Global Hydrogen Review 2021

INTERNATIONAL ENERGY AGENCY

The IEA examines the full spectrum of energy issues including oil, gas and coal supply and demand, renewable energy technologies, electricity markets, energy efficiency, access to energy, demand side management and much more. Through its work, the IEA advocates policies that will enhance the reliability, affordability and sustainability of energy in its 30 member countries, 8 association countries and beyond.

Please note that this publication is subject to specific restrictions that limit its use and distribution. The terms and conditions are available online at www.iea.org/t&c/

This publication and any map included herein are without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers and boundaries and to the name of any territory, city or area.

IEA member countries:
Australia
Austria
Belgium
Canada
Czech Republic
Denmark
Estonia
Finland
France
Germany
Greece
Hungary
Ireland
Italy
Japan
Korea
Luxembourg
Mexico
Netherlands
New Zealand
Norway
Poland
Portugal
Slovak Republic
Spain
Sweden
Switzerland
Turkey
United Kingdom
United States

IEA association countries:
Brazil
China
India
Indonesia
Morocco
Singapore
South Africa
Thailand

International Energy Agency
Website: www.iea.org

Table of Contents

Executive summary

Executive Summary

After several false starts, a new beginning around the corner

The time is ripe to tap into hydrogen's potential contribution to a sustainable energy system. In 2019, at the time of the release of the IEA's landmark report The Future of Hydrogen for the G20, only France, Japan and Korea had strategies for the use of hydrogen. Today, 17 governments have released hydrogen strategies, more than 20 governments have publicly announced they are working to develop strategies, and numerous companies are seeking to tap into hydrogen business opportunities. Such efforts are timely: hydrogen will be needed for an energy system with net zero emissions. In the IEA's Net Zero by 2050: A Roadmap for the Global Energy Sector, hydrogen use extends to several parts of the energy sector and grows sixfold from today's levels to meet 10% of total final energy consumption by 2050. This is all supplied from low-carbon sources.

Hydrogen supplies are becoming cleaner … too slowly

Hydrogen demand stood at 90 Mt in 2020, practically all for refining and industrial applications and produced almost exclusively from fossil fuels, resulting in close to 900 Mt of CO_2 emissions. But there are encouraging signs of progress. Global capacity of electrolysers, which are needed to produce hydrogen from electricity, doubled over the last five years to reach just over 300 MW by mid-2021. Around 350 projects currently under development could bring global capacity up to 54 GW by 2030. Another 40 projects accounting for more than 35 GW of capacity are in early stages of development. If all those projects are realised, global hydrogen supply from electrolysers could reach more than 8 Mt by 2030. While significant, this is still well below the 80 Mt required by that year in the pathway to net zero CO_2 emissions by 2050 set out in the IEA Roadmap for the Global Energy Sector.

Europe is leading electrolyser capacity deployment, with 40% of global installed capacity, and is set to remain the largest market in the near term on the back of the ambitious hydrogen strategies of the European Union and the United Kingdom. Australia's plans suggest it could catch up with Europe in a few years; Latin America and the Middle East are expected to deploy large amounts of capacity as well, in particular for export. The People's Republic of China ("China") made a slow start, but its number of project announcements is growing fast, and the United States is stepping up ambitions with its recently announced Hydrogen Earthshot.

Sixteen projects for producing hydrogen from fossil fuels with carbon capture, utilisation and storage (CCUS) are operational today, producing 0.7 Mt of hydrogen annually. Another 50 projects are under development and, if realised, could increase the annual hydrogen production to more than 9 Mt by 2030. Canada and the United States lead in the production of hydrogen from fossil fuels with CCUS, with more than 80% of global capacity production, although the United

Kingdom and the Netherlands are pushing to become leaders in the field and account for a major part of the projects under development.

Expanding the reach of hydrogen use

Hydrogen can be used in many more applications than those common today. Although this still accounts for a small share of total hydrogen demand, recent progress to expand its reach has been strong, particularly in transport. The cost of automotive fuel cells has fallen by 70% since 2008 thanks to technological progress and growing sales of fuel cell electric vehicles (FCEVs). Thanks to the efforts by Korea, the Unites States, China and Japan, the number of FCEVs on the road grew more than sixfold from 7 000 in 2017 to over 43 000 by mid-2021. In 2017, practically all FCEVs were passenger cars. Today, one-fifth are buses and trucks, indicating a shift to the long-distance segment where hydrogen can better compete with electric vehicles. However, the total number of FCEVs is still well below the estimated 11 million electric vehicles on the road today. Several demonstration projects for the use of hydrogen-based fuels in rail, shipping and aviation are already under development and are expected to open new opportunities for creating hydrogen demand.

Hydrogen is a key pillar of decarbonisation for industry, although most of the technologies that can contribute significantly are still nascent. Major steps are being taken. The world's first pilot project for producing carbon-free steel using low-carbon hydrogen began operation this year in Sweden. In Spain, a pilot project for the use of variable renewables-based hydrogen for ammonia production will start at the end of 2021. Several projects at a scale of tens of kilotonnes of hydrogen are expected to become operational over the next two to three years. Demonstration projects for using hydrogen in industrial applications such as cement, ceramics or glass manufacturing are also under development.

Governments need to scale up ambitions and support demand creation

Countries that have adopted hydrogen strategies have committed at least USD 37 billion; the private sector has announced an additional investment of USD 300 billion. But putting the hydrogen sector on track for net zero emissions by 2050 requires USD 1 200 billion of investment in low-carbon hydrogen supply and use through to 2030.

The focus of most government policies is on producing low-carbon hydrogen. Measures to increase demand are receiving less attention. Japan, Korea, France and the Netherlands have adopted targets for FCEV deployment. But boosting the role of low-carbon hydrogen in clean energy transitions requires a step change in demand creation. Governments are starting to announce a wide variety of policy instruments, including carbon prices, auctions, quotas, mandates and requirements in public procurement. Most of these measures have not yet entered into force. Their quick and widespread enactment could unlock more projects to scale up hydrogen demand.

Low-carbon hydrogen can become competitive within the next decade

A key barrier for low-carbon hydrogen is the cost gap with hydrogen from unabated fossil fuels. At present, producing hydrogen from fossil fuels is the cheapest option in most parts of the world. Depending on regional gas prices, the levelised cost of hydrogen production from natural gas ranges from USD 0.5 to USD 1.7 per kilogramme (kg). Using CCUS technologies to reduce the CO_2 emissions from hydrogen production increases the levelised cost of production to around USD 1 to USD 2 per kg. Using renewable electricity to produce hydrogen costs USD 3 to USD 8 per kg.

There is significant scope for cutting production costs through technology innovation and increased deployment. The potential is reflected in the IEA's Net Zero Emissions by 2050 Scenario (NZE Scenario) in which hydrogen from renewables falls to as low as USD 1.3 per kg by 2030 in regions with excellent renewable resources (range USD 1.3-3.5 per kg), comparable with the cost of hydrogen from natural gas with CCUS. In the longer term, hydrogen costs from renewable electricity fall as low as USD 1 per kg (range USD 1.0-3.0 per kg) in the NZE Scenario, making hydrogen from solar PV cost-competitive with hydrogen from natural gas even without CCUS in several regions.

Meeting climate pledges requires faster and more decisive action

While the adoption of hydrogen as a clean fuel is accelerating, it still falls short of what is required to help reach net zero emissions by 2050. If all the announced industrial plans are realised, by 2030:

- Total hydrogen demand could grow as high as 105 Mt – compared with more than 200 Mt in the NZE Scenario
- Low-carbon hydrogen production could reach more than 17 Mt – one-eighth of the production level required in the NZE Scenario
- Electrolysis capacity could rise to 90 GW – well below the nearly 850 GW in the NZE Scenario
- Up to 6 million FCEVs could be deployed – 40% of the level of deployment in the NZE Scenario (15 million FCEVs)

Much faster adoption of low-carbon hydrogen is needed to put the world on track for a sustainable energy system by 2050. Developing a global hydrogen market can help countries with limited domestic supply potential while providing export opportunities for countries with large renewable or CO_2 storage potential. There is also a need to accelerate technology innovation efforts. Several critical hydrogen technologies today are in early stages of development. We estimate that USD 90 billion of public money needs to be channeled into clean energy innovation worldwide as quickly as possible – with around half of it dedicated to hydrogen-related technologies.

Stronger international co-operation: a key leaver for success

International co-operation is critical to accelerate the adoption of hydrogen. Japan has spearheaded developments through the Hydrogen Energy Ministerial Meeting since 2018. Several bilateral and multilateral co-operation agreements and initiatives have since been announced, including the Clean Energy Ministerial Hydrogen Initiative, the Hydrogen Mission of Mission Innovation and the Global Partnership for Hydrogen of the United Nations Industrial Development Organization. These join the existing International Partnership for Hydrogen and Fuel Cells in the Economy and the IEA Hydrogen and Advanced Fuel Cells Technology Collaboration Programme. Stronger coordination among such initiatives is important to avoid duplication of efforts and ensure efficient progress.

IEA policy recommendations

Governments must take a lead in the energy transformation. In The Future of Hydrogen, the IEA identified a series of recommendations for near-term action. This report offers more detail about how policies can accelerate the adoption of hydrogen as a clean fuel:

- **Develop strategies and roadmaps on the role of hydrogen in energy systems**: National hydrogen strategies and roadmaps with concrete targets for deploying low-carbon production and, particularly, stimulating significant demand are critical to build stakeholder confidence about the potential market for low-carbon hydrogen. This is a vital first step to create momentum and trigger more investments to scale up and accelerate deployment.

- **Create incentives for using low-carbon hydrogen to displace unabated fossil fuels**: Demand creation is lagging behind what is needed to help put the world on track to reach net-zero emissions by 2030. It is critical to increase concrete measures on this front to tap into hydrogen's full potential as a clean energy vector. Currently, low-carbon hydrogen is more costly to use than unabated fossil-based hydrogen in areas where hydrogen is already being employed – and it is more costly to use than fossil fuels in areas where hydrogen could eventually replace them. Some countries are already using carbon pricing to close this cost gap but this is not enough. Wider adoption combined with other policy instruments like auctions, mandates, quotas and hydrogen requirements in public procurement can help de-risk investments and improve the economic feasibility of low-carbon hydrogen.

- **Mobilise investment in production, infrastructure and factories**: A policy framework that stimulates demand can, in turn, prompt investment in low-carbon production plants, infrastructure and manufacturing capacity. However, without stronger policy action, this process will not happen at the necessary pace to meet climate goals. Providing tailor-made support to selected shovel-ready flagship projects can kick-start the scaling up of low-carbon hydrogen and the development of infrastructure to connect supply sources to demand centres and manufacturing capacities from which later projects can benefit. Adequate infrastructure planning is critical to avoid delays or the creation of assets that can become stranded in the near or medium term.

- **Provide strong innovation support to ensure critical technologies reach commercialisation soon**: Continuous innovation is essential to drive down costs and increase the competitiveness of hydrogen technologies. Unlocking the full potential demand for hydrogen will require strong demonstration efforts over the next decade. An increase of R&D budgets and support for demonstration projects is urgently needed to make sure key hydrogen technologies reach commercialisation as soon as possible.

- **Establish appropriate certification, standardisation and regulation regimes**: The adoption of hydrogen will spawn new value chains. This will require modifying current regulatory frameworks and defining new standards and certification schemes to remove barriers preventing widespread adoption. International agreement on methodology to calculate the carbon footprint of hydrogen production is particularly important to ensure that hydrogen production is truly low-carbon. It will also play a fundamental role in developing a global hydrogen market.

Introduction

Overview

In the run-up to the 26th Conference of the Parties to the UN Framework Convention on Climate Change (COP 26), a growing number of countries are announcing targets to achieve net zero GHG emissions over the next decades. In turn, more than 100 companies that consume large volumes of energy or produce energy-consuming goods have followed suit. As demonstrated in the IEA Net zero by 2050 roadmap, achieving these targets will require immediate action to turn the 2020s into a decade of massive clean energy expansion.

Hydrogen will need to play an important role in the transition to net zero emissions. Since the first Hydrogen Energy Ministerial (HEM) meeting in Japan in 2018, momentum has grown and an increasing number of governments and companies are establishing visions and plans for hydrogen.

At the Osaka Summit in 2019, G20 leaders emphasised hydrogen's role in enabling the clean energy transition. The IEA prepared the landmark report The Future of Hydrogen for the summit, with detailed analysis of the state of hydrogen technologies and their potential to contribute to energy system transformation, as well as challenges that need to be overcome. In addition, during the 10th Clean Energy Ministerial (CEM) meeting in Vancouver, the Hydrogen Initiative (H2I) was launched to accelerate hydrogen deployment, and during the 6th Mission Innovation Ministerial, the Clean Hydrogen Mission to reduce the cost of clean hydrogen was announced.

This Global Hydrogen Review is an output of H2I that is intended to inform energy sector stakeholders on the current status and future prospects of hydrogen and serve as an input to the discussions at the HEM of Japan. It comprehensively examines what is needed to address climate change and compares actual progress with stated government and industry ambitions and with key actions announced in the Global Action Agenda launched in the HEM 2019. Focusing on hydrogen's usefulness in meeting climate goals, this Review aims to help decision makers fine-tune strategies to attract investment and facilitate deployment of hydrogen technologies while also creating demand for hydrogen and hydrogen-based fuels.

This Review's analysis comprises seven chapters. First, the chapter on **policy trends** describes progress made by governments in adopting hydrogen-related policies. Next, two comprehensive chapters on **global hydrogen demand** and **supply** provide in-depth analyses of recent advances in different sectors and technologies and explore how trends could evolve in the medium and long term.

A chapter on **infrastructure and hydrogen trade** emphasises the need to develop both these areas while ramping up demand and supply. It also details the status and opportunities for deploying hydrogen infrastructure, as well as recent trends and the outlook for hydrogen trade.

Investments and innovation are combined into one chapter to reflect how they mutually underpin trends in the development and uptake of hydrogen technologies. Meanwhile, the chapter on **insights on selected regions** recaps progress in regions and countries where governments and industry are particularly active in advancing hydrogen deployment.

The final chapter provides **policy recommendations** to accelerate the adoption of hydrogen technologies in the next decade, with a view to ensuring it becomes economically and technically viable and socially acceptable.

The Hydrogen Initiative

Developed under the CEM framework, H2I is a voluntary multi-government initiative that aims to advance policies, programmes and projects that accelerate the commercialisation and deployment of hydrogen and fuel cell technologies across all areas of the economy. Ultimately, it seeks to ensure hydrogen's place as a key enabler in the global clean energy transition.

The IEA serves as the H2I co-ordinator to support member governments as they develop activities aligned with the initiative. H2I currently comprises the following participating governments and intergovernmental entities: Australia, Austria, Brazil, Canada, Chile, the People's Republic of China (hereafter China), Costa Rica, the European Commission, Finland, Germany, India, Italy, Japan, the Netherlands, New Zealand, Norway, Portugal, the Republic of Korea (hereafter Korea), the Russian Federation (hereafter Russia), Saudi Arabia, South Africa, the United Kingdom and the United States. Canada, the European Commission, Japan, the Netherlands and the United States co-lead the initiative, while China and Italy are observers.

HYDROGEN INITIATIVE

AN INITIATIVE OF THE CLEAN ENERGY MINISTERIAL

H2I is also a platform to co-ordinate and facilitate co-operation among governments, other international initiatives and the industry sector. The Initiative has active partnerships with the Hydrogen Council, the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE), the International Renewable Energy Agency (IRENA), Mission Innovation (MI), the World Economic Forum (WEF) and the IEA's Advanced Fuel Cells and Hydrogen Technology Collaboration Programmes (TCPs), all of which are part of the H2I Advisory Group. In addition, several industrial partners actively participate in the H2I Advisory Group's bi-annual meetings, including Ballard, Enel, Engie, Nel Hydrogen, the Port of Rotterdam and Thyssenkrupp.

The Global Hydrogen Review

Following IEA recommendations in The Future of Hydrogen, this Global Hydrogen Review aims to track progress in hydrogen production and demand, as well as in other areas of critical importance such as policy, regulation and infrastructure development. To do this effectively and comprehensively, the IEA has established co-operative relationships with other relevant institutions to provide sound analysis based on the best possible data, and to create synergies among other international efforts, building on their respective strengths and experiences.

The Hydrogen Council in particular shared critical information on technology costs and performance from its industry network, which enriched IEA databases, modelling assumptions and techno-economic parameters.

Meanwhile, the IPHE contributed inputs on the developmental status of standards, codes and regulations. Leveraging its government network and established process to collect data and work collaboratively on regulatory issues, it also provided valuable information on the technology deployment and policy targets of its member governments.

The IEA TCPs and their networks of researchers and stakeholders also provided valuable inputs. The Hydrogen TCP helped the IEA update its latest assessment of the technology readiness levels of specific hydrogen technologies and offered insights on emerging technologies and barriers that need to be overcome to facilitate their deployment. The Advanced Fuel Cells TCP contributed with its annual tracking of fuel cell electric vehicles and infrastructure deployment.

Types of hydrogen in the Global Hydrogen Review

Hydrogen is a very versatile fuel that can be produced using all types of energy sources (coal, oil, natural gas, biomass, renewables and nuclear) through a very wide variety of technologies (reforming, gasification, electrolysis, pyrolysis, water splitting and many others). In recent years, colours have been used to refer to different hydrogen production routes (e.g. green for hydrogen from renewables and blue for production from natural gas with carbon capture, utilisation and storage [CCUS]), and specialised terms currently under discussion include “safe”, “sustainable”, “low-carbon” and “clean”. There is no international agreement on the use of these terms as yet, nor have their meanings in this context been clearly defined.

Because of the various energy sources that can be used, the environmental impacts of each production route can vary considerably; plus, the geographic region and the process configuration applied also influence impacts. For these reasons, the

IEA does not specifically espouse any of the above terms. Recognising that the potential of hydrogen to reduce CO_2 emissions depends strongly on how it is produced, this report highlights the role low-carbon hydrogen production routes can have in the clean energy transition. Low-carbon hydrogen in this report includes hydrogen produced from renewable and nuclear electricity, biomass, and fossil fuels with CCUS.[1]

Production from fossil fuels with CCUS is included only if upstream emissions are sufficiently low, if capture – at high rates – is applied to all CO_2 streams associated with the production route, and if all CO_2 is permanently stored to prevent its release into the atmosphere. The same principle applies to low-carbon feedstocks and hydrogen-based fuels made using low-carbon hydrogen and a sustainable carbon source (of biogenic origin or directly captured from the atmosphere).

This report also highlights the importance of establishing standards and certification to properly recognise the carbon footprints of the different hydrogen production routes. Since no standards have been internationally agreed and adopted, the IEA continues to differentiate the types of hydrogen by the technology used in their production, and uses this as the basis of its current definition of low-carbon hydrogen. This may evolve as dialogue within the international hydrogen community advances and more evidence and agreement emerge.

.

[1] In this report, CCUS includes CO_2 captured for use (CCU) as well as for storage (CCS), including CO_2 that is both used and stored (e.g. for enhanced oil recovery [EOR] or building materials) if some or all of the CO_2 is permanently stored. When use of the CO_2 ultimately leads to it being re-emitted to the atmosphere (e.g. urea production), CCU is specified.

Scenarios used in this Global Hydrogen Review

Outlook for hydrogen production and use

This Global Hydrogen Review relies on three indicators to track progress on hydrogen production and use:

- on-the-ground progress in hydrogen technology deployment
- government ambitions to integrate hydrogen into long-term energy strategies
- gaps between on-the-ground progress, government ambitions and projected energy transition requirements.

In this report, the Projects Case reflects on-the-ground progress. It takes all projects in the pipeline[2] into account as well as announced industry stakeholder plans to deploy hydrogen technologies across the entire value chain (from production to use in different end-use sectors).

Government targets and ambitions related to deploying hydrogen technologies are presented as hydrogen pledges. To gather relevant information from governments around the world, a joint IEA–European Commission work stream was established within the framework of the CEM Hydrogen Initiative, to consult governments around the world about their hydrogen targets and ambitions.

Pledges presented in this report include official targets (i.e. clear goals of national hydrogen strategies and roadmaps) as well as ambitions (i.e. plans communicated in consultations through the H2I work stream, but for which governments have not yet made official announcements or adopted a strategy or roadmap).

For the first time, the IEA's May 2021 report Net zero by 2050 lays out in detail what is needed from the energy sector to reach net zero CO_2 emissions by 2050, in line with the Paris Agreement's ambitious target to limit global temperature rise to 1.5°C. Based on these findings, this Review compares actual implemented actions with clean energy transition needs using two IEA scenarios: the Net zero Emissions by 2050 Scenario and the Announced Pledges Scenario.

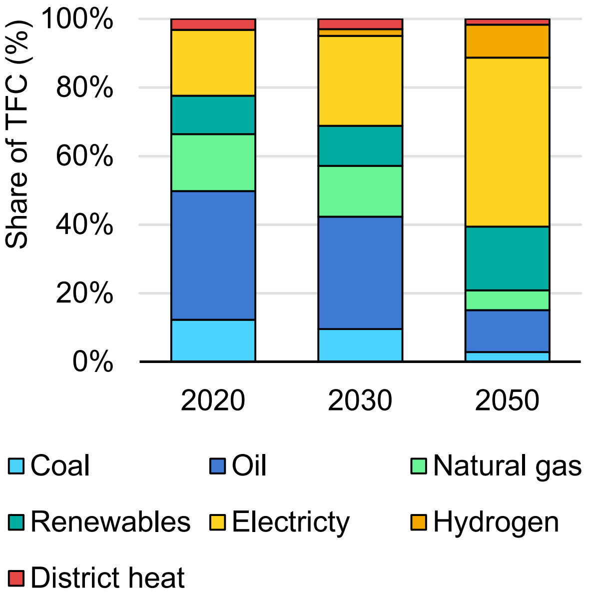
The Announced Pledges Scenario considers all national net zero emissions pledges that governments have announced to date and assumes they are realised in full and on time. This scenario thereby shows how far full implementation of national net zero emissions pledges would take the world towards reaching climate goals, and it highlights the potential contributions of different technologies, including hydrogen.

[2] In addition to projects already operational, this includes those currently under construction, that have reached final investment decision (FID) and that are undergoing feasibility studies.

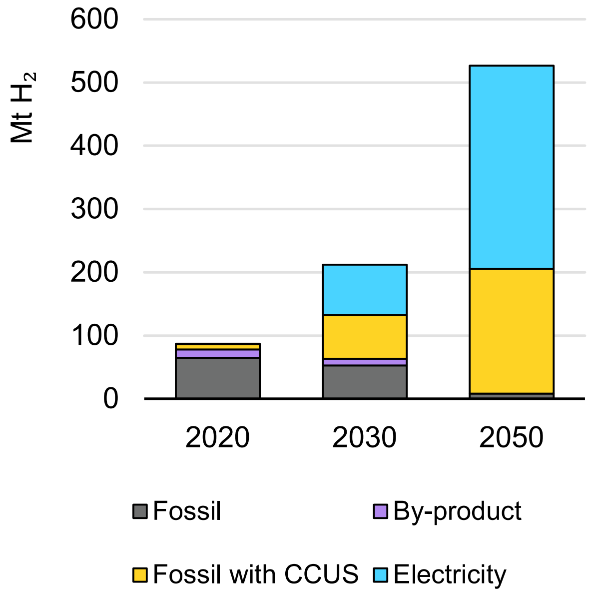
The role of hydrogen in the Net zero Emissions by 2050 Scenario

Hydrogen is an important part of the Net zero Emissions Scenario, but is only one piece of the puzzle

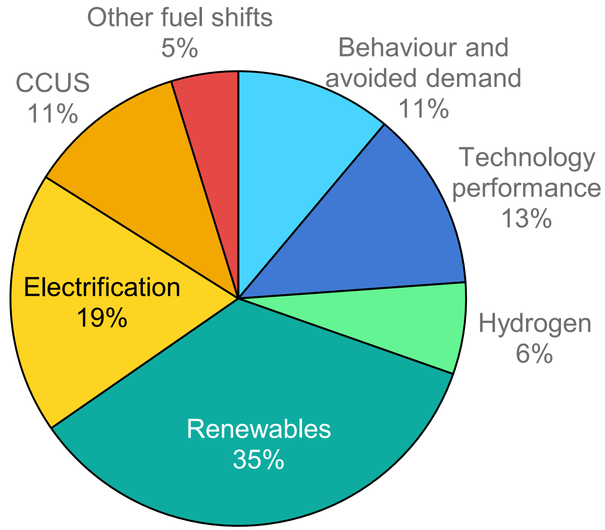
Share of total final energy consumption by fuel in the NZE, 2020-2050



Sources of hydrogen production in the NZE, 2020-2050



Cumulative emissions reduction by mitigation measure in the NZE, 2021-2050



Notes: NZE = Net zero Emissions Scenario. TFC = total final energy consumption. CCUS = carbon capture, utilisation and storage. “Behaviour” refers to energy service demand changes linked to user decisions (e.g. heating temperature changes). “Avoided demand” refers to energy service demand changes from technology developments (e.g. digitalisation). “Other fuel shifts” refers to switching from coal and oil to natural gas, nuclear, hydropower, geothermal, concentrating solar power or marine energy. “Hydrogen” includes hydrogen and hydrogen-based fuels.

Source: IEA (2021), Net zero by 2050.

Achieving net zero emissions by 2050 will require a broad range of technologies to transform the energy system. The key pillars of decarbonising the global energy system are energy efficiency, behavioural change, electrification, renewables, hydrogen and hydrogen-based fuels, and CCUS. The importance of hydrogen in the Net zero Emissions Scenario is reflected in its increasing share in total final energy consumption (TFC): in 2020, hydrogen and hydrogen-based fuels accounted for less than 0.1%,[3] but by 2030 they meet 2% of TFC and in 2050, 10%.

Nevertheless, this demand increase alone is not enough to make hydrogen a key pillar of decarbonisation. Hydrogen production must also become much cleaner than it is today. For instance, of the ~90 Mt H_2 used in 2020, around 80% was produced from fossil fuels, mostly unabated. Practically all the remainder came from residual gases produced in refineries and the petrochemical industry. This resulted in almost 900 Mt CO_2 emitted in the production of hydrogen, equivalent to the CO_2 emissions of Indonesia and the United Kingdom combined.

In the Net zero Emissions Scenario, hydrogen production undergoes an unparalleled transformation. By 2030, when total production reaches more than 200 Mt H_2, 70% is produced using low-carbon technologies (electrolysis or fossil fuels with CCUS). Hydrogen production then grows to over 500 Mt H_2 by 2050, practically all based on low-carbon technologies. Reaching these goals will require that installed electrolysis capacity increase from 0.3 GW today to close to 850 GW by 2030 and almost 3 600 GW by 2050, while CO_2 captured in hydrogen production must rise from 135 Mt today to 680 Mt in 2030 and 1 800 Mt in 2050.

Strong hydrogen demand growth and the adoption of cleaner technologies for its production thus enable hydrogen and hydrogen-based fuels to avoid up to 60 Gt CO_2 emissions in 2021-2050 in the Net zero Emissions Scenario, representing 6.5% of total cumulative emissions reductions. Hydrogen fuel use is particularly critical for reducing emissions in the hard-to-decarbonise sectors in which direct electrification is difficult to implement, i.e. heavy industry (particularly steel manufacturing and chemical production), heavy-duty road transport, shipping and aviation. In the power sector, hydrogen can also provide flexibility by helping to balance rising shares of variable renewable energy generation and facilitating seasonal energy storage.

[3] This excludes industry sector on-site hydrogen production and use, which consumes around 6% of final energy consumption in industry today. Including on-site hydrogen production in industry, hydrogen and hydrogen-based fuels meet 1% of total final energy consumption today, 4% by 2030 and 13% by 2050 in the Net Zero Emissions Scenario.

Policy trends across key areas for hydrogen deployment

Progress in five key areas for hydrogen policymaking