysis and gas reform in the GCC countries, based on hydrogen production projections for the region.

The GCC countries' current hydrogen production level requires 6 billion m^3 of seawater for cooling per year. Annual demand for desalinated water for hydrogen production processes is 136 million m^3, or about 1.1% of the countries' total desalination demand.
By 2040, under the 1.5°C Scenario, seawater withdrawal will triple to 20 billion m^3, while desalinated water demand increases by 137% to 32 million m^3. The difference in projected growth rates reflects a change in the hydrogen production technology mix, with electrolysis accounting for about 58% of total production by 2040, and natural gas with CCS for the remainder. Alkaline electrolysis requires less desalinated water than SMR to produce the same amount of hydrogen, but more seawater for cooling. PEM is more water efficient than SMR on both counts.

FIGURE 4.7 Current and projected seawater withdrawals and desalinated seawater requirements of hydrogen production in the Gulf Cooperation Council countries



Note: Seawater withdrawals include withdrawals for both desalination for reforming and electrolysis and cooling. Desalinated water demand refers to the amount of purified water needed for reforming and electrolysis after desalination. Key assumptions are: (1) all cooling systems are seawater once-through cooling; (2) the permeate rate of seawater desalination is 34.5%; (3) for electrolysis, 50% alkaline and 50% PEM by 2040; (4) for natural gas with CCS, 50% SMR+ CCUS and 50% ATR+CCUS by 2040; and (5) no technology improvements or equipment degradation. ATR = autothermal reforming; CCS = carbon capture and storage; CCUS = carbon capture, utilisation and storage; PEM = proton exchange membrane; SMR = steam methane reforming

Moving towards more alkaline and PEM electrolysis would require less cooling seawater withdrawal and discharge as well as less demand for desalinated water, compared with what is required for CCUS in natural-gas-based hydrogen production. Reducing the need for both sea- and desalinated water means less thermal pollution, less energy and money, and less pollution from the resulting brine.

Europe

The European Union (EU) has set an ambitious target: reduce GHG emissions by at least 55% as of 2030, compared with 1990 levels (EC, 2020a). In pursuit of this aim, the European Union has identified hydrogen as a key component of its energy transition strategy. In particular, the bloc is prioritising renewable hydrogen in its efforts to decarbonise the economy. In 2021, less than 2% of the energy consumed in the European Union was derived from hydrogen, and 96% of that hydrogen was produced using natural gas, resulting in significant CO_2 emissions.

The EU Hydrogen Strategy (COM/2020/301) was adopted in 2020. It was then complemented by the Fit-for-55 package (July 2021) and REpowerEU package (May

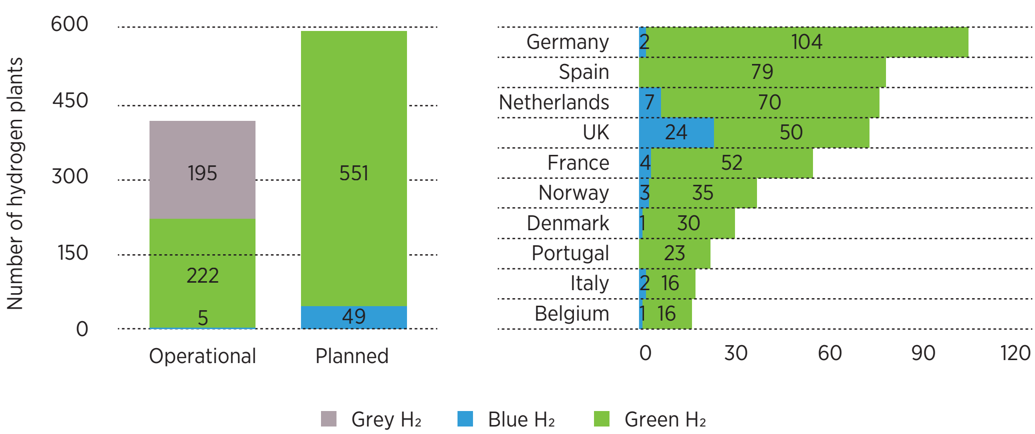
2022), which put forward several legislative proposals that translate the European hydrogen strategy into concrete policy frameworks, including proposals for the uptake of green hydrogen in industry and transport by 2030. By 2030, the European Union plans to produce 10 Mt of green hydrogen and import a similar quantity. As Figure 4.8a shows, 200 operational hydrogen plants run on natural gas, and only 5 are equipped with CCS. Among pre-operational projects, none centre on grey hydrogen (EC, 2020b, 2021, 2022a).
In addition, Member States are pursuing national hydrogen strategies to support local industry. Germany and the Netherlands, in particular, are signing various memoranda of understanding with non-EU countries to import hydrogen in the next few years. While not within the EU framework, other European countries, in particular Norway and the United Kingdom, are supporting the decarbonisation of hydrogen production: these two countries, in particular, also aim to become hydrogen exporters. As illustrated in Figure 4.8b, Germany has the largest number of green (177) and grey (34) hydrogen projects in Europe. The United Kingdom has a higher number of blue (24) hydrogen projects than other countries.

Given current and projected investments, as well as levels of interest in hydrogen production in Europe, a significant amount of additional water will likely be needed. Europe has experienced increasingly intense and frequent droughts over the past decade. The most recent mega drought occurred in 2022, Europe's driest year in 500 years (EC, 2022b), four years after the second-worst European drought. It affected the energy sector in particular. Nuclear plants in France were partially shut down because cooling water temperatures

FIGURE 4.8 An overview of hydrogen projects in Europe

(a) Number of operational and pre-operational projects, by production technology

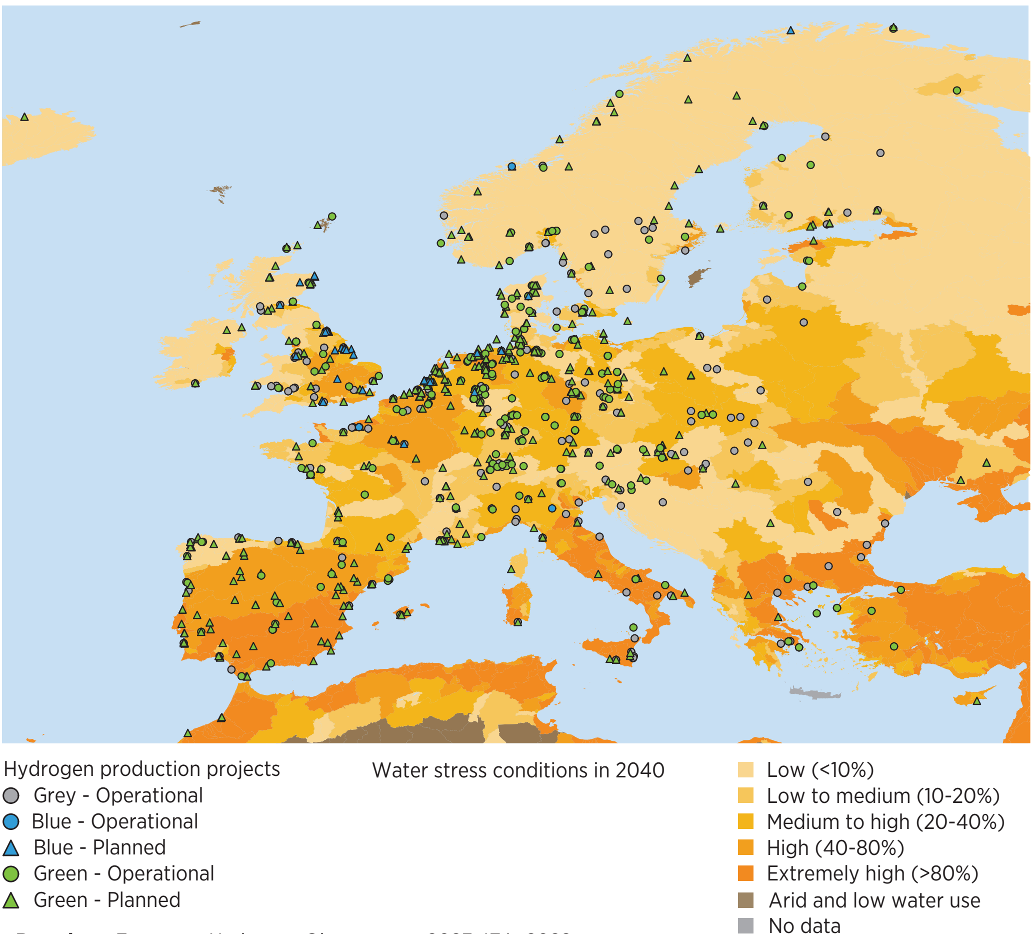
(b) Top 10 countries, by number of operational and pre-operational projects



Source: European Hydrogen Observatory 2023; IEA 2022

Note: Estimates include both operational and pre-operational projects. (1) Pre-operational includes projects that have been announced, announced in the pipeline, at the final investment decision, and under construction; and (2) of 222 operational green hydrogen projects, all are small-scale projects which collectively account for less than 1% of Europe's hydrogen production today; UK= United Kingdom were too high, hydropower production in Italy diminished due to drying rivers, and coal-fired power plant output in Germany was cut as coal transport was disrupted due to low river levels. Water considerations need to be integrated into energy and development plans. As depicted in Figure 4.9, Europe's operational and planned hydrogen projects are scattered across the continent, with a significant majority near coastlines and along major rivers in Germany, the United Kingdom, Spain, the Netherlands and France. By 2040, about 13% of all blue hydrogen projects in Europe are likely to be located in areas with high or extremely high water stress, as shown in Figure 4.10a.

FIGURE 4.9 A map of water stress and operational and planned hydrogen projects by production technology in Europe



Based on: European Hydrogen Observatory, 2023; IEA, 2022

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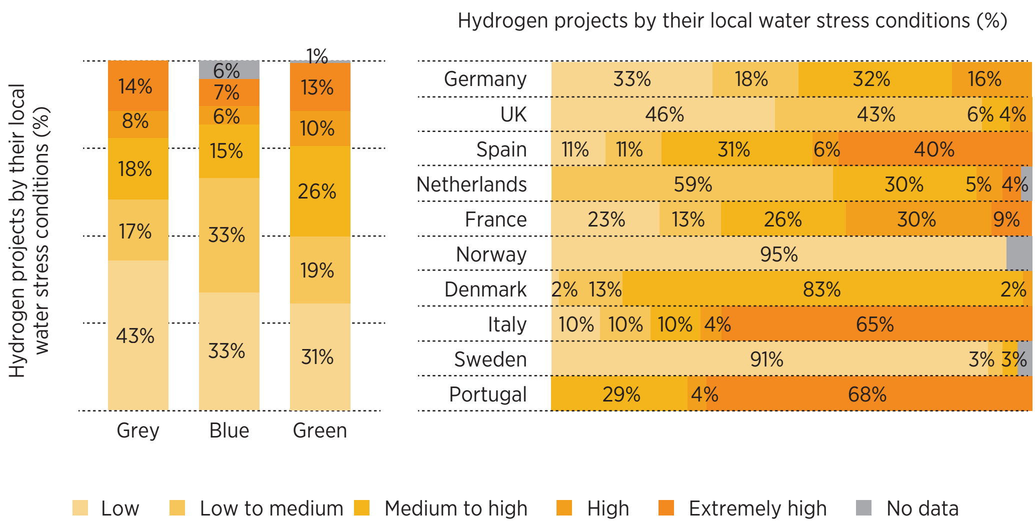
Most of these blue hydrogen projects will be in the United Kingdom, the Netherlands and Norway, where most local watersheds exhibit relatively low water stress levels. Conversely, this percentage is notably higher for grey and green hydrogen projects, standing at 23% and 22%, respectively.

Many of the hydrogen projects in Europe are located or are being developed in Germany, the United Kingdom and Spain. As shown in Figure 4.10b, more than 46% of all operational and planned blue and green hydrogen projects in Spain are likely to be located in highly water-stressed areas by 2040, followed by Germany at 16% and the United Kingdom at 4%. Among the top ten countries with the most operational and planned projects, Portugal and Italy have the highest percentages of projects located in high or extremely high water-stressed areas, at 71% and 69%, respectively. This indicates that hydrogen production in those countries faces a high degree of competition for water from other sectors.

FIGURE 4.10 The distribution of Europe's operational and planned hydrogen projects by water stress levels in 2040

(a) By hydrogen production technology

(b) By number of national projects

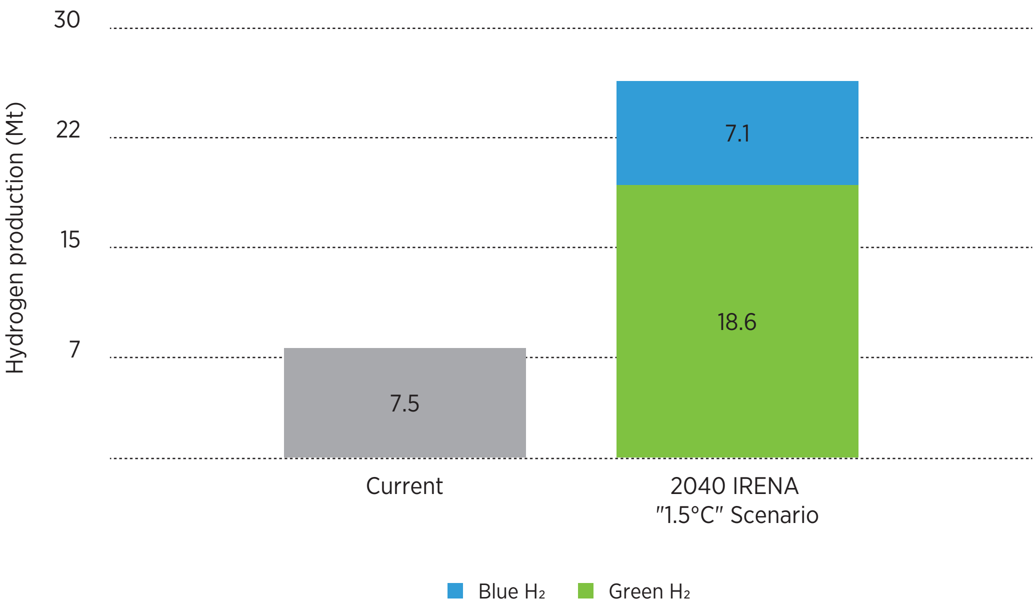


Note: UK = United Kingdom.

Europe produces 7.5 Mt of hydrogen annually, almost all of which is grey hydrogen from SMR without CCS. By 2040, all grey production will be either retired or upgraded with CCS. As shown in Figure 4.11, Europe's annual production is projected to be 25.7 Mt by 2040 in the 1.5°C Scenario, of which 18.6 Mt are from green hydrogen, accounting for over 72% of the total.

Over 150 million m^3 of freshwater withdrawal and 132 million m^3 of consumption are required to support Europe's current hydrogen production. In the years until 2040, while hydrogen production rises by about 243% from 7.5 Mt to 25.7 Mt, the sector's total water withdrawal and consumption could increase by 419% and 334%, respectively, as inferred from Figure 4.12. Water requirements are increasing much faster than hydrogen production as Europe's hydrogen production mix shifts from grey hydrogen to a mix of blue and green hydrogen, which are both more water intensive than grey hydrogen on average (except for PEM-based electrolysis).

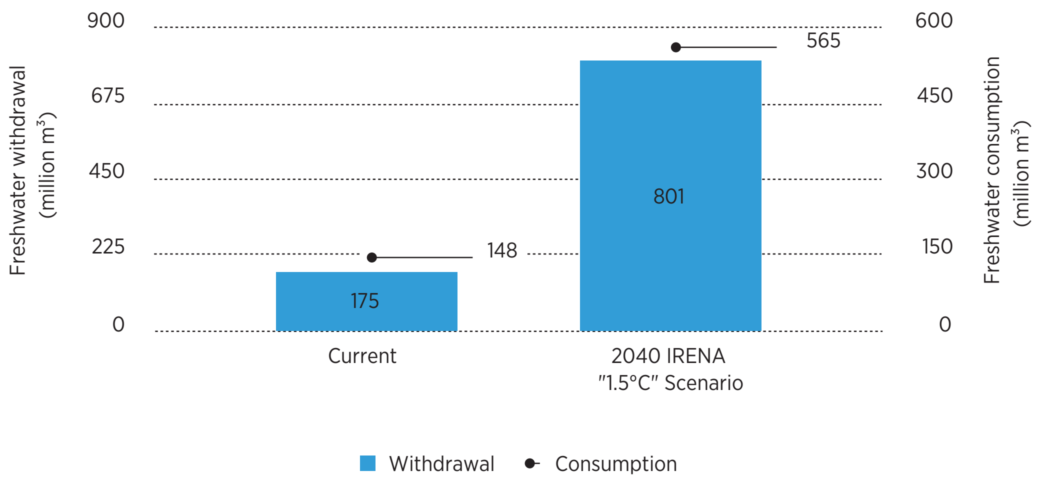
FIGURE 4.11 Current and projected hydrogen production in Europe



Source: IRENA, 2023a.

While hydrogen production represents a fraction of the water demand from all industries, Europe's ambition to grow and decarbonise its hydrogen sector means yet more competition for water. Demand must be properly managed, especially in regions already experiencing water stress, or at times of drought.

FIGURE 4.12 Current and projected future freshwater withdrawal and consumption requirements of hydrogen production in Europe



Note: Key assumptions include: (1) all cooling systems are freshwater evaporative systems; (2) for electrolysis, 50% alkaline and 50% PEM by 2040; (3) for natural gas with CCS, 50% SMR+CCS and 50% ATR+CCS by 2040; and (4) no seawater cooling or desalination for production water. ATR = autothermal reforming; CCS = carbon capture and storage; PEM = proton exchange membrane; SMR = steam methane reforming.

Chapter 5: Conclusions and Recommendations

Conclusions

The water and energy sectors are deeply intertwined, and a joint approach is necessary to identify trade-offs and mitigate future challenges and risks. The energy sector relies heavily on water during the fuel extraction and production, processing and conversion stages. Water's lack of availability, both in terms of quantity and quality, can impact energy production processes and supply security. Amid rising water use in the sector, competition with other end uses also emerges, particularly for extremely limited freshwater resources. As the energy sector transforms, in line with the SDGs and 2050 climate goals, it is crucially important to analyse the water implications of various technology pathways to ensure sustainability and minimise conflicts. The analysis presented here has focused on better understanding the water implications of clean hydrogen production – a key decarbonisation solution that will need to scale up, particularly in hard-to-decarbonise sectors.

Hydrogen projects consumer significant water volumes which could be concerning for regions facing local water stress. However, overall, the industry's water demand is only a small fraction of the energy sector's and will likely remain so in the next two to three decades.

Typically, a 237 kt hydrogen facility today would withdraw anywhere between 4 and 19 million m^3 of freshwater every year, which is about 26-104% of what is needed by a typical 1 GW coal-fired power plant or 12-49% of the domestic water needs of London for an entire year. Commercial-scale hydrogen projects can be large water consumers and introduce significant competition for water resources at a local scale, which is an issue that cannot be ignored in water-stressed regions. However, their impact should be contextualised within the broader industrial landscape. At the global or even the national level, the total amount of water required to produce hydrogen is very small, about 0.6% of what is required by the entire energy sector today. This could rise to 2.4% by 2040, as the water withdrawal demand of hydrogen is projected to increase by 600%, while the energy sector's water demand is projected to stay at about the same level as today (IEA, 2017).

Water use intensities of different hydrogen production technologies vary greatly: coal-based hydrogen production is by far the most water intensive, SMR consumes the least amount of water and PEM electrolysis is the least water-intensive clean hydrogen production technology.

A complete review of hydrogen production technologies' water withdrawal and consumption levels was conducted. Producing hydrogen via the gasification of coal is estimated to consume 31 L/kg of hydrogen on average, more than any other non-coal-based technology.

On average, SMR has the lowest water withdrawal and consumption intensities, 20.0 and 17.5 L/kg of hydrogen, respectively, among all hydrogen production technologies, while PEM is the least-water-intensive clean hydrogen production technology.

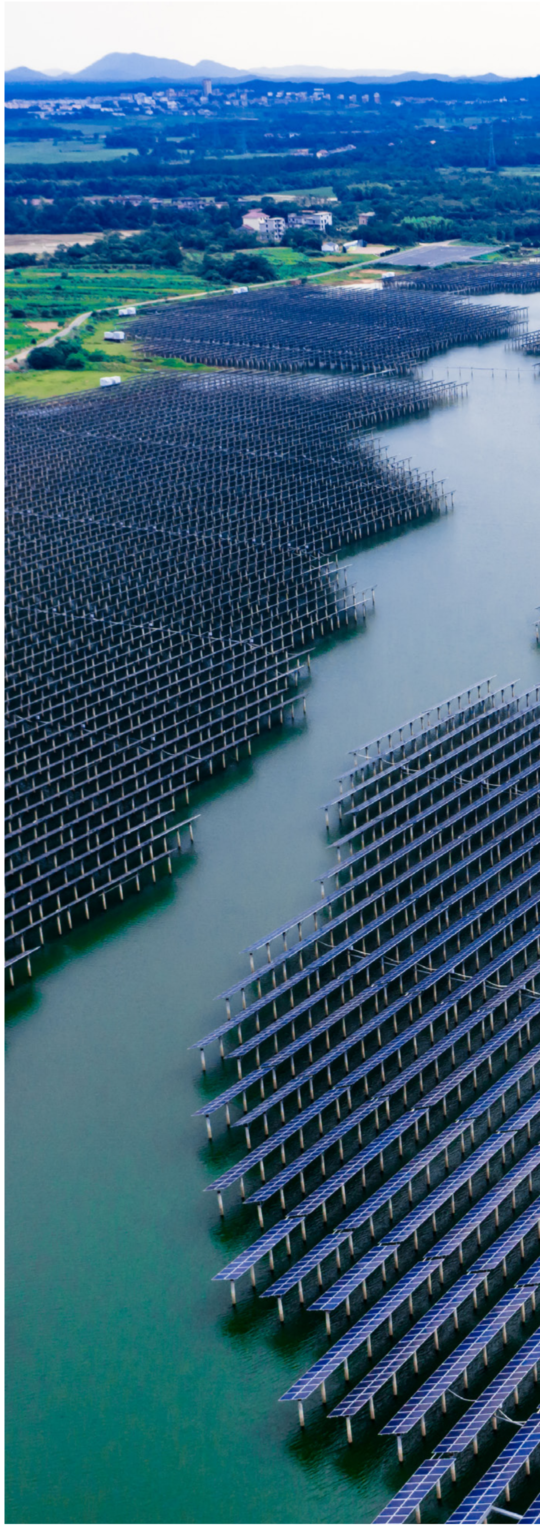
In pursuit of the energy transition, focusing on green hydrogen becomes paramount. Not only does green hydrogen excel in terms of emission intensity, but it also stands out as the least-water-intensive option on average. While blue hydrogen is championed as a clean alternative to grey hydrogen, it is essential to note that blue hydrogen has significant water consumption intensity. Therefore, when considering broader sustainability goals and water resource conservation, green hydrogen technologies prove to be a more environmentally responsible choice.

For the same technology, higher energy-to-hydrogen conversion efficiency means lower water use intensities, while adding CCUS reduces water use efficiency.

The production and cooling processes of hydrogen production collectively determine the water withdrawal and consumption intensities of any given technology. A more-energy-efficient production process results in reduced waste heat generation, leading to decreased demand for cooling and subsequently lowering the water requirements. Among green hydrogen projects, every 1 percentage point increase in electrolysis efficiency translates into about 2% less water intensity in both water withdrawal and consumption. On the other hand, adding CCUS dramatically raises cooling demand and reduces system efficiency, pushing up water withdrawal by 61-83% and consumption by 59-83% depending on project characteristics.

Water use for cooling accounts for a sizable portion of the total water requirements of hydrogen production, and increasing its efficiency offers an opportunity to reduce overall demand.

Commercial-scale projects that rely on freshwater are recirculating water for cooling. For such plants, water



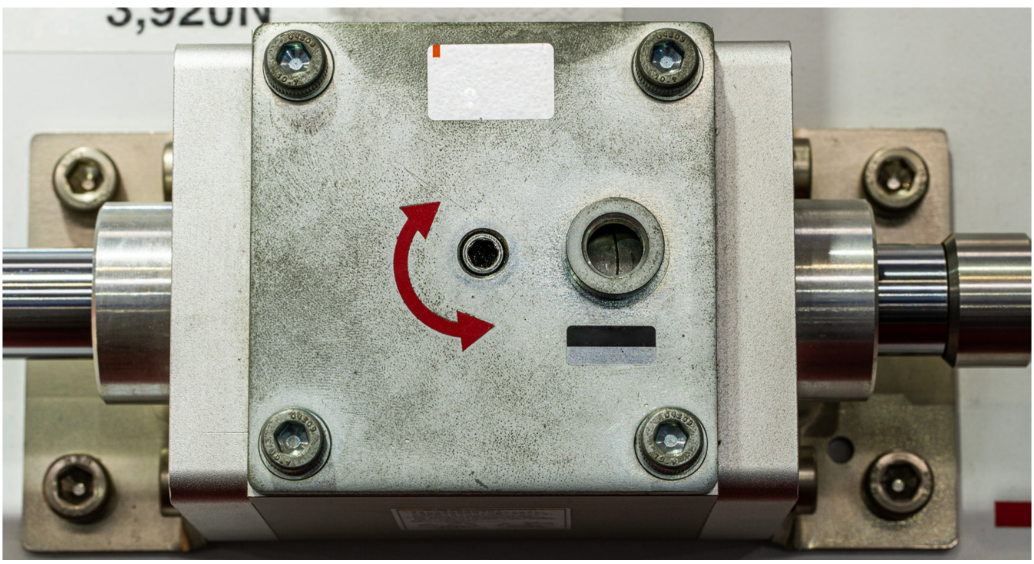
for cooling accounts for over 50% of the total withdrawal demand of green and coal-based hydrogen production, and more than 90% for blue hydrogen. Technologies or processes that can optimise cooling efficiency and alternative cooling methods that are less water dependent could lead to substantial water savings for the sector. For example, the thermal power generation sector (*e.g.* concentrated solar power plants in deserts and others) has long been adopting air-cooling technologies, reducing its water demand by over 98%.

Seawater is an option for both hydrogen production and cooling, yet the effects of desalination need to be carefully managed.

Using seawater for hydrogen production eliminates both the stress on local freshwater resources and its exposure to water-shortage-related risks of potential production disruption. For regions that have extreme freshwater scarcity but abundant access to the ocean, seawater may be the only realistic option for cooling processes. Thermal pollution from seawater cooling and brine generated by desalination can have environmental impacts. These should be carefully evaluated and managed to minimise their negative effects on marine ecosystems.

Hydrogen projects can be disrupted, or sometimes even cancelled, because of a lack of access to water. A considerable portion of operational and planned green and blue hydrogen projects are in areas with high water stress, exposing them to water shocks and the tightening of local water use regulations.

One important concern is the geographical distribution of projects: 36% of planned green and blue capacity is in areas with high water stress, which makes them more vulnerable to water shocks and their impacts on local water availability more pronounced. Solar-powered green hydrogen is a case in point, as regions with high solar energy potential are often dry.



Recommendations

Green hydrogen projects need to be prioritised in hydrogen development.

Green hydrogen offers a unique pathway to a low-carbon economy. Its water intensity is competitive with that of grey hydrogen, which has a larger carbon footprint. To promote this technology, policy makers could offer preferential permits, subsidies, tax incentives or expedited regulatory approval for green hydrogen projects. Setting up green hydrogen hubs in water-stressed areas would foster knowledge transfer, infrastructure development and market growth, and also lower costs by achieving economies of scale.

Water-related impacts and risks need to be carefully evaluated in hydrogen production development plans, particularly in water-stressed regions where stringent water use regulations must be established and enforced for the sector.

Policy makers can thus ensure sustainable growth of hydrogen production, preserve scarce resources and reduce the possibility of production disruptions due to climate risks or competition with other end-uses. Key steps are to (1) conduct thorough water risk and impact assessments and (2) establish stringent usage guidelines and robust enforcement to safeguard the environment.

Retiring fossil-fuel-based hydrogen plants in favour of green hydrogen should be prioritised in hydrogen development plans, particularly in areas where water is already scarce.

This transition reduces both carbon emissions and water use, delivering climate and environmental gains. Policy makers can speed the process by setting clear retirement deadlines while bolstering support for green hydrogen through funding, incentives and a supportive regulatory framework.

Water withdrawal and consumption may be used as project performance indicators, to be evaluated before operations commence and metered afterwards.

Given hydrogen production's substantial need for water, tracking and managing this resource is critical to its judicious use, which not only reduces environmental impacts but also signals efficient operations. Policy makers can require companies to include water use metrics in their environmental impact assessments and compliance reports. An industrywide water use standard would provide a benchmark for performance.

Regulations and financial incentives would do well to favour projects that demonstrate efficient rates of energy conversion and water consumption.

Such measures can rapidly reduce projects' impact on water resources and encourage technological innovation and sustainable practices by rewarding projects that perform better in these areas. Policy makers can implement a tiered system of incentives, with greater rewards for higher efficiency. This system could include tax breaks, subsidies, or low-interest loans for qualifying projects, while imposing penalties for underperformance. This kind of tiered approach becomes viable once the technology advances beyond the initial pilot project phase.

More investment and research would boost the efficiency of commercial-scale electrolysers and reduce freshwater consumption for cooling.

This would drive innovation, efficiency and sustainability in the industry. Policy makers can support the process by dedicating funds to research and development, offering grants and other incentives for breakthrough technologies, and fostering a conducive environment for collaboration among researchers in industry and academia.

Hydrogen projects in regions where water is already scarce can utilise water-efficient cooling technologies such as air cooling.

This balances environmental protection with economic development, by reducing water use, and may lower costs and mitigate environmental impacts. To support this shift, policy makers and industry can research air-cooling technologies for electrolysers, aiming to optimise hydrogen production processes and significantly reduce freshwater consumption. Next, policy makers can mandate water-efficient cooling, and offer incentives for early adoption and innovation. Mandates of closed-loop or dry cooling in thermal power generation offer useful lessons.

In present and future freshwater-stressed coastal areas, it is important to incentivise the use of seawater for hydrogen production and cooling processes and at the same time mitigate thermal pollution and manage brine.

This dual strategy leverages the benefits of an abundant resource while minimising environmental damage. To this end, policy makers would do well to provide financial support for infrastructural adaptations, and simultaneously establish clear guidelines and enforcement mechanisms for thermal pollution and brine management, including penalties for non-compliance.

References

Bloomberg (2023), "France Utility EDF Cuts Nuclear Output as Heat Triggers Water Restrictions", *Bloomberg*, https://www.bloomberg.com/news/articles/2023-07-13/france-cuts-nuclear-output-as-heat-triggers-water-restrictions

Caldera, U., and Breyer, C. (2017), "Learning Curve for Seawater Reverse Osmosis Desalination Plants: Capital Cost Trend of the Past, Present, and Future", *Water Resources Research*, vol. 53/12, pp. 10523–38, https://doi.org/10.1002/2017WR021402

Cui, P., *et al.* (2021), "Life cycle water footprint comparison of biomass-to-hydrogen and coal-to-hydrogen processes", *Science of The Total Environment*, vol. 773, pp. 145056, https://doi.org/10.1016/j.scitotenv.2021.145056

Delpisheh, M., *et al.* (2021), "Desalinated water and hydrogen generation from seawater via a desalination unit and a low temperature electrolysis using a novel solar-based setup", *International Journal of Hydrogen Energy*, vol. 46/10, pp. 7211–29, https://doi.org/10.1016/j.ijhydene.2020.11.215

EC (2022a), "REPowerEU: affordable, secure and sustainable energy for Europe", European Commission, https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/repowereu-affordable-secure-and-sustainable-energy-europe_en (accessed 17 October 2023).

EC (2022b), "Droughts in Europe in August 2022: severe rainfall deficit is affecting crops and increasing fire risks", https://ec.europa.eu/commission/presscorner/detail/en/mex_22_5123 (accessed 17 October 2023).

EC (2021), "EU economy and society to meet climate ambitions", https://ec.europa.eu/commission/presscorner/detail/en/IP_21_3541 (accessed 17 October 2023).

EC (2020a), "European Climate Law", https://climate.ec.europa.eu/eu-action/european-climate-law_en (accessed 17 October 2023).

EC (2020b), "COM (2020) 301 - A hydrogen strategy for a climate-neutral Europe", https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52020DC0301 (accessed 17 October 2023).

EIA (2020), "U.S. electric power sector's use of water continued its downward trend in 2020", https://www.eia.gov/todayinenergy/detail.php?id=50698

Elgowainy, A., *et al.* (2016), "IX.5 Life Cycle Analysis of Emerging Hydrogen Production Technologies", https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/progress16/ix_5_elgowainy_2016.pdf (accessed 17 October 2023).

European Hydrogen Observatory (2023), "Hydrogen Production", *European Hydrogen Observatory*, https://observatory.clean-hydrogen.europa.eu/hydrogen-landscape/production-trade-and-cost/hydrogen-production (accessed 17 October 2023).

Global Times (2023), "Local govt in NW China arranges water, protective measures for tree farm amid controversy", *Global Times*, https://www.globaltimes.cn/page/202304/1288383.shtml (accessed 17 October 2023).

IEA (n.d.), "Global water withdrawal in the energy sector by fuel and power generation type in the Net Zero Scenario, 2021 and 2030 – Charts – Data & Statistics", International Energy Agency, Paris https://www.iea.org/data-and-statistics/charts/global-water-withdrawal-in-the-energy-sector-by-fuel-and-power-generation-type-in-the-net-zero-Scenario-2021-and-2030 (accessed 17 October 2023).

IEA (2023), *Global Hydrogen Review 2023*, IEA, Paris.

IEA (2022), *Global Hydrogen Review 2022*, IEA, Paris.

IEA (2017), *WEO-2016 Special Report: Water-Energy Nexus*, IEA, Paris.

IEA and ACCA21 (2022), *Opportunities for Hydrogen Production with CCUS in China*, IEA and Administrative Centre for China's Agenda 21, Paris, France, Beijing, China. (accessed 17 October 2023).

IPCC (2018), *IPCC, 2018: Global Warming of 1.5°C*, Intergovernmental Panel on Climate Change. https://www.ipcc.ch/sr15/

IRENA (2023), *World Energy Transitions Outlook 2023: 1.5°C Pathway*, International Renewable Energy Agency, Abu Dhabi.

IRENA (2023a), *World Energy Transitions Outlook*, IRENA, Abu Dhabi.

IRENA (2023b), *Renewable energy market analysis: GCC 2023*, IRENA, Abu Dhabi.

IRENA (2020), *Green hydrogen cost reduction: Scaling up electrolysers to meet the 1.5C climate goal*, IRENA, Abu Dhabi.

IRENA (2019), *Renewable energy market analysis: GCC*, IRENA, Abu Dhabi.

IRENA (2015), *Renewable energy in the water, energy and food nexus*, IRENA, Abu Dhabi.

IRENA and China Water Risk (2016), *Water use in China's power sector*, IRENA and China Water Risk, Abu Dhabi, Hong Kong.

IRENA and WRI (2018), *Water use in India's power sector: Impact of renewables and improved cooling technologies to 2030*, IRENA and World Resource Institute, Abu Dhabi, Washington D.C.

Jones, E., *et al.* (2019), "The state of desalination and brine production: A global outlook", *Science of The Total Environment*, vol. 657, pp. 1343–56, https://doi.org/10.1016/j.scitotenv.2018.12.076

Lewis, E., *et al.* (2022), *Comparison of Commercial, State-of-the-Art, Fossil-Based Hydrogen Production Technologies*, No. DOE/NETL-2022/3241, National Energy Technology Laboratory (NETL), https://doi.org/10.2172/1862910, Pittsburgh, United States.

Macknick J. *et al.* (2011), *A Review of Operational Water Consumption and Withdrawal Factors for Electricity Generating Technologies,* NREL/TP-6A20-50900, National Renewable Energy Laboratory (NREL), https://www.nrel.gov/docs/fy11osti/50900.pdf, Golden, United States.

MEE (2022), "Notice on the Issuance of the 'Yellow River Basin Ecological and Environmental Protection Plan' by the Ministry of Ecology and Environment of the People's Republic of China" [in Chinese], https://www.mee.gov.cn/ywgz/zcghtjdd/ghxx/202206/t20220628_987021.shtml (accessed 17 October 2023).

Mehmeti, A., *et al.* (2018), "Life Cycle Assessment and Water Footprint of Hydrogen Production Methods: From Conventional to Emerging Technologies", *Environments*, vol. 5/2, pp. 24, Multidisciplinary Digital Publishing Institute, https://doi.org/10.3390/environments5020024

NBS (2023), "National data", https://data.stats.gov.cn/ (accessed 17 October 2023).

Newborough, M., and Cooley, G. (2022), "Green hydrogen: water use implications and opportunities", *Fuel Cells Bulletin*, vol. 2021, pp. 12-15, https://doi.org/10.1016/S1464-2859(21)00658-1

Nikkei (2022), "China's hydrogen roadmap: 4 things to know", *Nikkei Asia*, https://asia.nikkei.com/Spotlight/Caixin/China-s-hydrogen-roadmap-4-things-to-know (accessed 17 October 2023).

Peacock, B. (2022), "Green hydrogen megaproject in SA discontinued", *PV Magazine*, https://www.pv-magazine-australia.com/2022/05/31/green-hydrogen-megaproject-in-sa-discontinued (accessed 17 October 2023).

Peter, J. (2019), "How does climate change affect electricity system planning and optimal allocation of variable renewable energy?", *Applied Energy*, vol. 252, pp. 113397–113397, https://doi.org/10.1016/j.apenergy.2019.113397

Qamar Energy (2020), "Hydrogen in the GCC", https://www.rvo.nl/sites/default/files/2020/12/Hydrogen%20in%20the%20GCC.pdf

Rosa, L., *et al.* (2021), "The water footprint of carbon capture and storage technologies", *Renewable and Sustainable Energy Reviews*, vol. 138, pp. 110511, https://doi.org/10.1016/j.rser.2020.110511

Simon, A. J., Daily, and White (2010), *Hydrogen and Water: An Engineering, Economic and Environmental Analysis*, No. LLNL-TR-422193, Lawrence Livermore National Lab. (LLNL), Livermore, United States, https://doi.org/10.2172/1010388

Spath, P. L., and Mann, M. K. (2001), *Life Cycle Assessment of Hydrogen Production via Natural Gas Steam Reforming*, No. NREL/TP-570-27637, 764485, https://doi.org/10.2172/764485

US EPA, O. (2017), "Lean & Water Toolkit: Chapter 2", United States Envorment Protecion agency https://www.epa.gov/sustainability/lean-water-toolkit-chapter-2 (accessed 17 October 2023).

Wang, Y., *et al.* (2022), "An integrated framework to assess climate change impacts on water use for thermoelectric power plants", *Journal of Cleaner Production*, vol. 376, pp. 134271–134271, https://doi.org/10.1016/j.jclepro.2022.134271

WRI (2023), *Aqueduct*, WRI, https://www.wri.org/aqueduct (accessed 17 May 2023).

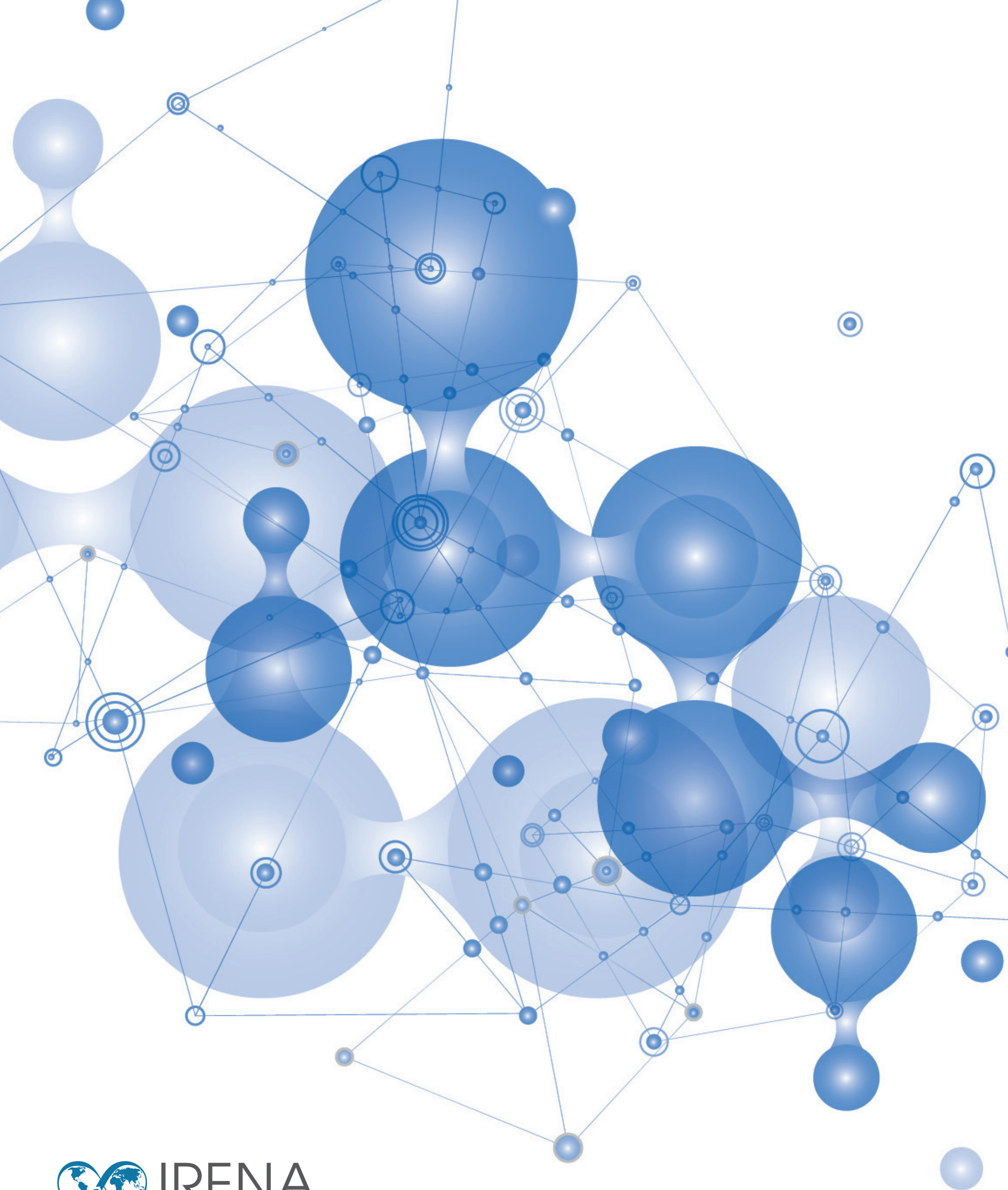
Xia, Y., *et al.* (2023), "Mapping the coal-water nexus in the Yellow River Basin", *Journal of Cleaner Production*, vol. 411, pp. 137249, https://doi.org/10.1016/j.jclepro.2023.137249

Appendix

TABLE A1 Water withdrawal and consumption intensity data sources

Type	Water withdrawal intensity (L/kg)	Water consumption intensity (L/kg)	Source
Coal-water slurry gasification	48.14	29.98	Design data from industry interviews
Coal-water slurry gasification	51.41	32.02	(Cui *et al.*, 2021)
Electrolysis-AE	34.61	23.59	Modelled data from industry interviews
Electrolysis-AE	29.88	20.96	Modelled data from industry interviews
Electrolysis-PEM	24.94	17.00	(Newborough and Cooley, 2022)
Electrolysis-PEM	26.46	18.04	(Mehmeti *et al.*, 2018)
Electrolysis-SOEC	15.86	10.81	(Elgowainy *et al.*, 2016)
Natural gas-ATR-CCS	30.76	24.22	(Lewis *et al.*, 2022)
Natural gas-SMR	16.40	15.80	(Lewis *et al.*, 2022)
Natural gas-SMR	25.16	17.27	Modelled data from industry interviews
Natural gas-SMR	20.55	19.80	(Spath and Mann, 2001)
Natural gas-SMR	17.92	17.27	(Simon, Daily, and White, 2010)
Natural gas-SMR-CCS	29.81	24.15	(Lewis *et al.*, 2022)
Coal-water slurry gasification CCS	73.85	46.53	Estimated based on (Cui *et al.*, 2021; and Rosa *et al.*, 2021) and industry interview data
Coal-water slurry gasification CCS	79.64	49.33	Estimated based on (Cui *et al.*, 2021; and Rosa *et al.*, 2021) and industry interview data
Coal-water slurry gasification CCS	87.21	52.47	Estimated based on (Cui *et al.*, 2021; and Rosa *et al.*, 2021) and industry interview data
Natural gas-SMR-CCS	31.15	31.09	Estimated based on (Lewis *et al.*, 2022; Rosa *et al.*, 2021; Simon, Daily, and White, 2010; Spath and Mann, 2001 and industry interview data
Natural gas-SMR-CCS	38.01	34.50	Estimated based on (Lewis *et al.*, 2022; Rosa *et al.*, 2021; Simon, Daily, and White, 2010; Spath and Mann, 2001 and industry interview data
Natural gas-SMR-CCS	47.79	38.96	Estimated based on (Lewis *et al.*, 2022; Rosa *et al.*, 2022; Simon, Daily, and White, 2010; Spath and Mann, 2001) and industry interview data.

Note: AE = alkaline electrolysis; ATR = autothermal reforming; CCS = carbon capture and storage; L/kg = litre per kilogramme; PEM = proton exchange membrane; SMR = steam methane reforming; SOEC = solid oxide electrolyser cell.



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P.O. Box 236 Abu Dhabi
United Arab Emirates
www.irena.org