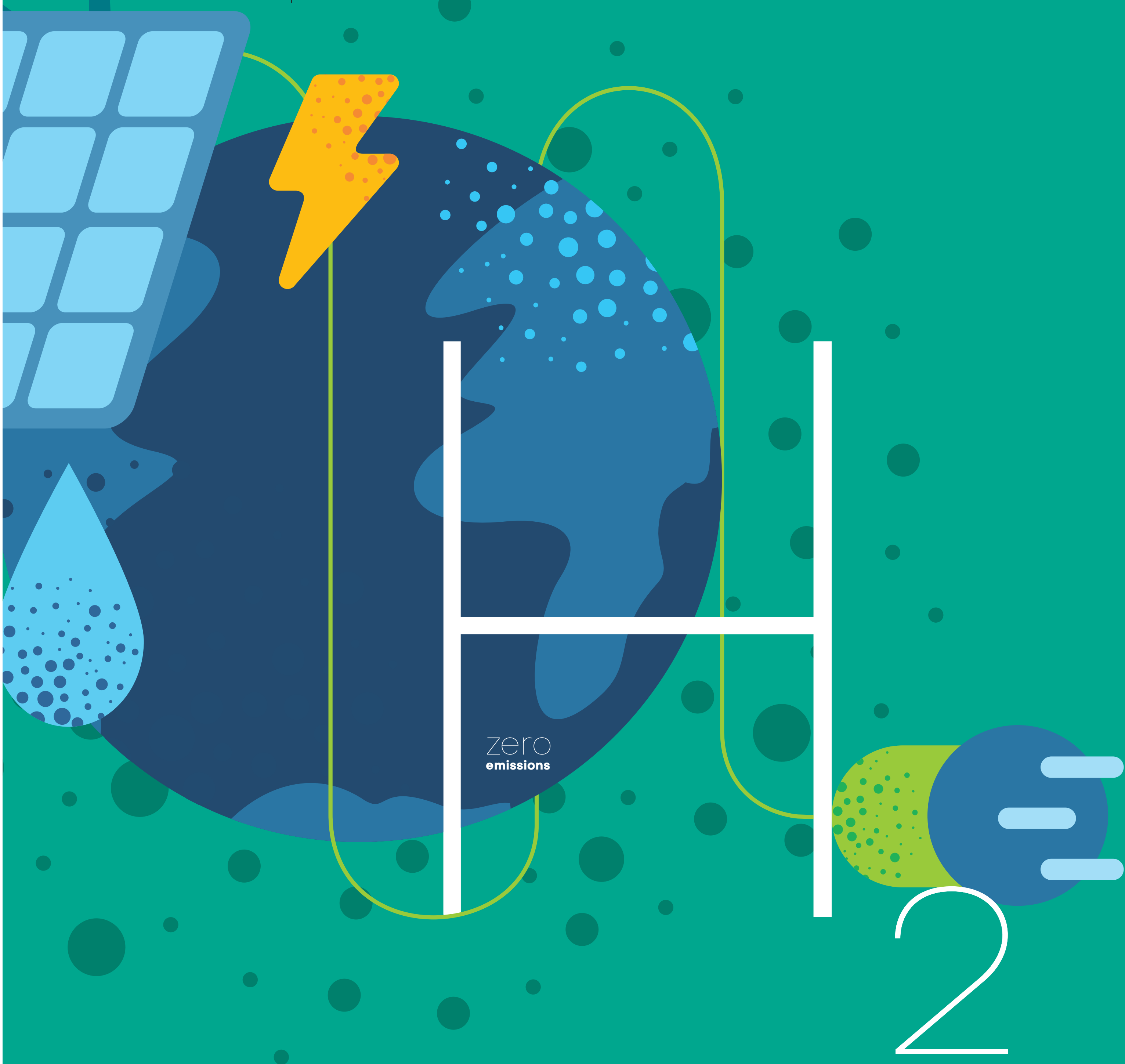
Technical potential & challenges of REnewable hydrogen

ISSUES IN THE GLOBAL SOUTH



Brot für die Welt
HEINRICH BÖLL STIFTUNG

Technical potential & challenges of REnewable hydrogen

ISSUES IN THE GLOBAL SOUTH

About the Authors: The Institute for Sustainable Futures (ISF) was established by the University of Technology Sydney in 1996 to work with industry, government, and the community to develop sustainable futures through research and consultancy. Our mission is to create change towards establishing sustainable futures that protect and enhance the environment, human well-being, and social equity. We use an interdisciplinary approach to our work and engage our partner organisations in a collaborative process that emphasises strategic decision-making. For further information visit: www.isf.uts.edu.au **Research team:** Associate Prof. Dr. Sven Teske, Dr. Sarah Niklas, Dr. Franziska Mey.

Co-operation partner: This project has been conducted in co-operation with Jaime Fernandez Medina and Dr. Joachim Fuenfgelt, Brot für die Welt.

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Please see the main dossier with all publications and activities on hydrogen of the Heinrich Böll Foundation and Brot für die Welt:
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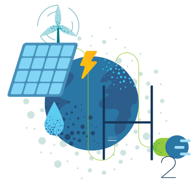

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Hydrogen energy storage system accompanied by a large wind turbine park.
© petrmalinak

Foreword

by Jaime Fernández, Brot für die Welt

The accelerating climate change and its severe implications highlight the importance of a global transition towards a "green economy" with lower fossil fuel consumption as well as with lower greenhouse gas emissions.

The need to drastically reduce CO_2 emissions will lead to the transformation of our current, carbon-based energy system to a more sustainable, renewable-based one. In this process, hydrogen is expected to increasingly gain importance as a 'clean' alternative fuel for decarbonising sectors with particularly stubborn emissions, such as heavy industry and aviation. Most current hydrogen production, however, is the result of extraction from fossil fuels, leading to large carbon emissions. The cleanest form of hydrogen – renewable hydrogen also called green hydrogen – comes from electrolysis of water, a process powered by electricity from renewable energy sources. Industrialised countries like Germany are set to import the lion's share of its future renewable hydrogen requirements.

Brot für die Welt and the Heinrich Böll Foundation have commissioned this report in order to support civil society organisations' participation in the hydrogen energy debate. Furthermore, the insights derived from this report seek to provide input for citizens to make informed decisions, to advocate and work with their governments in the development of a just hydrogen market. We are convinced that the civil society's participation in this process is crucial to guarantee that the public interest is adequately represented in the hydrogen strategies.

Hydrogen has long been touted as an innovative energy source, able to store electricity and supply heat for homes and fuel for ships or airplanes. Frequently, hydrogen is presented as the energy vector of the future. So why aren't we reading about airplanes flying, and emitting nothing but water vapour?

This publication portrays the status quo of the hydrogen technology but also investigates the technology's opportunities and challenges. In addition to the technicalities surrounding hydrogen, this report examines three further issues. Firstly, this report explores the main players in the hydrogen economy. Secondly, it sheds light on hydrogen strategies from different countries. Finally, the report's authors also outline recommendations for international trade in green hydrogen. The policy recommendations were further developed in an additionalpublication focused only upon the policy aspect of a hydrogen economy.

In order to establish a successful hydrogen market, inclusive and sustainable partnerships with countries of the global south must be ensured. These partnerships need to take place on an equal footing in which the exporting and the importing country can both share the benefits of the new market. Only when win-win constellations are developed, sustainable cooperation will emerge. This also includes meeting the countries' demand for renewable energies necessary to decarbonise their own energy system, lifting people out of poverty and promoting sustainable development in the global south taking into consideration potential resource conflicts, for example over land or water and legal aspects for participants and stakeholders, and compliance with environmental and social safeguards in project planning and implementation.

While green hydrogen projects may sound like a good idea to help the world fulfil its targets of greenhouse emission cuts, that the promotion of projects must not result in the plunder of local resources, dispossession of communities, environmental damage or entrenchment of corrupt elites. It is therefore vital that the civil society sector is strengthened in this process to fulfil its role as advocate of the public's interest.

Acronyms and abbreviations

AU$	Australian dollar
bcm	billion cubic meters
BHRRC	Business and Human Rights Resource Centre
BMWi	German Federal Ministry for Economic Affairs and Climate Action
BMZ	German Ministry for Economic Cooperation and Development
BNEF	Bloomberg New Energy Finance
BUSD	billion USD
CCS	carbon capture and storage
CCU	carbon capture and utilisation
CO	carbon monoxide
CO_2	carbon dioxide
COVID-19	Corona virus pandemic
CRMs	critical raw materials
CSP	concentrated solar power
ct	Euro cent
DA	Delegated Act
DESA	United Nations Department of Economic and Social Affairs
DII	Desertec Industrial Initiative
EC	European Commission
EOI	Expression of Interest
EU	European Union
EVs	electric vehicles
FAO	Food and Agriculture Organization of the United Nations
FCHEA	Fuel Cell and Hydrogen Energy Association
GHG	greenhouse gas
GO	Guarantees of Origin
GW	Giga watt
H_2	hydrogen
HSRM	Hydrogen Society Roadmap
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
kt	kilo tons
kWh	kilowatt-hour
LHV	lower heating value
LNG	Liquid Natural Gas
MASEN	Moroccan Agency for Sustainable Energy
MENA	Middle East and North Africa
Mt	Mega tonnes
MWh	megawatt-hour
OECD	Organisation for Economic Co-operation and Development
OECM	One Earth Climate Model
R&D	Research and Development
REI4P	Renewable Energy Independent Producers Procurement Programme
REIPPPP	Renewable Energy Independent Power Producer Programme
SAF	Sustainable Aviation Fuels
SDGs	Sustainable Development Goals
SE4All	Sustainable Energy For All
SEZ	Special Economic Zone
SLO	social licence to operate
SNG	synthetic natural gas
Solar PV	solar photovoltaic
SWOT	Strengths, Weaknesses, Opportunities, and Threats
THE	Tianjin Mainland Hydrogen Equipment Co. Ltd.
UBA	Umweltbundesamt (German Environment Agency)
UK	United Kingdom
UNGPs	United Nations Guiding Principles on Business and Human Rights
US	United States
US$	US dollar
W/m^2	watts per square metre
WWF	World Wildlife Fund

Executive summary

The shift towards renewable hydrogen is required to reduce CO_2 emissions in hard to abate industry sectors, where electrification is not an option, including the steel, cement, chemical and transport (fright) sectors.

Hydrogen is a colourless gas; it can be produced via two routes: by fossil fuels or renewable electricity. Currently, 96% of hydrogen is produced in processes with a fossil-fuel based feedstock such as steam methane reforming, which are powered by fossil fuels. Hydrogen as an energy source is highly versatile, in its gaseous state, it can be converted to energy powering mobility, industrial heat or electricity and it can be used as energy storage. Hydrogen has similar properties to natural gas, and if liquefied, can be transported over long distances. However, a major technical challenge related to energy efficiency remains, about half of the energy is lost over the whole cycle, from producing renewable electricity for hydrogen production to generating electricity from hydrogen use in power plants. It is expected that the energy efficiency will reach 75% in 2050.

While the production of renewable hydrogen opens new opportunities for developed nations to decarbonise emission-intensive industrial processes, hydrogen production via electrolysis requires a massive upscale of renewable energy capacities (wind and solar PV). Developed nations will struggle to meet this electricity demand and will rely on hydrogen imports from the Global South.

The purpose of this report is to provide the technical background of processes of renewable hydrogen production and its applications in key sectors. The report also discusses factors which will determine the costs reductions for the commercialisation of renewable hydrogen to reach economies of scale.

The One Earth Climate Model proposes the contribution of renewable hydrogen towards key sectors of the economy until 2050, and its emissions reduction potential to limit global warming to 1.5°C by 2050.

In addition, the report discusses the main players – the key producers and consumers worldwide – with a focus on countries of the Global South. In this context, the report describes the impacts of the Russian invasion of the Ukraine in February 2022, which exposed the strong dependence of Europe on Russian gas imports. The report, in its analysis, draws on evaluations by the International Energy Agency (IEA) and the political responses by the European Union, which cover the phase-out of Russian gas imports by 2030 and potential replacements.

The report has identified nations with strong hydrogen strategies, including countries of the Global South, which have the potential to produce hydrogen for the export market. Morocco, South Africa and Chile have the greatest export potential. However, the relationship between future export and import countries, is complex due to a long history of fossil fuel exploration by energy companies in the Global South.

The SWOT analysis on the next page shows the strength & opportunities and the weaknesses & threats, which need to be considered when developing guidelines and recommendations for future renewable hydrogen trade involving countries from the Global South.

The main take away message for renewable hydrogen developers and investors is to engage with local communities early on, facilitate their participation in strategic groups to identify and plan projects in ways that avoid adverse social, cultural and environmental impacts.

Communities must benefit from major energy developments and export markets, through community acceptance (social license), access to energy services, the creation of local employment and opportunities of project ownership.

Community consultation combined with mapping of renewable energy capacity can protect critical resources including fresh water, environmental biodiversity and support sustainable land use.

Finally, the transition towards renewable hydrogen can provide equal benefits for industrialised and developing nations, but only if the energy sector and investors, are willing to learn from failures of energy colonialism of the past.

SWOT for renewable hydrogen production in the Global South

Strengths

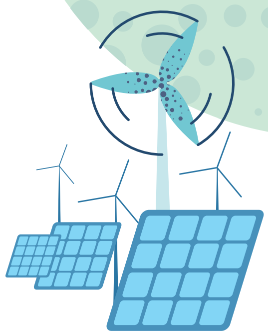
1. Use of available local resources for solar and wind (deserts, coastlines, non-arable or uninhabitable land due to mining and/or climate change)
2. Renewable energy strengthens the focus on ecological sustainability
3. Young and growing population
4. Support equitable development and bolster community livelihoods

Weaknesses

1. Political instability in form of institutional set ups and governance structures
2. Low investment capacity
3. High legal uncertainty
4. Lack of required infrastructure
5. Long distance transport required
6. Lack of technological and skills transfer by donor countries

Opportunties

1. Fast-tracked access to energy services, e.g. through electrification benefits for rural areas, industry and small to large businesses
2. Enhanced access to technology, education and training
3. Additional employment opportunities
4. Local economic development (manufacturing, profit shares from community energy)



Threats

1. Land use conflicts
2. Lack of social acceptance
   - a. risk of corruption and disengagement if community engagement is neglected
   - b. risk of project cost increase due to poor planning
   - c. risk of conflict over the use of local resources, related to water use, water scarcity and land use and land scarcity
3. Negative impacts on local ecosystems
4. Technology failures
5. Financial dependence on donor countries

Hydrogen energy storage gas tank with solar panels, wind turbine and energy storage container unit. © petrmalinak

01

Introduction

Significant efforts are needed to tackle the climate crisis by achieving the greenhouse gas (GHG) emission reduction targets of the Paris Agreement and limit global warming to 1.5°C. Since the Paris Agreement, approaches have been developed which support the reduction of greenhouse gas (GHG) emissions at the sector level. This approach highlights the importance of including emission-intensive and hard-to-mitigate sectors and the challenges these sectors face in mitigating emissions substantially. Hard to mitigate sectors include heavy industry, including metal working, transport, including aviation and shipping, and the chemical industry. The main challenge is the inability to electrify industrial processes which require process heat to achieve high temperatures, for example in the steel industry.

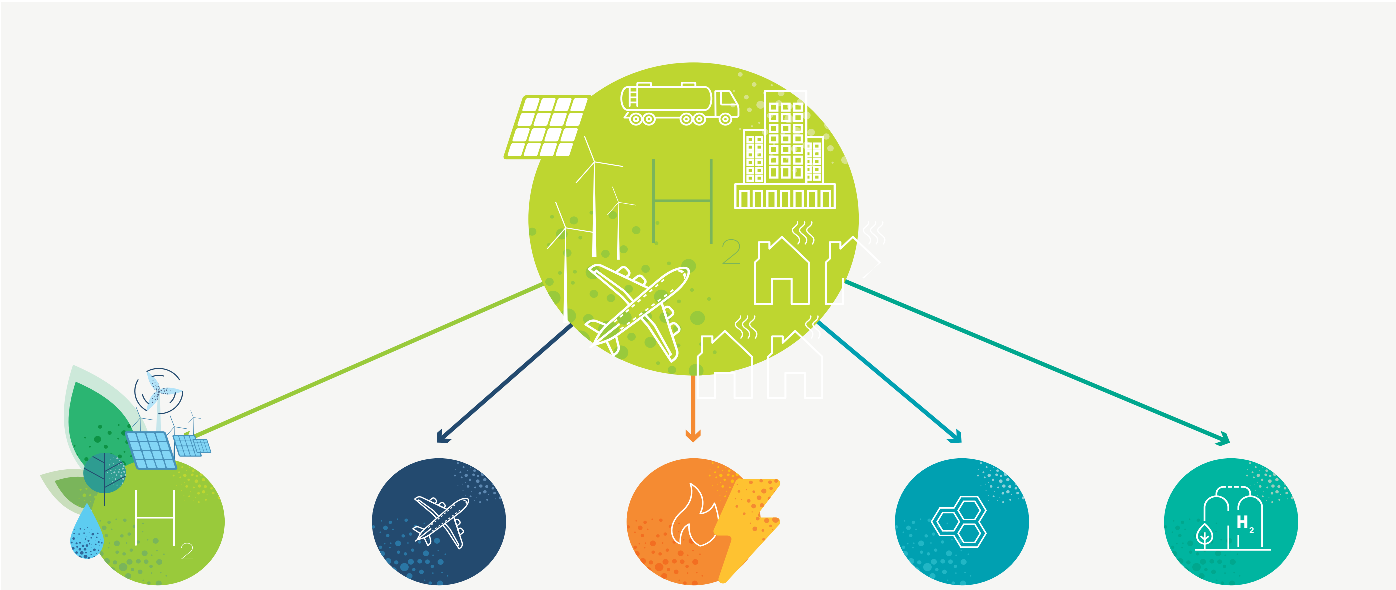
In 2016, the Federal German Government set the goal to reduce GHG emissions by 80% to 95% by 2050 compared to 1990s levels.[1] By 2050 Europe has decided to become the first continent that emits only unavoidable greenhouse gases and completely offsets these few remaining emissions.[2]

Achieving this goal entails a massive change in the supply and utilisation of energy as we know it today. This applies not only to the power generation sector but is also essential for all other energy consuming sectors such as transport, industry and buildings. One way to accelerate the reduction of global GHG emissions and facilitate the decarbonisation of industrial sectors is to shift from coal towards renewable electricity and replace natural gas with hydrogen technology. Recently, Green Hydrogen has received much attention within the energy transition debate.

One important aspect of hydrogen technology is the opportunity to convert the gaseous state of hydrogen into a liquid with a higher energy density. One option is to liquify the gaseous hydrogen with low temperatures or high pressures in a similar process as applied to converting natural gas to Liquid Natural Gas (LNG). Another option is conversion pathways that allow energy to be stored and transported in the form of a new chemical compound with a higher energy density. Technologies which enable such pathways are referred to as Power-to-X technologies (see Appendix A for further explanation), here hydrogen would be converted to energy for powering mobility, providing industrial heat, replacing industry feedstocks or electricity and storage (Figure 1).

Introduction continued

Figure 1: Applications of hydrogen in the economy



Source: Fuel Cells and Hydrogen 2 Joint Undertaking (2021)[3], modified. **Note:** Figures based on the Global CCS Institute 2008. The figures do not include hydrogen that is currently obtained as a by-product and vented or burned. Around 80 % of the total amount of ammonia produced globally is used to produce inorganic nitrogen-based fertilisers.

The aim of this report is to create a better and more comprehensive understanding of hydrogen and renewable hydrogen technology. The reference to technical and economic data covers hydrogen production and other related processes, which are crucial to distinguish between different types of hydrogen i.e. different pathways to produce hydrogen, and evaluate their economic and environmental impacts. The report discusses the role of hydrogen in the future energy market, its implication on the world economy and outlines the opportunities and risks related to hydrogen technology uptake for the Global South.

The report provides an overview of the main countries expected to drive the future hydrogen market. The country studies include high- and low-income countries and discusses their role in the hydrogen economy. For many industrialised countries including European countries, the energy demand can only be met by energy imports. Therefore, imported renewable-produced hydrogen will play an important role. Whether this hydrogen will be produced in developing countries of the Global South, or oil and gas producing regions such as the Middle East or Australia remains to be seen (Figure 1).

This study focuses on hydrogen produced with renewable electricity via an electro-chemical process known as electrolysis. Today, electrolysers are expensive and only deployed at a small scale, costs for electrolysers need come down to reach economies of scale.

However so far, mostly economic questions such as the potential of hydrogen production and use, distribution, costs and market readiness are at the centre of attention. Questions about the human rights-based socio-economic and environmental implications of hydrogen production and the subsequent massive increase in renewable energy deployment, are still niche research areas. Future research must provide a better understanding of the scale of renewable hydrogen production worldwide and must focus on consequences for the Global South.[4] As the discussion is already emerging in the public discourse, research findings are crucial to inform further debates. Case studies show that the involvement of local communities by project developers is key to avoid conflicts and costly legal disputes (IGWA, 2021).[5] The voice of local communities and their concerns must be at the core of renewable energy developments, only this will contribute to a large-scale transition towards renewable energy which benefits all parties involved.

Compared to the price range for oil, gas and coal in 2020, the production costs of renewable hydrogen, were significantly higher because the required technical equipment has not entered economies of scale yet (Longden et al., 2022).[6] In addition, the current carbon-pricing has yet to reach the price level that incentivises the use of renewable hydrogen over alternative fossil-fuel energy sources in buildings, transportation and power generation. Policy support is required to incentivise companies to produce it in large amounts. Hence policy makers must define the course renewable hydrogen production is taking, in particular for countries in the Global South.

The discussion of the different elements will be based on qualitative and quantitative assessment. The One Earth Climate Model -Teske et al (2019)[7] – a global 100% renewable energy scenario – was used as a basis. This study focuses on hydrogen produced with renewable electricity via an electro-chemical process known as electrolysis (here two water molecules are split using electricity). Due to the significant cost reduction of solar photovoltaic (PV) and onshore wind power generation over the last decade, renewable electricity and fossil fuels-based electricity are now cost competitive. This development increased the viability of renewable hydrogen considerably. Today, electrolysers, the technology to produce hydrogen, is expensive and only deployed at a small scale, costs for electrolysers need come down to reach economies of scale.

The 1.5°C pathway of the One Earth Climate Model (OECM) provides the basis for the amounts of required hydrogen and synthetic fuels for the global market.

A hydrogen fueling station in Irvine, CA . Station attendant Yanea Williams supervises. © Dennis Schroeder / NREL

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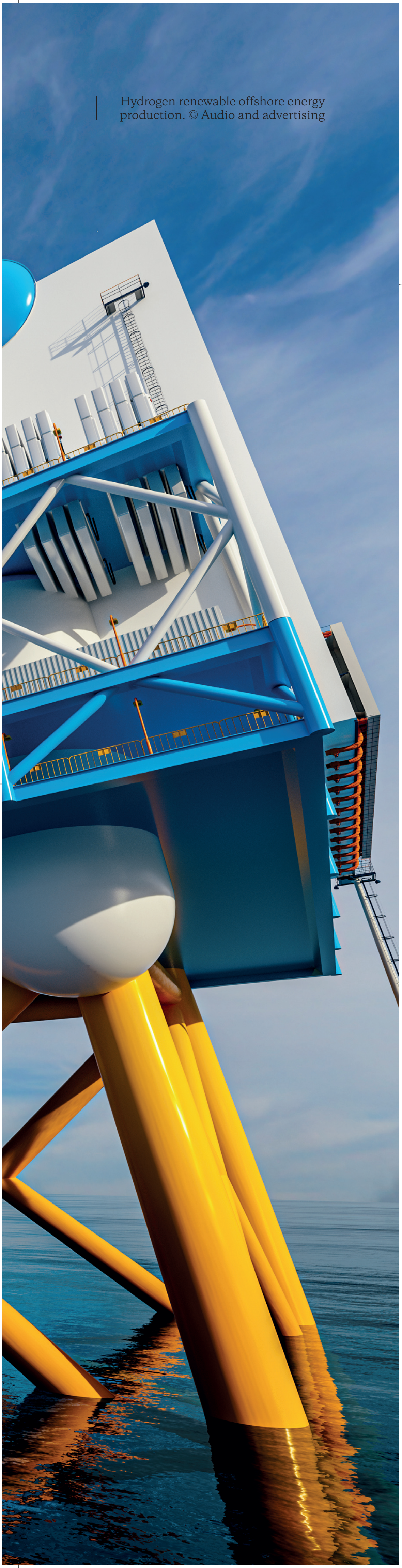

Hydrogen renewable offshore energy production. © Audio and advertising

02

Hydrogen: The basics

2.1 Hydrogen Production, GHG emissions and projected global demand

Hydrogen production is not a new development, but a common industrial process, conventionally fuelled by fossil fuels. This section introduces existing and new ways to produce hydrogen.

To understand what hydrogen is and how it is produced, a short glance into the chemistry of hydrogen is required. Hydrogen consists of two hydrogen (H) molecules, this chemical arrangement is often referred to as H_2, it occurs as a gas.

There are two ways of producing hydrogen: from fossil fuels (gas, coal, oil) and from renewable electricity. In the public debate, colours are often used to refer to different production processes of hydrogen (Figure 2).[8] The colour scheme is solely symbolical as hydrogen, which is a gas, has no colour.

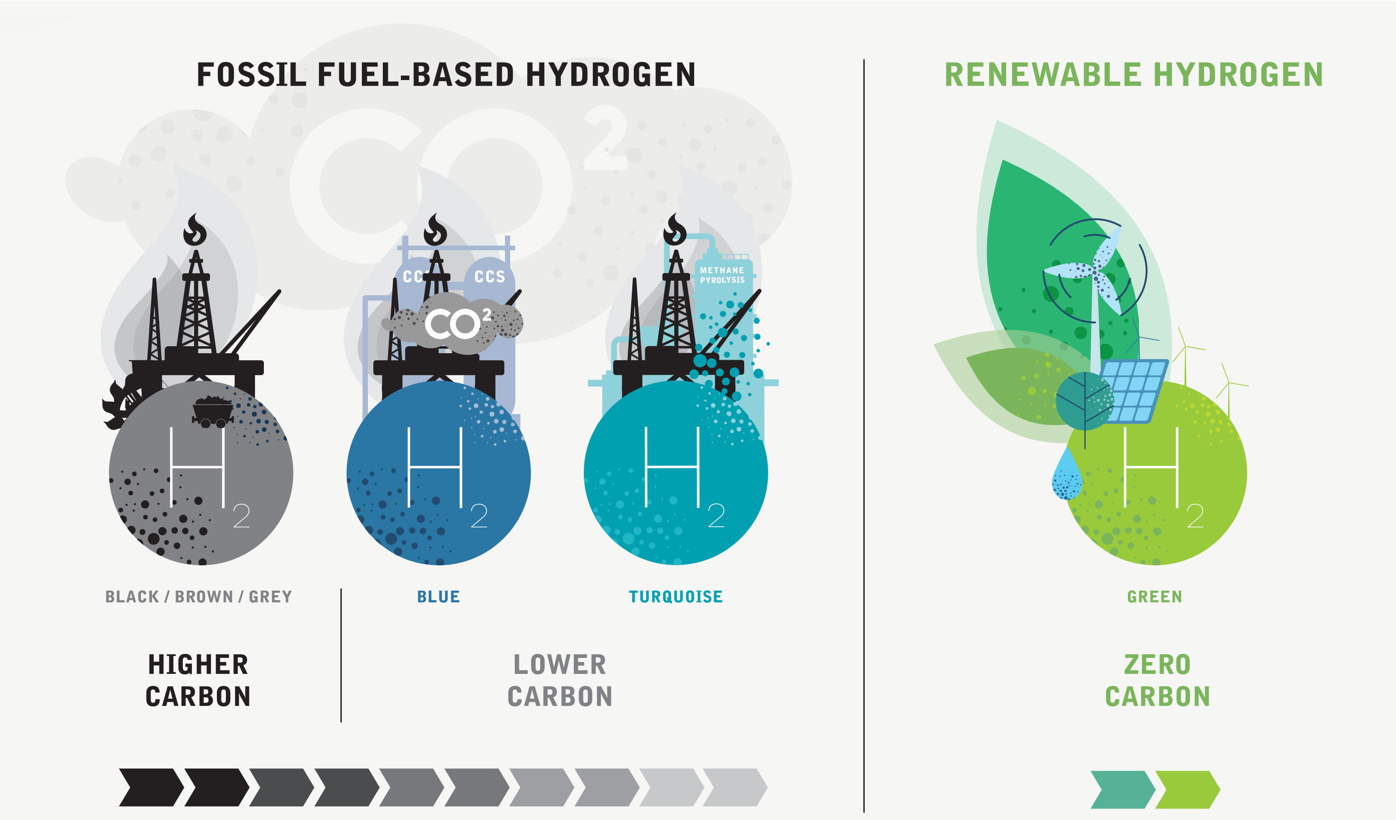
Hydrogen: The basics continued

However, in the public debate the colour scheme is used frequently and therefore it is explained below:

- **"Green"** is a term applied to production of hydrogen using water and electricity from renewable energy sources. As there is no legal definition for 'green' hydrogen, we will use the term 'renewable hydrogen'.
- **"Black"**, **"grey"** or **"brown"** refer to the production of hydrogen from coal, natural gas and brown coal respectively. The GHG emissions of the production of fossil-based hydrogen are very high.
- **"Blue"** is grey hydrogen with the addition that CO_2 emissions are reduced by the use of carbon capture and storage (CCS) technology. It is also referred to as "low-carbon hydrogen" due to its GHG emission reduction potential.
- **Turquoise** (aqua, sea green) is hydrogen produced from methane in a thermal process (methane pyrolysis). Instead of CO_2, the process results in solid carbon (fixed carbon).

All colours other than "green" are grouped in the category of fossil fuel-based hydrogen, as shown in Figure 2. The colours only stand for variations in the production process, yet they can differ significantly in their environmental and social impacts depending on the energy source and region.

Figure 2: The various colours of hydrogen based on production sources as used in public debates



Data: Sembcorp (2021).[9]

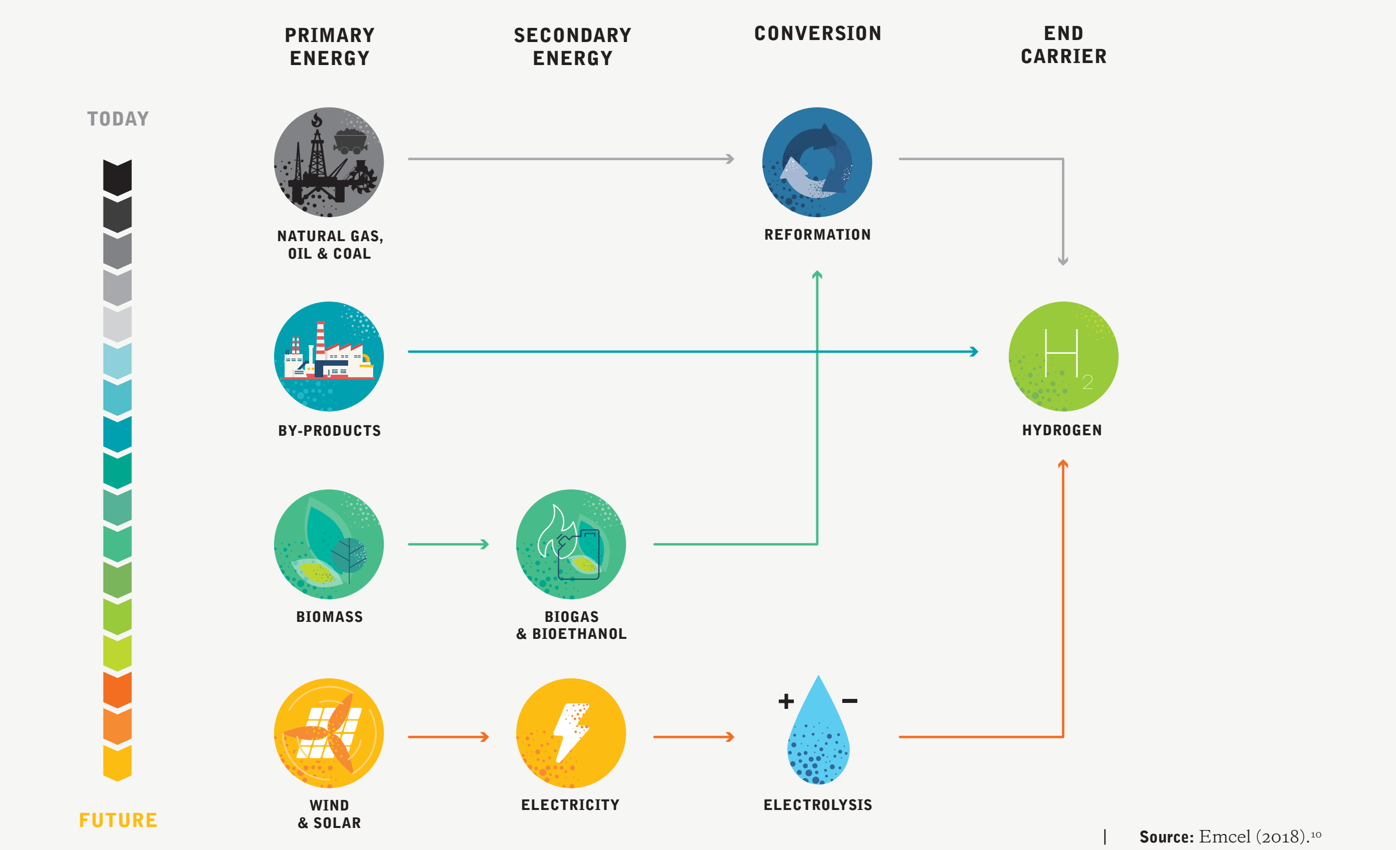
Today, most of the world's hydrogen is still produced through carbon intensive processes. In 2020, the main processes for hydrogen production were based on natural gas/methane (48%), oil (30%) and coal (18%).

Production methods for Hydrogen

Hydrogen (H_2) does not exist in nature, but can be produced via gasification, steam methane reforming (SMR) and electrolysis (Figure 3).

- **Gasification:** Traditionally, hydrogen has been produced through gasification of coal or oil. This method was developed in the mid 1800's, and until the early 1900s hydrogen, produced through gasification, supplied "town gas" for heating and lighting purposes. In the gasification process, coal or oil are converted at high temperature and under high pressure to produce syngas, a mixture consisting of carbon-monoxide (CO) and hydrogen (H_2). This reaction is faster than steam reforming, which is introduced next, however costs are higher for the treatment of syngas to separate the hydrogen (syngas cleaning).
- **Steam Methane Reforming:** Another method to produce hydrogen is via steam methane reforming (SMR), in this production process high-temperature steam (up to 1000°C) is used to produce hydrogen from a methane source, such as natural gas. The high temperature steam separates methane and water (steam) into hydrogen (H_2) and carbon monoxide (CO), also known as syngas. The first two processes are highly carbon-intensive depending on the feedstock and conversion efficiency.
- **Electrolysis:** The future of hydrogen production is via electrolysis (a chemical process) and powered by electricity. Electricity can be supplied by various energy sources including fossil fuels, such as natural gas, oil and coal or by renewable energy including solar PV, wind and bioenergy. To ensure the decarbonisation of hydrogen production, the electrolysis must be powered by renewable energy sources. This pathway is described as green hydrogen.

Figure 3: Existing and future methods of hydrogen production

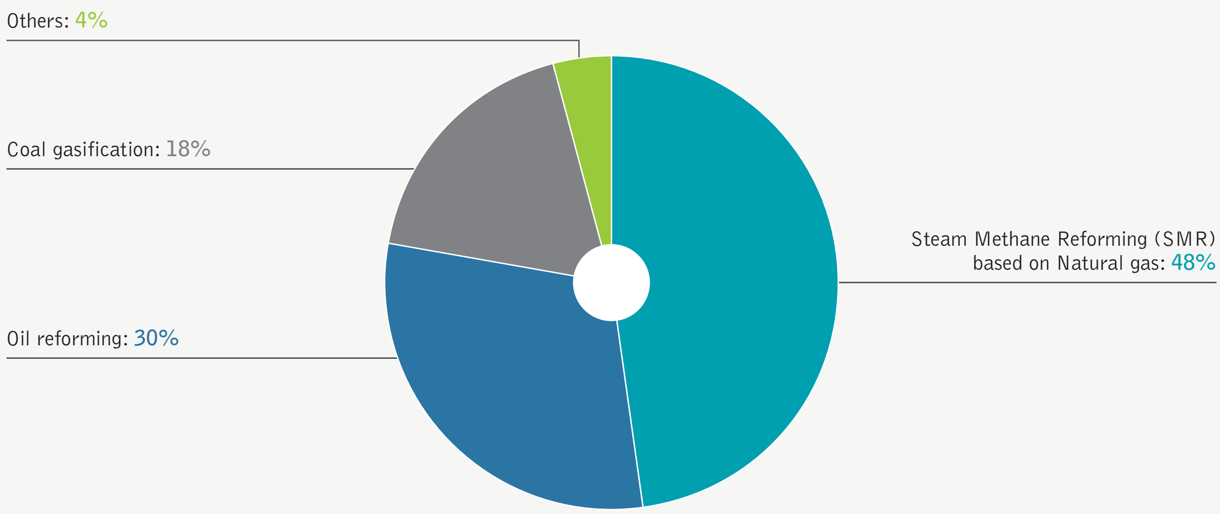


Source: Emcel (2018).[10]

Hydrogen: The basics continued

Today, most of the world's hydrogen is still produced through carbon intensive processes. In 2020, the main processes for hydrogen production were based on natural gas/methane (48%), oil (30%) and coal (18%) (Nikolaidis & Poullikkas, 2017; see Figure 4).

Figure 4: Current methods of global Hydrogen (H_2) production, 2020



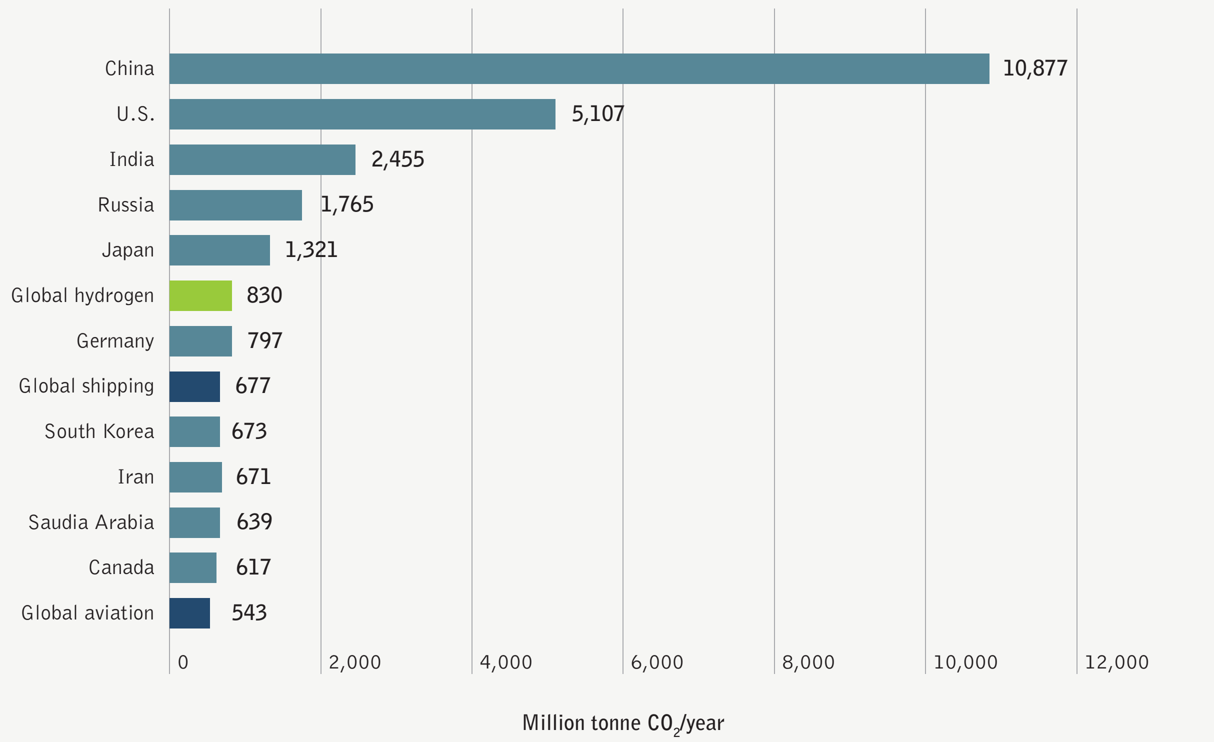
Data: based on Nikolaidis & Poullikkas (2017).[11]

In 2017, hydrogen production was responsible for 830 Mega tonnes of GHG emissions, which is equivalent to the CO_2 emissions of the United Kingdom and Indonesia combined.

Considering the large share of fossil fuels used for hydrogen production, the process is extremely carbon intensive. Coal gasification is the most carbon intensive path, with an emission factor of around 675 grams of CO_2 per kilowatt of hydrogen, which is twice as carbon intensive as Steam Methane Reforming (285 grams of CO_2 per kilowatt-hour (kWh) (Committee on Climate Change, 2018).[12]

According to the IEA report on The Future of Hydrogen, 6% of global natural gas and 2% of global coal were used to produce hydrogen in 2019. As a result, hydrogen production was responsible for 830 Mega tonnes (Mt) of GHG emissions in 2017 (Figure 5, blue bar), which is equivalent to the CO_2 emissions of the United Kingdom and Indonesia combined (IEA 2019),[13] and from a single country perspective it is equivalent to the annual GHG emissions emitted by Germany (Figure 5).

Figure 5: CO_2 emission by country and sector from hydrogen production (Mt CO_2/ year), 2017



Source: WoodMacKenzie (2019).[14]

Hydrogen: The basics continued

In this context, carbon capture and storage (CCS) is discussed as a possible opportunity to mitigate CO_2 emissions in these processes. The fossil fuel industry considers CCS as an important process to establish a fossil fuel-based hydrogen industry. The main argument is that a renewable hydrogen industry will follow at a later point in time. The Australia Institute (2022, 2019) cautions that this approach is likely to lock in high carbon infrastructure and undermine the renewable hydrogen opportunity.[15,16] For example, hydrogen made from fossil fuel methods and electrolysis use different processes and require different infrastructure. Furthermore, fossil fuel-based hydrogen requires proximity to fossil fuel sources and carbon storage sites whereas renewable hydrogen requires proximity to water and renewable energy sources. In addition, CCS technology is far from commercial maturity and in addition faces many social acceptance issues.

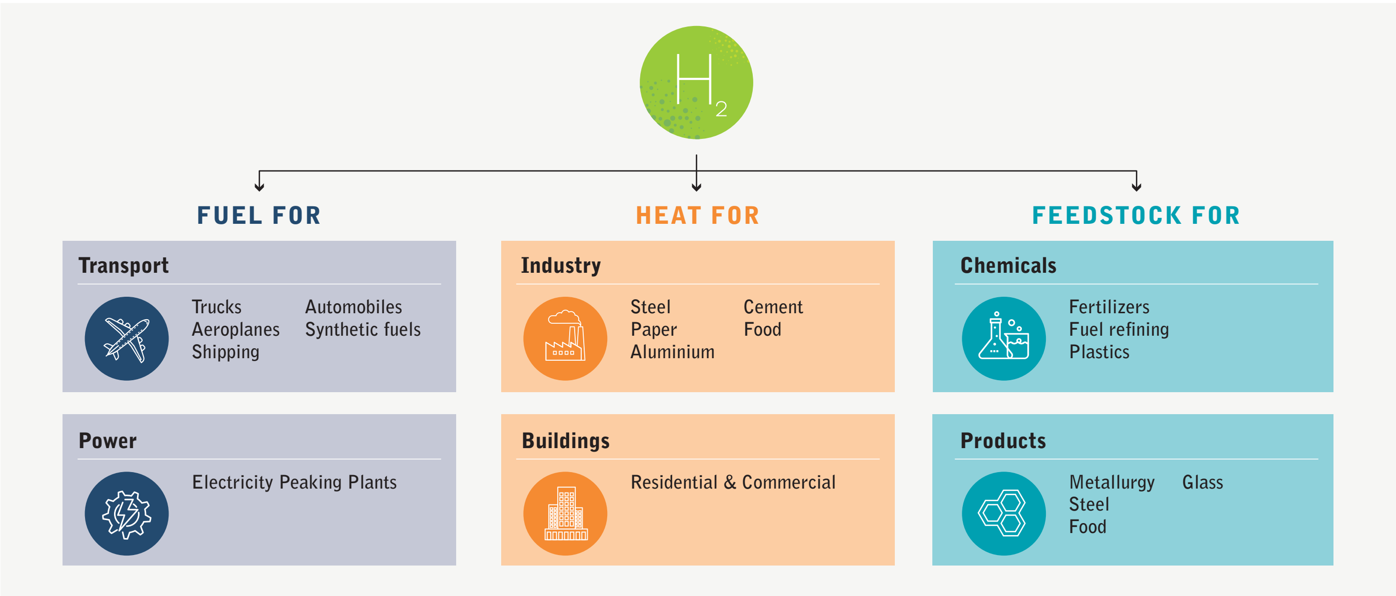
The only viable and desirable production route is renewable hydrogen ("green") – only in this case it is a zero emissions technology and an actual climate solution. Currently, only 0.1% of global hydrogen production is produced with water electrolysis[2]. For all other "coloured" cases, production involves coal and gas and so continues to create demand for fossil fuels, which are the largest contributor to GHG emissions and thus climate change. Consequently, our report focuses on renewable hydrogen as the only climate friendly solution of this technology and therefore does not use the "colour code" for the different production forms. In this report we simply use the terms 'renewable' hydrogen and 'fossil' hydrogen. For hydrogen to contribute to climate neutrality, it needs to achieve a far larger scale and its production must become fully decarbonised.

Hydrogen use, industry applications, and projected future demand

Hydrogen can be used as a feedstock, a fuel or an energy carrier and as a storage medium, it has many possible applications across industry, energy utilities, and the transport and building sector (Figure 6).

The agricultural sector and the chemical industry are the main areas which take up most of the global hydrogen market.

Figure 6: Areas of application for hydrogen



Source: BNEF (2020).[17]

The agricultural sector and the chemical industry are the main areas which take up most of the global hydrogen market. In 2018, an estimated 43% of the global hydrogen demand was used for Ammonia production and 52% for refining processes.

In 2018, an estimated 43% of the global hydrogen demand was used for Ammonia production and 52% for refining processes (Figure 7; IEA, 2019).

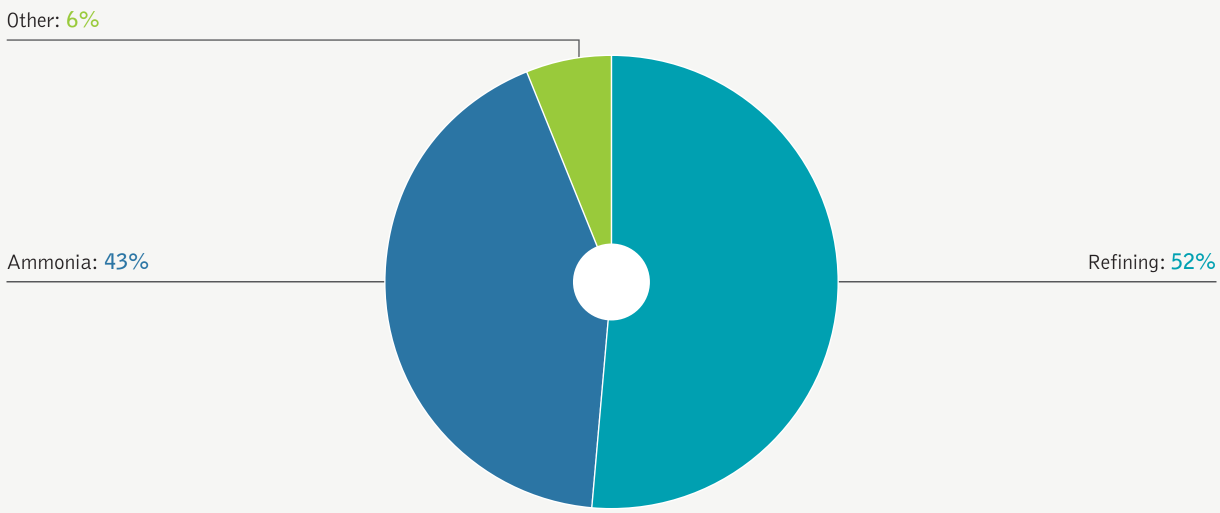
For Ammonia production, hydrogen is one of two main components. Globally, 90 percent of Ammonia produced is used for fertiliser production,[19] the remainder is used in refining processes and in the production of cleaning products. Refineries use hydrogen to lower the sulphur content of diesel fuel. The remaining 6% of global hydrogen production are distributed across other applications, including metal manufacturing and food processing (Table 1).

Table 1: Applications of hydrogen by Sector

Industry sector	Key applications for hydrogen
Chemical	Feedstock for chemicals, Ammonia, Polymers, Resins
Refining	Hydrocracking, Hydrotreating
Iron & Steel	Annealing, Blanketing gas, Forming gas, Reduction gas
General Industry	Semiconductors, Propellant fuel, Glass production, Hydrogenation of fats (liquid vegetable oils made creamy), Cooling of generation

Source: IRENA based on FCH JU (2016, p.14).[20]

Figure 7: Global demand for pure hydrogen, 2018, estimated (IEA 2019)



Data: IEA (2019).[18]

Hydrogen: The basics continued

The demand for hydrogen has grown constantly over the past decades (Figure 8), however the market shares for hydrogen demand in the applications of Ammonia production and refinery processes remained similar.

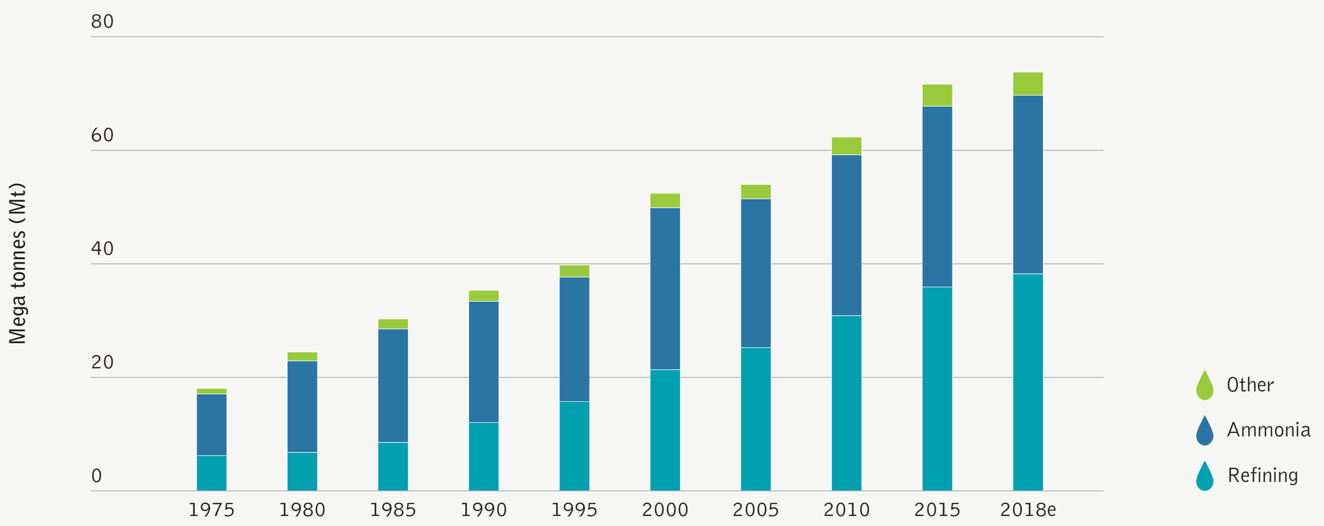
The FAO confirms the steady increase of global ammonia supply from 2016 to 2022 and the increasing global demand for fertilisers over the same period.[22] Projected population growth will further stress food security in developing nations (UN, 2021).[23] According to the United Nations Department of Economic and Social Affairs, there are several measures to improve food security, including the reduction of food waste and a fairer global distribution of agricultural products.[24] However, trends in population growth will likely increase the demand for agricultural products and the use of synthetic fertilisers. The department also mentions the environmental impacts of nitrogen and phosphorus applications. Overall, there must be a shift towards food products with lower GHG emissions, such as plant-based products, which have lower GHG emissions than dairy and meat products. One exception is rice production, which has the highest GHG emissions of the plant-based products due to methane release in rice paddies (Clune et al., 2017).[25]

Meeting future global ammonia demand and ensuring a reduction of GHG emissions during ammonia production is needed to increase food production without rising emissions. There are examples of scientific efforts and success stories to produce green ammonia using renewable electricity as a power source (Text box 1).

Global hydrogen demand and what that could mean for global GHG emission reductions

While there is a huge diversity of market projections and possible future application for hydrogen, there is a broad consensus of all market analysts that the market for hydrogen is expected to grow significantly over the coming decade. Besides the current applications as a feedstock (see Text box 1) – mainly to produce ammonia and as a technical gas for fossil fuel refineries, hydrogen is expected to expand in the energy sector.

Figure 8: Global demand for pure hydrogen, 1975-2018



Data: IEA (2019).[21] **Note:** Hydrogen for energy storage is not reflected in the global statistic.

Other potential applications for hydrogen are clearly in the emission-intensive metal-working and heavy industry, transport (particularly in long-distance freight transport), and in the building sector (heating). An important new industry sector for hydrogen is the steel industry.

Once electricity has been generated and used to produce hydrogen, it can store energy in form of a gas or (pressurised) liquid and replace fossil and/or biofuels in power plants (including fuel cells), cogeneration or heating plants to generate electricity, heat or as a transport fuel for vehicles. Figure 1 and 3 show possible applications for hydrogen in the future.

Other potential applications for hydrogen are clearly in the emission-intensive metal-working and heavy industry, transport (particularly in long-distance freight transport), and in the building sector (heating). An important new industry sector for hydrogen is the steel industry (Figure 6). Based on current knowledge, the use of hydrogen for steel production is the preferred possibility to decarbonise steel.[26]

Hydrogen can be used as a storage medium. This property of hydrogen is particularly useful to capture excess electricity, store it, and use it when it's needed. Green hydrogen, similar to gas power plants, which operate during times of high electricity demand (peak times), could be used to fuel peaking plants. The series of processes involved in producing renewable hydrogen via electrolysers powered by renewable electricity (solar, wind), and then use the renewable hydrogen to produce electricity, reduces the efficiency of this process to below 40%. This means for every 10kWh of wind or solar energy required, the overall output provides less than 4kWh of electricity (Recharge, 2021).[27] While the idea of hydrogen power plants fuelled by renewable energy seems inefficient and wasteful, the ability to store energy is important. According to the Siemens Energy hydrogen team *"if you really want to [store power] for days, weeks, months, or for seasonal storage — which is using solar power from the summer in winter, or wind power from the autumn to the summer — you need to store electricity in a chemical way"* (Recharge, 2021).

At this point of the energy transition, i.e. after the phase out of nuclear power plants, coal-fired power plants and the expected reduction of natural gas use in Europe as a result of the Russian war on Ukraine (see Section 2.2), the energy industry is interested in investing in future-proof infrastructure. A safe investment involves natural gas infrastructure, including the conversion of existing and retrofitting of new gas-fired power plants which will be compatible with the burning of renewable hydrogen (Recharge, 2021).

In terms of reducing GHG emissions, the energy sector and other stakeholders involved in hydrogen production consider the legislation to be crucial to *"...enforce the switch [from natural gas to renewable hydrogen], whether it's through subsidies or CO_2 taxes, or higher CO_2 certificate prices, or by limiting emissions or whatever. It will come sooner or later"* (Recharge, 2021).

Box 1

Developments in Low-Carbon Ammonia Production

Worldwide, 90 percent of ammonia production is used for fertiliser production. Ammonia is produced in large chemical plants using the Haber-Bosch-process, which was developed in the early 20th century in Germany.

The Haber-Bosch process can be described as an artificial nitrogen fixation process using thermochemical equipment. It combines nitrogen (N_2), which occurs naturally in the air we breathe (separated from air via cryogenic air separation), and hydrogen (H_2) produced via the Steam Methane Reforming process, to produce ammonia (NH_3) at high temperatures and pressures. Considering the substantial resources demanded for ammonia, its production is responsible for 2% of global GHG emissions.

Scientific efforts have focused on reducing the carbon emissions associated with the production of synthetic chemicals such as ammonia-based fertilisers. Main challenges for its decarbonisation, i.e. using renewable energy to fuel the Haber-Bosch process is the fossil-fuel based hydrogen used as a feedstock and the required high process temperatures and pressures.

There are scientific efforts towards low temperature and pressure production of ammonia (MacFarlane,2021), however these technologies are not expected to reach maturity before 2040. A more mature solution to decarbonise ammonia production is to replace the feedstock of fossil-fuel based H_2 with green H_2, produced from renewable energy with water electrolysis. There are already ammonia plants that use hydrogen from water electrolysis indicating the high maturity of the technology.

Source: MacFarlane, Doug (2021) Breakthrough brings green ammonia production closer to reality. LENS, Monash University. 29 November 2021. url: https://lens.monash.edu/@science/2021/11/29/1383516/breakthrough-brings-green-ammonia-production-closer-to-reality

Hydrogen: The basics continued

2.2
The Economics of hydrogen

Low-cost hydrogen is required to commercialise production methods of renewable hydrogen for industrial applications. According to Bloomberg New Energy Finance in early 2022, the cost of renewable hydrogen is determined by several developments, including

i) the development of the cost curve for electrolysers,

ii) the total investment costs into hydrogen projects,

iii) hydrogen policy and the availability of government subsidies

iv) the uptake by heavy industry and the transport sector (BNEF, 2022)[28]

v) the price of renewable electricity to operate electrolysers

The trends in the clean hydrogen sector, and in particular the renewable hydrogen market, can be compared to the development of other clean energy technologies, such as solar PV. In 2020, the global market value of hydrogen was estimated at US$ 147.67 billion,[29] in comparison the global solar photovoltaic market value in the same year was US$ 154.47 billion.[30]

In 2017, investments in electrolysers, the core technology to produce renewable hydrogen, was only around 10% of the total market value. This, however, is expected to change, global investments in electrolysers is expected to quadruple in 2022, it is expected that the market will be dominated by China (BNEF, 2022).

Another key aspect that determines the production costs of hydrogen, is the price of electricity to operate the electrolysers. Electricity can be generated by fossil fuels, including gas, or renewable energy such as solar PV and wind. Text box 2 summaries the main aspects driving the hydrogen economy.

Section C in the Appendix provides more detailed information of predictions of future hydrogen prices.

Hydrogen energy storage container units with solar panels and wind turbine. © petrmalinak

Box 2

Effects on the cost developments of Hydrogen

There are three main aspects that effect hydrogen costs developments: overall investment, utilisation, and electricity costs.

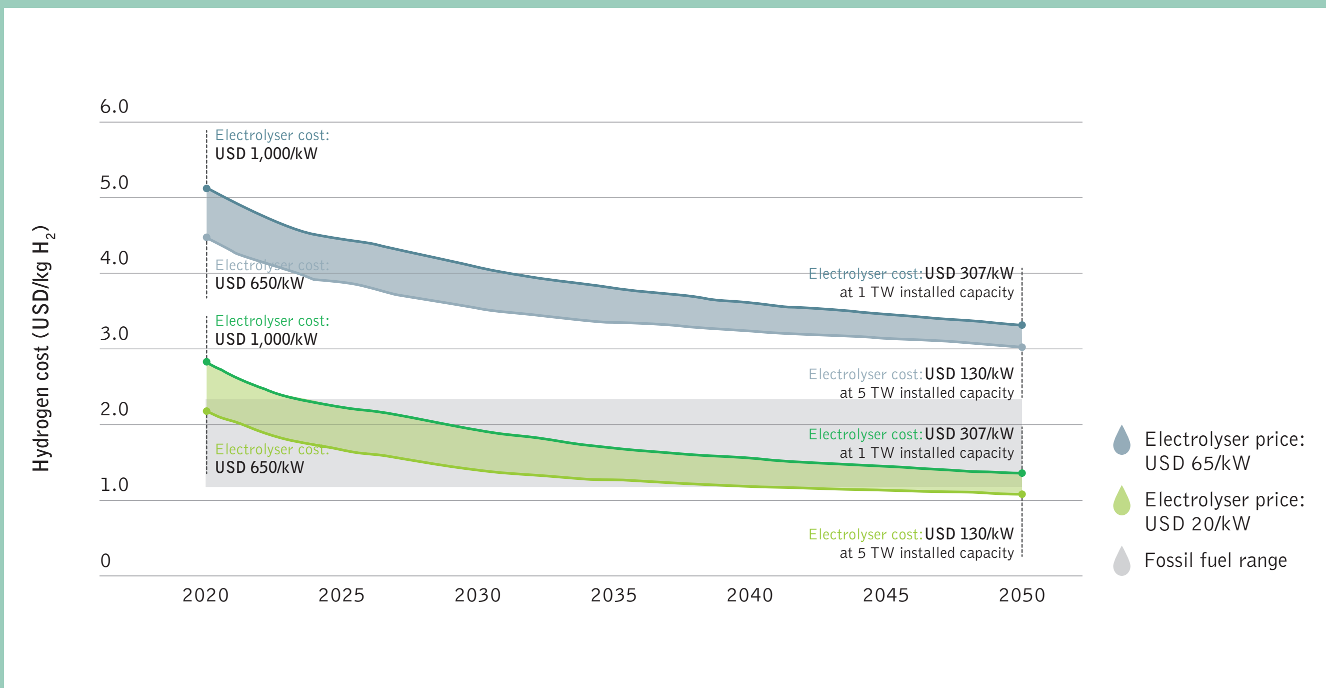
First, the investment costs for electrolysers differ among different technologies and are determined by political strategies. In 2020, IRENA set cost reduction targets to bring costs below US$100 per kW for the stack and below US$ 200 per kW for the system by 2050.

Second, another parameter to reduce the production costs for each unit of hydrogen are the operating hours per year. The higher the annual utilisation, the lower the hydrogen production costs. Thus, hydrogen production with 'surplus' electricity from wind or solar farms will lead to high costs and battery storage will most likely be more economic. Therefore, electrolysers must be largely dedicated to hydrogen production as a fuel and not only as a short-term storage technology.

Third, the actual electricity price per unit to operate the electrolyser is significant. Figure 9 shows the production costs for one kg of hydrogen in relation to the electrolyser costs per kilowatt. The figure shows the calculated production cost with a US$ 200 electrolyser system and three different electricity prices: US$ 40, US$ 20 and US$ per megawatt-hour (MWh). The dashed lines indicate the costs for fossil hydrogen.

Electrolysers must be at US$ 20 per MWh and electrolyser costs must be at least halved – below US$ 300 per kW – to be competitive with fossil fuels (without carbon pricing).

Figure 9: Cost of green hydrogen production as a function of electrolyser deployment



Note: on the IRENA analysis: The analysis is based on an average (USD 65/MWh) and a low (USD 20/MWh) electricity price, constant over the period 2020-2050 (IRENA, 2020). Efficiency at nominal capacity is 65%, with a LHV of 51.2 kilowatt hour/kilogram of hydrogen (kWh/kg H_2) in 2020 and 76% (at an LHV of 43.8 kWh/kg H2) in 2050, a discount rate of 8% and a stack lifetime of 80 000 hours. The electrolyser investment cost for 2020 is USD 650-1000/kW. Electrolyser costs reach USD 130-307/kW because of 1-5 TW of capacity being deployed by 2050. **Source:** IRENA (2020), Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5°C Climate Goal, International Renewable Energy Agency, Abu Dhabi. https://irena.org/-/media/Files/IRENA/Agency/Publication/2020/Dec/IRENA_Green_hydrogen_cost_2020.pdf

Hydrogen: The basics continued

Current political environment supporting renewable hydrogen and makes it a viable technology

Political momentum for hydrogen has built up in the last 2 to 3 years since commercialising renewable hydrogen has enormous potential for GHG emission reductions due to its broad industrial applications.

According to the IEA (2019),[31] it is both the breadth of possibilities for renewable hydrogen use being discussed and the depth of political enthusiasm for those possibilities around the world. This mainly refers to the rapid cost decline of renewable energy, technological developments, and the urgency to drastically reduce greenhouse emissions. IEA (2020)[32] finds that the current level of attention has opened a genuine window of opportunity for policy and private-sector action. Indeed, a coalition of voices in favour of renewable hydrogen includes renewable electricity suppliers, industrial gas producers, electricity and gas utilities, automakers, oil and gas companies, major engineering firms and the governments of most of the world's largest economies. It also includes those who use, or could use, renewable hydrogen as a feedstock for industrial production, not only energy.

The number of countries with polices that directly support investment in hydrogen technologies is increasing, along with the number of sectors they target. Globally, about 50 targets, mandates and policy incentives were in place by mid-2019, to directly support hydrogen (IEA 2019).

Between November 2019 and March 2020, market analysts increased the list of planned global investments from 3.2 GW to 8.2 GW of electrolysers by 2030 (of which 57% in Europe). The number of companies joining the International Hydrogen Council has grown from 13 in 2017 to more than 90 today.

The dominant drivers for hydrogen production are national climate targets in the context of achieving the international commitment of the Paris Agreement to keeping global average temperature rise well below 2°C and 1.5°C (degree Celsius) above pre-industrialised levels.[33] The focus lies on reducing emissions in hard-to-abate sectors including aviation, shipping, iron and steel production, chemicals manufacture, high-temperature industrial heat, long-distance and long-haul road transport and, especially in dense urban environments or off-grid, heat for buildings. The technology can enable what is called "sector coupling", the direct and indirect integration of renewable electricity into processes that so far depend on fossil fuels. Hence renewable hydrogen can play an important role in the energy transition and support the phase out of fossil fuels in various industries.

Cost reduction of renewable energy is seen as another driver for hydrogen deployment, making the still expensive technology (slowly and in long term) more competitive. A Bloomberg study (BNEF 2020) finds that the cost of the electrolyser technology has fallen by 40% in the last five years and can continue to slide if deployment increases. Despite this development, the cost of the technology is still high.

Further, some countries are also driven by the aspiration of leadership, technical expertise and new jobs in these areas, particularly when they reinforce existing skills and capacities. In 2018, one study estimated that hydrogen exports could contribute USD 1.2 billion and provide 2,800 jobs in Australia by 2030 (Commonwealth of Australia, 2018).

Hydrogen has some characteristics that are seen as advantageous for the future energy market. It can be transported relatively easily, for instance in pipelines, and could therefore use existing natural gas transport systems. It can be stored, adding to energy security and to manage variable power generation.

Global energy policy and crisis – Responses to the Russian war on Ukraine

While the world is still (re)emerging from the 2008 financial crisis and the COVID-19 pandemic shocks, global energy policy continues to be driven by the growing demand for a global energy transition to achieve net zero emissions by mid-century. However, this "global" policy must take into consideration challenges related to economic inequality between the global north and south, and challenges resulting from conflict, i.e. the Russian war on the Ukraine. The world is clearly divided in terms of economic development and consequently, the share and responsibility of GHG emissions. Globally, 81 countries, which are home to about half of the world's population, are experiencing energy poverty. Their collective GHG emission contributions amount to 8% of global carbon emissions since the industrial revolution. Without a global approach to supporting energy transitions and securing energy security it is unlikely that global climate targets will be met.

Is EU's attempt to restore energy security in line with Net Zero targets?

In January 2022, Bloomberg New Energy Finance projected that renewable hydrogen will dominate the hydrogen market, while blue hydrogen, produced from natural gas with carbon capture and storage, will remain a strong player despite its high costs, when supported by government subsidies (BNEF, 2022).[34] This prediction might change completely in the light of Russia's invasion of the Ukraine which began in late February 2022.

At the time of writing, the invasion of the Ukraine by Russia has escalated into a war. The two nations are key players in the European gas import market. In 2021, the EU imported 90% of its gas supplies. Of those, 45% of natural gas imports into the European Union were

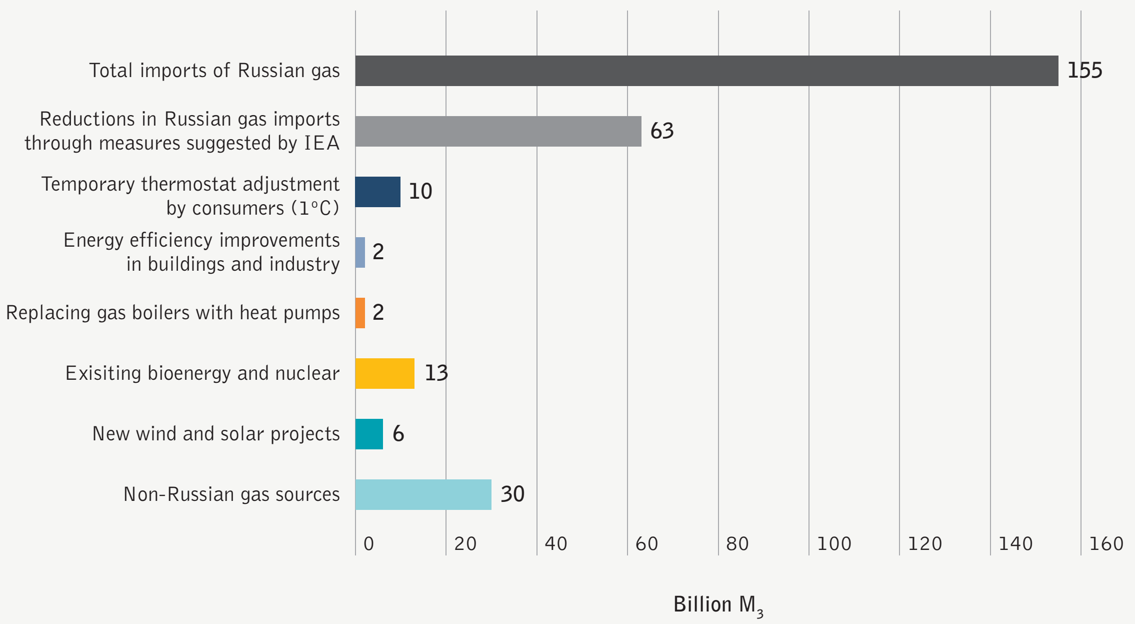
The EU aims to reduce fossil fuel gases by 30% until 2030, as a result hydrogen production and imports will play a larger role. Russian gas will be replaced by 10 mega tonnes of imported hydrogen and 5 mt of domestic hydrogen (EC, 2022).

supplied by Russia, accounting for 40% of the EU's total gas consumption (IEA, 2022).[35] In terms of volume, Europe imports 150 billion cubic meters (bcm) of natural gas in addition to 14-18 bcm of LNG from Russia every year (BNEF 2022, Figure 10). Nord Stream 1 is the main gas pipeline transporting natural gas from Russia via the Baltic Sea to Europe/Germany, the pipeline has a capacity to transport 55 bcm of gas a year (Nord Stream, 2022a).[36] A second gas pipeline, Nord Stream 2, was completed in September 2021, due to the current crisis outstanding certification processes are currently frozen (Reuters, 2022).[37] In March 2022, Nord Stream confirmed that operations, i.e. gas transport, is currently ongoing (Nord Stream, 2022b).[38]

The invasion of the Ukraine by Russia triggered the European Union to revise its energy security strategy and consequently end its reliance on Russian gas imports. On 8 March, the European Commission presented REPowerEU, a plan to completely phase out Russian gas well before 2030 by diversifying energy supply and drawing on new sources for gas imports (EC, 2022).[39] By the end of 2022, the EU aims to phase out two thirds of Russian gas imports equivalent to 100 bcm, a major step in ending the Union's "overdependence on a single supplier" (EC, 2022).

Further restrictions on energy imports have been following in April 2022, including sanctions on Russian coal (Reuter, 2022).[40] The share of Russian coal imports in terms of percentage value is similar to gas imports i.e. 45% of total coal imports. Reuter (2022) states that Colombia, the US, and potentially Australia are among those new countries considered for coal trade, overall alternatives exist, but come with a higher price tag. European energy costs are expected to increase and so is coal mining in the EU (Reuter, 2022). The IEA released a 10-point plan to reduce the EU's reliance on Russian gas by 50% within year. The plan outlines replacement energy sources and technologies in addition to energy efficiency measures (Figure 10).

Figure 10: Options to reduce the European Union's reliance on Russian natural gas within a year, in billion cubic meters, March 2022



Source: based on IEA (2022) data.[41]

Hydrogen: The basics continued

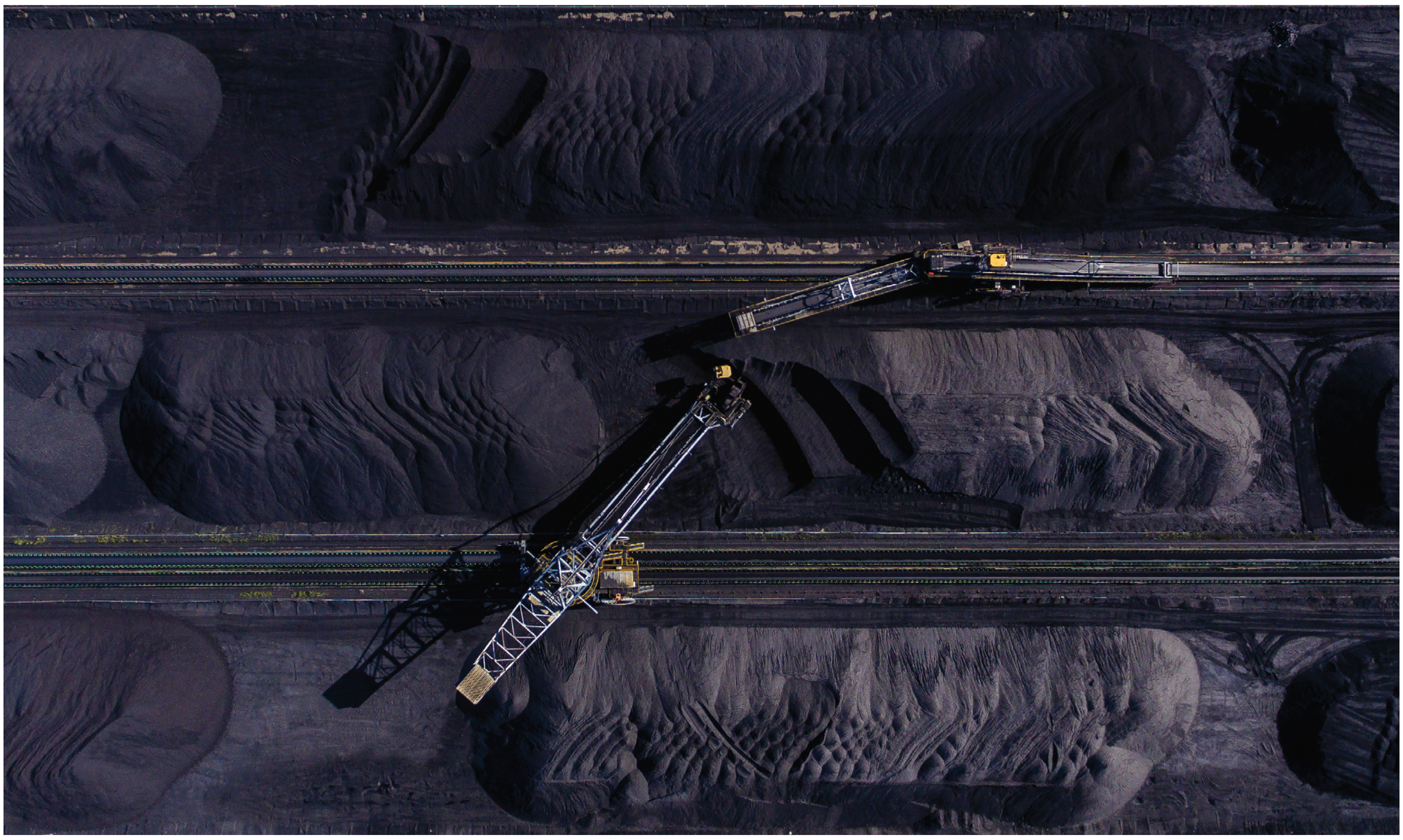
Opportunities and risks related to the large-scale gas phase out

The announcement entails various opportunities to accelerate the transition to net zero by 2050, the EU aims to reduce fossil fuel gases by 30% until 2030, as a result hydrogen production and imports will play a larger role. Russian gas will be replaced by 10 mega tonnes (mt) of imported hydrogen and 5 mt of domestic hydrogen (EC, 2022).

There is a risk of increasing the shares of coal and nuclear energy in electricity generation and delaying planned phase outs of both energy sources, coal and nuclear. Germany had planned to phase out coal by 2038 and nuclear energy by 2022.[42] Several EU member states, including Czechia, Bulgaria, Romania, Italy and Germany, have already indicated delays related to coal phase outs.[43]

Another risk concerns the extraction methods used for replacing Russian gas by new sources. The US is expected to increase its share of gas imports into the EU gradually, an initial agreement between the EU and the US, plans for the US to cover 15 bcm of gas imports by the end of 2022, which covers only a small fraction of imported gas (BNEF 2022).[44] More than 40% of natural gas is extracted in the US states of Texas and Pennsylvania, in these inland states, gas is extracted from shale, often referred to dry natural gas.[45] The drilling for and production of shale gas, also known as fracking, has major environmental impacts on water, soil and air quality.[46] Studies have shown that fracking, predominately undertaken in the US, has been responsible for a spike in atmospheric methane concentrations since the start of the fracking boom in 2008.[47]

Coal being loaded for export, Nakhodka bay, Russia.
© Alexander Khitrov



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Hydrogen
H_2
H_2 HYDROGEN
CLEAN ENERGY

Hydrogen energy production.
© Audio und werbung

03

The role of renewable hydrogen in climate mitigation pathways

Scenario studies cannot predict the future, but they can describe what is needed for a successful pathway in terms of technology implementation and investments. Scenarios also help us to explore the possible effects of transition processes, such as supply costs and emissions. The energy demand and supply scenarios in this study are based on information about current energy structures and today's knowledge of energy resources and the costs involved in deploying them. As far as possible, we also take into account potential regional constraints and preferences.

Section D in the Appendix provides detailed information on the future role of hydrogen in energy scenarios, and includes models from the IEA and universities, it also provides detailed information on sector specific scenarios based on the One Earth Climate Model (OECM) developed by the Institute for Sustainable Futures at the University of Technology Sydney, outlined in the next section.

The role of renewable hydrogen in climate mitigation pathways continued

3.1 The use of renewable hydrogen under a 1.5°C climate scenario

This study explores the future applications of renewable hydrogen until 2050 using the One Earth Climate Model (OECM), this model is compatible with the Paris Climate Agreement of limiting global warming to 1.5°C. The OECM is solely based on 100% renewable energy and includes wind, solar PV, hydro power, bio and geothermal energy, concentrated solar power (CSP) and renewable hydrogen. In comparison to other models and scenarios, the OECM does not support hydrogen produced from fossil fuels or fossil gas at any point in time until 2050. In the OECM model, renewable hydrogen is primarily used as an energy storage medium rather than a direct power source. The following section outlines the use of renewable hydrogen in energy intensive sectors until 2050 under 1.5°C global warming scenario.

Power sector

The production of renewable hydrogen requires large amounts of renewable electricity to operate the electrolyser. Only 5% of global electricity will be generated from hydrogen to reduce its application in power generation.

Transport sector

Hydrogen plays a minor role in road transport, while synthetic fuels are vital for aviation and shipping.

- In road transport, hydrogen and synthetic fuels are mainly used for heavy duty vehicles (freight, public transport). Passenger transport will be dominated by EVs with battery storage, hydrogen plays a small role.
- Rail transport will be fully electrified by 2050, synthetic fuels are only considered for remote trains to replace diesel.
- In aviation, synthetic fuels play a significant role in replacing fossil fuels. By 2050, synthetic fuels provide 50% of fuel supply, the other half is covered by bio kerosene.
- In the shipping industry, synthetic fuels replace 50% of diesel and heavy fuel oil and the other half is fuelled by bio diesel.

Overall, synthetic fuels and hydrogen will supply 35% of all transport energy needs, the remaining transport energy for road and rail will be electrified and complemented with battery storage.

Industry sector

There are challenges to decarbonise the heavy industry sector, typically black coal and natural gas is used to provide high temperatures in the metal working industry. There is a particularly strong dependence on fossil fuels in steel making, which makes the steel sector an emission intensive sector, responsible for 8% of global GHG emissions.[48] For most industry sectors, including the aluminium and cement industry, electrification of processes is an option. As a result, the application of hydrogen will be limited to the steel sector, hydrogen use in industry will increase to 4% of total hydrogen in 2050.

Building sector

The building sector includes residential housing and commercial buildings. The sector has a huge potential for electrification, gas heating can be replaced by heat pumps and hot water heating can be electrified. The use of renewable hydrogen will be limited to large commercial spaces and facilities including airports or shopping centres. By 2050, hydrogen will supply only 1% of total electricity used in the building sector.

Bunker fuels

Bunker fuels describe fuels used in international aviation and shipping (see Text box 3 for more details). The decarbonisation of bunker fuels is crucial to reduce global emissions. In the OECM scenarios, bunker fuels are replaced by synthetic fuels and biofuels (Table 9 in Appendix).

In the 2.0°C scenario, the production of syn and biofuels is assumed to take place in three world regions: Africa, the Middle East, and OECD Pacific (especially Australia), where synfuel generation for export is expected to be the most economic option.

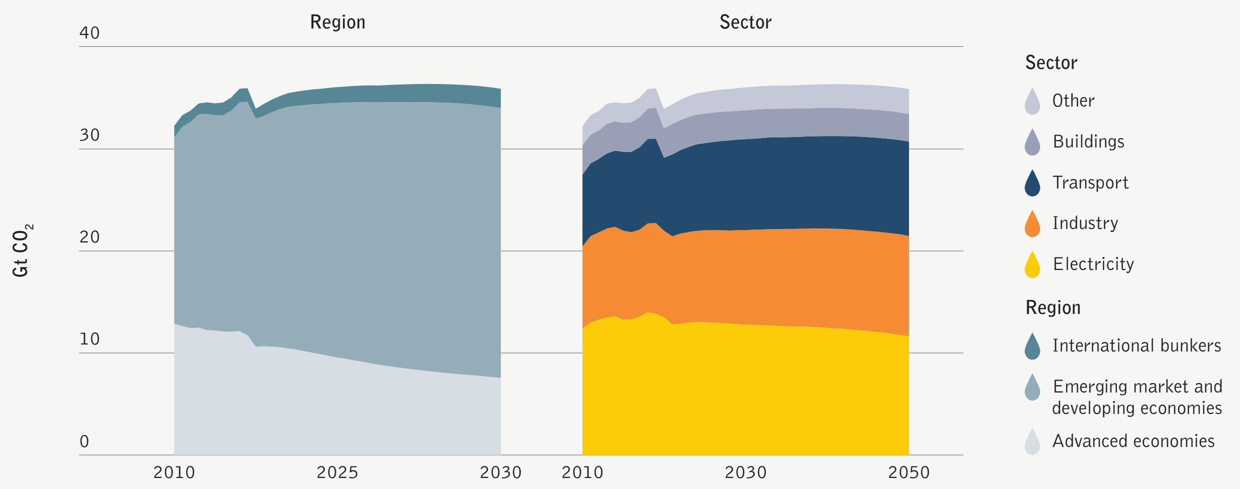
In the 1.5°C scenario, the biomass consumption for energy supply is limited and will decrease in the long term, whereas power-to-liquid will continue to increase as the main fuel option for international aviation and navigation (Table 9 in Appendix).

Box 3

What are Bunker fuels and why are they relevant for reducing global GHG emissions?

Bunker fuels describe any fuel used on board a ship (McKinsey, 2022) or on board an international airplane. Considering energy data is collected and assessed on a regional level, fuels used in international airspace and waters, cannot be allocated to a particular region, and therefore form a separate category named bunker fuels. Between 2009 and 2015, bunker fuel consumption increased by 13%. During the COVID-19 pandemic, the demand for bunker fuels showed their largest annual decline. In 2020, demand for jet fuel and kerosene used in aviation dropped by 41% and oil demand for shipping was reduced by 8% (IEA, 2021a). Although, demand in aviation is only recovering slowly in 2021, bunker fuels are expected to increase until 2050, contributing to an increase in global GHG emissions and increased global warming. According to the IEA Net Zero report, by 2050, GHG emissions are reduced by one third in developed countries or advanced economies, but are outweighed by emerging markets in developing countries, causing an increase of GHG emissions by 20% until 2040 (Figure 11), which is projected to lead to a rise in global temperatures of 2.7°C in 2100 (IEA, 2021b).

Figure 11: Energy-related and industrial process CO_2 emissions by region and sector (IEA 2021b)



Note: In the illustration on the right, showing all sectors, bunker fuels are the production of synthetic fuels will lead to a significant increase in electricity demand and a corresponding expansion of the renewable power-generation capacities. In addition, high amounts of electrolyser capacity and hydrogen storage are required to allow flexibility in the power system, and high utilization rates of synthetic fuel production processes. Other options for renewable synthetic fuel production are solar thermal chemical processes, which directly use high-temperature solar heat.

References: McKinsey (2022). Bunker Fuel. https://www.mckinseyenergyinsights.com/resources/refinery-reference-desk/bunker-fuel/
IEA (2021a), Global Energy Review, IEA, Paris https://www.iea.org/reports/global-energy-review-2021
IEA (2021b), Net Zero by 2050, IEA, Paris https://www.iea.org/reports/net-zero-by-2050

The role of renewable hydrogen in climate mitigation pathways continued

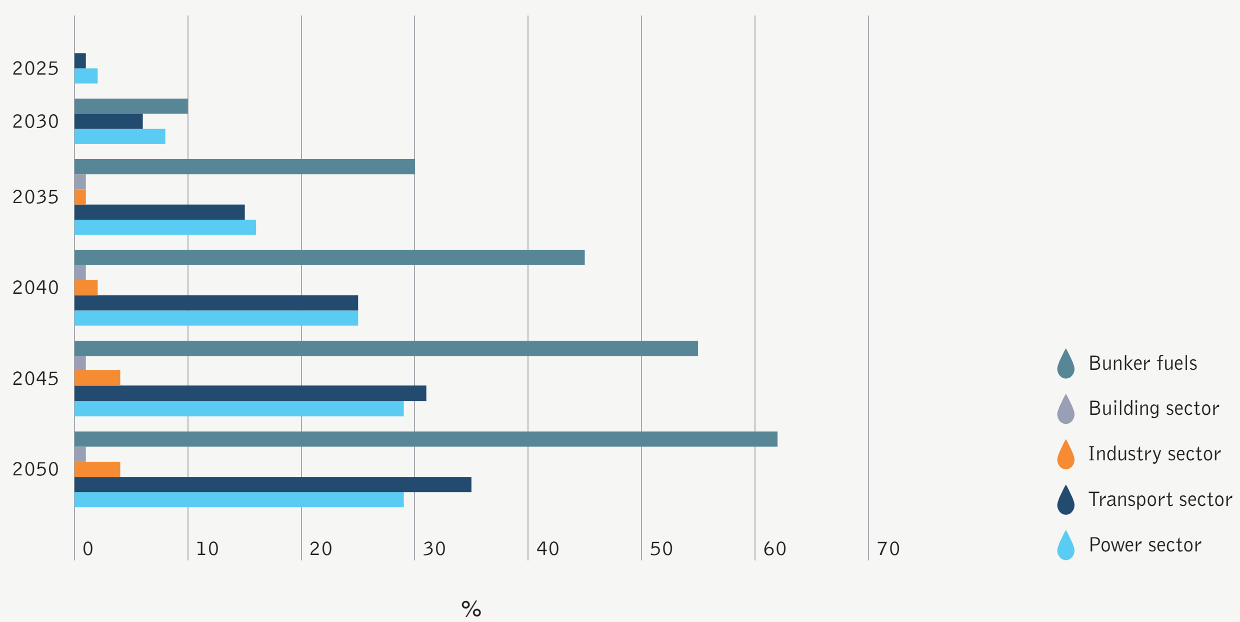
Summary of how renewable hydrogen use in different sectors can support a 1.5°C scenario

The use of hydrogen as a share of total energy per sector varies among different industrial sectors. Figure 12 summarises the development of renewable hydrogen uptake by sectors until 2050 under a 1.5°C scenario. It is shown that in the category of bunker fuels, the uptake of hydrogen is much larger than in other sectors. For bunker fuels, hydrogen uptake is crucial. Its uptake will increase gradually, from providing 10% of energy in 2030 to covering 60% of total energy demand by 2050 (Figure 12). The second largest uptake of hydrogen is expected for the transport sector, by 2035 hydrogen will cover 15% of energy demand in the transport sector and will increase to 35% by 2050 (Figure 12). The industry sector will account for the third largest uptake of hydrogen, its uptake is similar to the transport until 2040, by 2050 hydrogen will cover just under 30% of energy demand in the industry sector.

Job creation in renewable hydrogen under a 1.5°C scenario

A 2022 study estimated that worldwide direct energy jobs associated with the power, heat, transport, and desalination sectors will almost triple until 2050, and increase from about 57 million in 2020 to about 134 million by 2050 (Ram et al., 2022).[49] The article considers storage and power-to-X technologies along with renewable hydrogen and e-fuels critical components of the net zero system. New employment related to the production of hydrogen, synthetic natural gas (SNG) and Fischer-Tropsch fuels (syn fuels), will be as large as 3.6 million jobs. However, job creation in these sectors will occur in a later part of the transition, following new jobs in electrification and defossilisation (Ram et al., 2022). Although, job losses will occur in conventional energy sectors, such as coal, the number of jobs generated in the renewable energy sector is growing and will exceeds job losses in the fossil fuel export sector. Ram et al. (2022), estimate that across the MENA region, the high shares of renewables will create 6 million jobs by 2050, compared to about 4 million jobs in 2020.

Figure 12: Share of global renewable hydrogen, in %, 2025-2050, under a 1.5°C scenario



Source: OECM model outputs (ISF, 2020).

It is estimated that by 2050, new employment related to the production of hydrogen, synthetic natural gas (SNG) and Fischer-Tropsch fuels (syn fuels), will be as large as 3.6 million jobs. (Ram et al. 2022)

Engineer at a wind park.
© Mr.Cheangchai Noojuntuk

48. McKinsey, Decarbonization challenge for steel, https://www.mckinsey.com/industries/metals-and-mining/our-insights/decarbonization-challenge-for-steel

49. Ram, M., Osorio-Aravena, J. C., Aghahosseini, A., Bogdanov, D., & Breyer, C. (2022). Job creation during a climate compliant global energy transition across the power, heat, transport, and desalination sectors by 2050. Energy, 238. https://doi.org/10.1016/j.energy.2021.121690


Hydrogen
Hydrogen
H2

A hydrogen fuel cell tram.
© Scharfsinn

04

International and national hydrogen strategies

The current political environment is highly favourable of renewable hydrogen technology due to its broad application in mitigating emission intensive sectors, including the heavy industry and transport sector including synthetic fuels for aviation. Section 2.2 discussed several aspects which facilitate the accelerated uptake of hydrogen and improve its viability. The cost effectiveness of renewables in addition to the discussion around net zero and mitigating climate risks, has led to a paradigm shift in the industrial sectors, private-sector and governments. For the first time since the topics of climate change and the environmental impacts of global economic activities were first voiced in the 1970s, by the Club of Rome, renewable energy policy including renewable hydrogen strategies are considered as political priorities. Importantly, when assessing who will benefit from the opportunities of renewable hydrogen, it should be done so within an energy justice (also referred to as "energy equity") framework in mind.

This section introduces countries with strong national hydrogen strategies.

International and national hydrogen strategies continued

4.1 Germany

Hydrogen is a key component of the German decarbonisation strategy, particularly to reduce emissions in hard to abate sectors such as steel, transport and the chemical industries. In June 2020, Germany announced the National Hydrogen Strategy, which represents a key pillar in decarbonising its economy and its target "to keep global warming well below 2°C and if possible, below 1.5°C" (BMWi, 2020).[50]

Germany's energy policy has been deeply impacted by the invasion of the Ukraine by Russia in late February 2022, Section 2.2. discussed the EU's sanctions on energy imports from Russia and its implications for Europe's shift to renewable energy.

The support for hydrogen technologies has also become part of the Economic Stimulus Package to deal with the economic impacts of the COVID-19 pandemic by supporting a sustainable re-orientation of German industry. The federal government announced, it will support the emergent industry with Euro 9 billion[51] and remove hurdles with new regulations. The National Strategy highlights that fossil hydrogen will continue to play a role in the next few years and traded temporarily. However, after some debate between different ministries, only renewable hydrogen will receive government funding. The Strategy identifies steel production and transport as the key end-use sectors for renewable hydrogen (BMWi, 2020).

Since Germany's energy demand exceeds planned production capacities, the nation will rely on international cooperation projects to produce and trade hydrogen. According to the German Ministry for Economic Cooperation and Development (BMZ) "the purpose of the strategy is to foster the production of affordable climate-neutral hydrogen and to make Germany a global provider of state-of-the-art hydrogen technology. Pilot projects for the production of renewable hydrogen are to be implemented in the [ministries] partner countries ... *Green [renewable] hydrogen atlases* [will be developed and] present the potential for renewable hydrogen production in our partner countries and highlight opportunities for sustainable development in Africa" (BMZ, 2022).[52] While, Africa – as a continent – faces major challenges related to energy poverty, food poverty, waste management, environmental degradation and biodiversity loss, there are huge opportunities associated with renewable energy in facilitating Africa's path towards a 'green' economy (GermanWatch, 2022).[53]

Currently, only 5% of the 55 TWh hydrogen produced in Germany, is from renewable energy sources, the remaining 95% is produced from fossil fuels (referred to as grey hydrogen).[54] As a result the review of current hydrogen costs reflect the dominant produced methods based on fossil fuels. Production costs for renewable hydrogen average around 16.5 ct/kWh, twice as expensive as gas-based hydrogen with CCS (6.3ct/kWh) and the production costs of gas-based hydrogen without CCS are 4.5 ct/kWh (Bukold, 2020, p. 6).[55]

The German Government predicts a hydrogen demand of 91 TWh per year until 2030. Hydrogen production facilities are expected to be built by 2030,[56] planned production capacities are expected to reach 5 GW in 2030 and 50-80 in 2050, hydrogen demand is expected to reach 4-20 TWh in 2030 and increase to 250-800 TWh in 2050, see Figure 13 (dena, 2018).[57] In 2030, domestic production will only cover 15% of total hydrogen demand.

The federal government's main goal is to ensure that the additional electricity demand required for electrolysis plants does not result in an increase in CO_2 emissions.

Predictions on hydrogen demand (in TWh) and electrolysis capacity (in GW) by 2030 and 2050 for the European Union, (Figure 14) see 6-fold larger than the figures shown for Germany.

Yet, it is also acknowledged that hydrogen imports are required as Germany's renewable energy generation capacity is limited. As a result, Germany will continue energy imports from abroad.

Scheller et al. (2022) compared 12 hydrogen studies and future scenarios with GHG emission reduction targets ranging between 55-95% until 2050.[60] Overall, the study estimates the value creation effects for hydrogen-based carriers, produced domestically, are Euro 5 billion per year in 2030 and up to Euro 16 billion annually in 2050. It is estimated that synthetic fuels are imported.

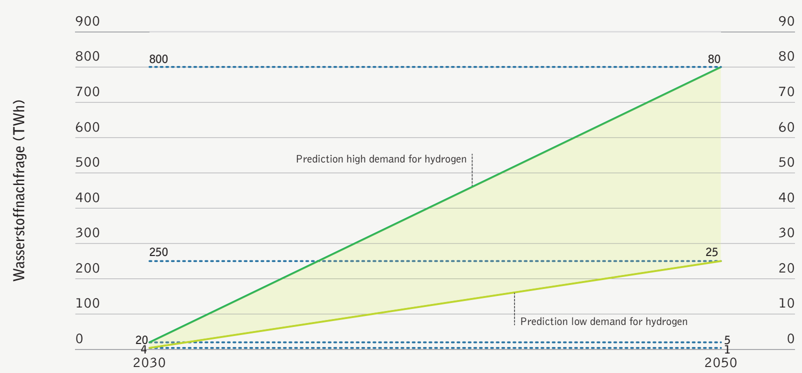
Since Germany's energy demand exceeds planned production capacities, the nation will rely on international cooperation projects to produce and trade hydrogen.

The costs of importing synthetic energy sources (and small amounts of hydrogen) are estimated in the TM95 scenario (dena 2018) for the year 2050 at Euro 77 billion. For the 95% path, the information from the study (BDI 2018, p.202)[61] can be used to derive PtX import costs in the year 2050 of around 50 billion Euros. In scenario 95 developed by Forschungszentrum Jülich, the import costs in 2050 are only around 40 billion Euros (FZ Jülich 2020, p.23)[62] – compared to the other two scenarios mentioned, lower import volumes are assumed here. According to these studies, the import costs for a climate-neutral energy system could be in the order of magnitude of the current costs for imports of fossil fuels to Germany (63 billion Euros in 2018, according to FZ Jülich (2019).

The German government is developing a strategic partnership with West-Africa for the deployment of renewable hydrogen (BMBF February 2020). In June 2020 Morocco and the German government signed a memorandum of understanding for future German-Moroccan hydrogen trade (Baumann, 2021; see section on Morocco).[63]

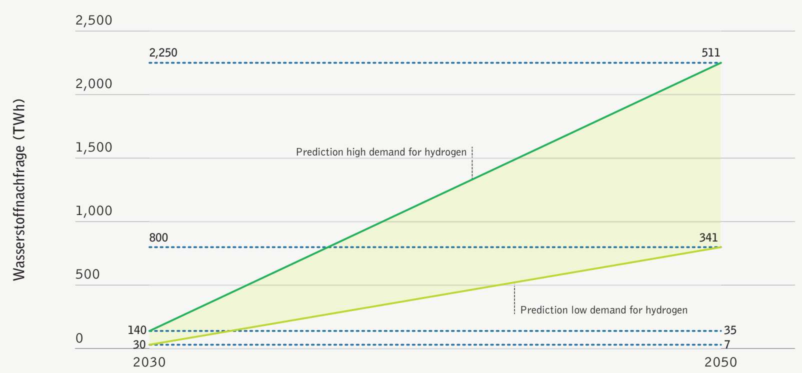
The Federal Government has appointed a National Hydrogen Council. The Council is made up of 26 high-level experts from business, science, and civil society who are not part of the public sector. Yet, no developing aid associations or social NGOs are involved.

Figure 13: Required renewable Hydrogen imports in Germany, 2030-2050, in TWh and GW



Source: Fraunhofer Institute for solar energy systems (2019).[58] **Note:** In Figure 13, the x-axis shows Hydrogen demand in TWh and the y-axis show electrolysis capacity in GW. For Germany, covering the timeframe 2030 to 2050. The dark green line is the demand for hydrogen predicting high demand and the light green line is predicting low hydrogen demand.

Figure 14: Required renewable Hydrogen imports in Europe, 2030-2050, in TWh and GW



Source: Fraunhofer Institute for solar energy systems (2019).[59] **Note:** In Figure 14, the x-axis shows hydrogen demand in TWh and the y-axis shows electrolysis capacity in GW for Europe, covering the timeframe 2030 to 2050. The dark green line is the demand for hydrogen predicting high demand and the light green line is predicting low hydrogen demand.

International and national hydrogen strategies continued

4.2
European Union

For the European Union, hydrogen is becoming an important technology to achieve the European Green Deal and Europe's energy transition focused on renewable energy. In the EU's strategic vision for a climate-neutral EU published in November 2018, the share of hydrogen in Europe's energy mix is projected to grow from the current less than 2% to 13-14% by 2050.

The European Union's energy strategy has been deeply impacted by the recent invasion of the Ukraine by Russia. To increase political and economy pressure on Russia, an accelerated phase out of Russian gas by 2030 has been announced by the European Commission supported by Germany. Prior to the unfolding of the Ukrainian-Russian war, Nord Stream 1 and particularly the recently completed Nord Stream 2 pipeline, held immersive potential for transporting Russian gas and future hydrogen between the two blocks. This possibility is no longer considered. The implications of this crisis on EU energy policy (gas and coal) and the impacts on achieving a net zero future have been discussed in Section 2.2.

The EU Commission published a hydrogen strategy for a climate-neutral Europe in July 2020 which highlights the development of renewable hydrogen as a long-term priority. It acknowledges that this requires the deployment of large-scale hydrogen production capacity alongside the roll-out of new renewable power generation which is yet to be achieved. The strategy comprises 40 gigawatt (GW) electrolyser capacity until 2040 and an additional 40 gigawatt hydrogen import. Hence for short and medium term, they suggest a tiered approach to slowly ramp up the renewable capacities. Particularly in Phase 1 and 2, existing hydrogen production plants (grey hydrogen) will continue to play a role though retrofitted with carbon capture and storage technologies. In Phase 3, starting from 2030 onwards and towards 2050, renewable hydrogen technologies should reach maturity and be deployed at a large scale to reach all hard-to-decarbonise sectors where other alternatives might not be feasible or have higher costs. In this phase, renewable electricity production needs to massively increase as about a quarter of renewable electricity might be used for renewable hydrogen production by 2050.

The Commission provides targeted funding and support for research and industrial development through pilot projects. In addition, the European Clean Hydrogen Alliance has also been established to build up a clear pipeline of viable investment projects and scale up production and demand for renewable and low-carbon hydrogen.

The EU hydrogen strategy also highlights the opportunities for cooperation on non-fossil fuel hydrogen with neighbouring countries and regions to contribute to their renewable energy transitions and foster sustainable growth and development. In this context, countries in the East, in particular the Ukraine, and in the South (North Africa) will become priority partners. For example, the Africa-Europe Green Energy Initiative will be used as an opportunity to support awareness raising of non-fossil fuel and renewable hydrogen opportunities amongst public and private partners, including joint research and innovation projects. This also includes the support for potential projects through the European Fund for Sustainable Development.

The EU is in the process of establishing a supportive policy framework and EU wide instruments such as including common low-carbon thresholds/standards for the promotion of hydrogen production installations based on their full life-cycle greenhouse gas (GHG) performance. Performance standards can be defined relative to be defined relative to the existing ETS benchmark for hydrogen production. In addition, it would include European-wide criteria for the certification of renewable and low-carbon hydrogen possibly building on the existing ETS monitoring, reporting and verification and the provisions set out in the Renewable Energy Directive.

While the strategy highlights the need for further research on labour market impacts and safety standards, an acknowledgment of potential environmental and social impacts related to a large-scale deployment of hydrogen particularly in non-EU countries is missing. As the EU's biofuels policy has shown, the support for technology innovations and their diffusion, generally involves certain risks. Hence it is even more important to learn from the past, create a better understanding of potential implications for countries in the global south, which go beyond socio-economic considerations.

IEA (2019) suggests that the cost of producing hydrogen from renewable electricity could fall 30% by 2030. However, since excellent renewable resource conditions are somewhat limited in developed countries and mainly found in countries of the global south, the conflict of local versus export use of renewable energy deployment must be addressed first.

4.3 International

Hydrogen currently enjoys a lot of international and national interest, both at the country and organisational level.

IRENA (2020) envisages that hydrogen has the potential to supply nearly 29 Exajoule (EJ) of global energy demand by 2050. Two-thirds of that would come from renewable sources, requiring at minimum around 7,500 TWh of renewable electricity, roughly equivalent to 30% of global electricity generation today.

IRENA highlights the potential of hydrogen, and yet points to the issue of scale for renewable hydrogen. For example, the installation of 50 GW of electrolysers, 330 times more than are in operation today, would still only allow, for the production of enough fuel to provide 10% of global shipping's energy needs. A significant increase in the production of renewable hydrogen would be needed – around 1,700 GW of electrolysers by 2050 – and despite this growth, renewable hydrogen would still only provide around 5-6% of global final energy. Hence, they point to the role of blue hydrogen which shall provide an additional 2.5% of global final energy, for a total of all hydrogen in the 7-8% range.

IEA (2019) finds that with declining costs for solar PV and wind generation, building electrolysers at locations with excellent renewable resource conditions could become a low-cost supply option for hydrogen. Their analysis suggests that the cost of producing hydrogen from renewable electricity could fall 30% by 2030. However, since excellent renewable resource conditions are somewhat limited in developed countries and mainly found in countries of the global south, the conflict of local versus export use of renewable energy deployment must be addressed first.

4.4 Morocco

The Kingdom of Morocco has the potential to develop into Europe's largest hydrogen supplier and dominate the export market. The target is to provide 52% of total electricity from renewable energy by 2030.[64] Since COP22 was held in Marrakesh, Morocco in 2016, the country has received considerable financial support to build the capacity and infrastructure to lead renewable hydrogen production for the export market. So far, trade agreements exist between Germany and Morocco (2020 Hydrogen agreement, Section 4.1) and between Spain and Morocco, Spain receives electricity generated from renewable energy via a sea cable (Baumann 2021).[65]

Although Morocco has immense renewable energy resources (solar, wind) to develop a hydrogen market and reduce its high dependency on energy imports, which account for 90% total energy consumption (IRENA 2022),[66] there are several systemic challenges. Most of the funding for renewable energy infrastructure is provided by international organisations, including the German Development Bank KfW (Euro 830 million for "Noor", its largest solar farm), (KfW 2021).[67]

A major challenge for the required renewable energy boom is the centralised structure of the Moroccan energy system (Baumann 2021). Currently two main companies dominate the market, one is government owned (National Office of Electricity and Drinking Water, also responsible for the national grid), the other, the Moroccan Agency for Sustainable Energy (MASEN), is semi-public and focuses on building renewable energy infrastructure (solar, wind). A result of the centralised and government-owned system is the large share of fossil fuels in domestic electricity generation, 70% coal versus 20% renewable electricity (IEA 2022).[68] The state-owned system allows coal-fired power plants to run at full capacity, while renewable energy plants operate at 50% capacity. This development stands in stark contrast to Morocco's ambitions goal to produce surplus renewable electricity to produce renewable hydrogen for export. The required decentralisation of energy supply systems is suppressed by a monopoly of players. Another barrier is the limited supply of fresh water required for hydrogen electrolysers, Morocco plans to supply freshwater through large desalination plants, powered by renewable electricity. Looking forward, the planned transition of the energy system, can lead to the liberalisation of the Moroccan electricity market and create major investment opportunities. Finally, the transition must support the local population, currently employment opportunities are very low. There is a real risk that generated renewable electricity will support the export market, while the share of fossil fuels in the domestic mix remains high (Baumann 2021).

International and national hydrogen strategies continued

4.5 China

China has the ambition to become a world leader in hydrogen technology production. In 2020, China started the construction of the world's largest solar powered hydrogen plant to power hydrogen buses.

In China, manufacturing capacity for electrolysers, alkaline in particular, is well established and very cost competitive (IRENA 2019).[69] The most important domestic producers are Tianjin Mainland Hydrogen Equipment Co., Ltd. (THE) and Beijing CEI Technology Co., Ltd. THE is a world leading supplier of alkaline electrolysers and has delivered more than 400 production plants since 1994, with units of up to 1,000 normal cubic metres per hour (THE Co., Ltd., 2019).[70] THE has a partnership with HydrogenPro from Norway for all projects involving equipment in Europe and the US. This includes a large scale power-to-gas project (five 100 MW hydrogen production units) over a five-year period in Dunkirk, France (discussed earlier).

4.6 Australia

Australia has great renewable energy potential and a stable political environment. There is great interest from renewable industry as well as NGOs such as WWF in the large-scale deployment of renewable hydrogen. Australia's government published Australia's National Hydrogen Strategy[71] defining 57 actions in areas such as regulation, infrastructure, mobility and R&D with the aim of positioning Australia as a world leader in hydrogen production and exports (IEA-H_2-2020).[72] In 2020 the Australian Renewable Energy Agency opened an Expression of Interest (EOI) for renewable hydrogen projects and the Clean Energy Finance Corporation created a new hydrogen finance program worth AU$300 million. Renewable hydrogen is feasible and pilot projects were announced across the country. The Australian National Hydrogen maps out various scenarios for hydrogen production, consumption and export. Australia aims to become a 'Hydrogen Powerhouse' by 2030 and beyond to replace coal and gas exports with hydrogen. The strategy is not exclusive to renewable hydrogen but includes fossil hydrogen with CCS as well.

4.7 Japan

In June 2019, hydrogen was the focal point of the G20 discussions in Osaka (Japan), where G20 leaders acknowledged the opportunities offered by further development of innovative, efficient and fossil-fuel free hydrogen technologies (IEA-H_2-2020). During the G20 meeting, Japan, the European Commission and the United States signed a partnership for future co–operation on hydrogen and fuel cell technologies (EnergyGov 2019).[73] Japan developed a hydrogen strategy mapping out goals for hydrogen production and consumption for 2020, 2030 and beyond. In 2020 Japan launched the Green Ammonia Consortium.

4.8 USA

The U.S. government is funding a dedicated initiative that focuses on emergent technologies and market development. The major hydrogen-producing states are California, Louisiana, and Texas. Today, almost all of the hydrogen produced in the United States is used for refining petroleum, treating metals, producing fertiliser, and processing foods. The push for hydrogen in the US is driven by a coalition of major oil and gas, power, automotive, fuel cell, and hydrogen companies. They published Road Map to a US Hydrogen Economy that sets out a 10-year timeline for new technology deployment and the opening of markets.

Solar power park in Qinghai, China. © Jenson

4.9 Chile

Chile published a National Green Hydrogen Strategy in November 2020 (Government of Chile, 2020).[74] Compared to the national hydrogen strategies of, for example, Japan – with a role of nuclear for hydrogen production – or Australia – which includes fossil hydrogen – Chile focusses entirely on renewable hydrogen. The production of renewable hydrogen is planned to take place in two regions, in the Atacama Desert and in the Magallanes Region, and will achieve the lowest levelised cost of production on the planet by 2030. The quality and abundance of the renewable resources found in these regions will enable a large scale competitive production.

The Chilean government plans to ramp up their hydrogen production in "3 waves" (Figure 15).

The following text is taken directly from the strategy document:

- *Wave I: 2020-2025 Domestic ramp up and export preparation*

  We will accelerate the deployment of [renewable or] green hydrogen in 6 prioritized applications to build local supply chains and acquire experience. Public action will kick start the local hydrogen industry by incentivizing production and create a tangible demand for this [fossil-fuel free] element and its derivatives. Uses with the earliest economic break even and largest concentrated demand will be targeted first. These actions will generate know-how, develop talent, deploy infrastructure, and attract financing. In doing so, the country will be better positioned to tap into export markets.

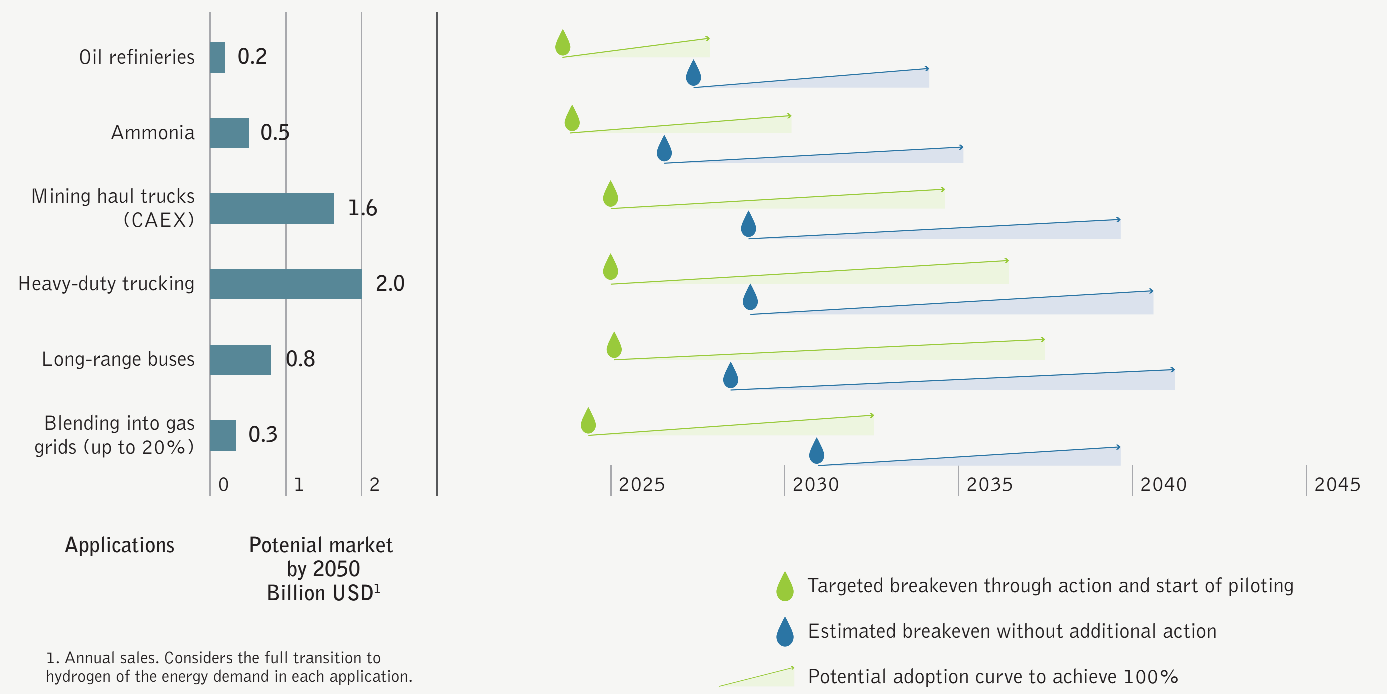
- *Wave II & III: 2025-2030 & 2030 onwards*
- *Wave II: We will leverage our domestic base to scale into a key player in export markets.*

  An industry of [renewable or] green ammonia production and exportation will be put in place through support for GW-scale consortiums. Off take and investment commitments for ammonia and hydrogen exports will be secured.

- *Wave III: We will exploit synergies and economies of scale to expand as a global supplier of [fossil-fuel free] fuels.*

As countries take action to decarbonize their economies and new technologies are developed, the export markets for [fossil-fuel free] fuels will scale and diversify, opening opportunities for further growth. Future applications for ammonia in shipping and synfuels in aviation are promising opportunities for additional scale-up (Government of Chile, 2020).

Figure 15: Six priority areas of hydrogen applications (potential market in billion USD (BUSD))



Source: Government of Chile (2020, p.17).[75]

International and national hydrogen strategies continued

4.10
South Africa

South Africa's economy is highly emission intensive, in 2021 the country was the world's 12th biggest source of GHG emissions (Bloomberg 2021).[76] In 2020, 79% of all electricity was generated from coal, 10% from nuclear power and 10% from renewable energy including hydro power. In June 2020, South Africa's Department of Science and Innovation (DSI), developed a hydrogen strategy with other government and industry stakeholders. In February 2022, the Department published its Hydrogen Society Roadmap (HSRM). The roadmap aims to decarbonise the South African economy and reach net zero by 2050 (Department of Science and Innovation, 2021).[77]

The hydrogen strategy aims to create an export market and at the same time decarbonise the domestic economy. The most energy intensive sectors are power generation, heavy transport, and the manufacturing sector, including the steel and chemical industry (ammonia production). The roadmap aims to produce 500 kilo tons (kt) of hydrogen every year and increase electrolysis capacity to at least 15GW by 2040.

The roadmap aims for a just transition, one of the main objectives is to upscale employment opportunities in the hydrogen economy by training and reskilling workers for new jobs. The workforce will support the localisation of hydrogen production and its supply chains. According to the roadmap, the South African government will create at least 20,000 jobs annually until 2030, this number increases to 30,000 annually by 2040.

There are four keystone projects which are "catalytic" for the transition (Department of Science and Innovation, 2021):

- the Platinum Valley Initiative (South African Hydrogen Valley) – linked to an existing platinum mine in Mokoplane – this will operate as a storage facility for marine ammonia
- the Coal CO_2 X project, CCS/CCU project related to flue gas from coal-fired power stations, will be connected to the Boegoebaai renewable hydrogen production facility
- the Boegoebaai renewable hydrogen project located in the Boegoebaai Special Economic Zone (SEZ) in the Northern Cape. The zone will have a renewable energy capacity of 30GW of solar and wind, and 5GW of electrolyser capacity to support ammonia production from renewable energy sources
- the Sustainable Aviation Fuels (SAF) project is set up in partnership with South Africa's largest Ammonia supplier Sasol and focuses on syn fuel production

According to the roadmap the flagship projects are expected to meet the hydrogen production and employment figures as listed above.

4.11
Summary – hydrogen strategies around the world

Many countries developed hydrogen strategies and the list continues to grow. The examples provided in this section cover only a fraction of countries which are either already in the implementation phase or still in the development of a strategy. Besides the presented countries, China, South Korea, France, the Netherlands, the UK and Brunei aim to develop hydrogen expertise.

Industrial nations focus predominately on technology development for hydrogen production and end-use application including infrastructure. Developing countries and countries with a focus on oil, gas and coal export, focus on hydrogen production for exports.

While the approaches and foci are different, they can be categorised by the following topics:

- Hydrogen Technology development
- Hydrogen networks and infrastructure development
- Heat industrial
- Heat residential
- Transport
- Hydrogen export
- New employment

The industrial nations focus predominately on technology development for hydrogen production and end use application including infrastructure. Developing countries and countries with a focus on oil, gas and coal export, focus on hydrogen production for exports to replace decreasing demands for fossil fuels. This development is based on the Paris Climate Agreement. While renewable hydrogen is presented as the long term goal, the production is believed to start with fossil hydrogen.

Policies are needed to moderate and steer the process towards a renewable hydrogen industry.

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Iron casting factory.
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05

Policy development: Hydrogen for Climate Protection

All sectors of the economy need to reduce consumption, improve efficiency where possible, and decarbonise. The overall cumulative carbon budget for the energy sector between 2015 and 2050 cannot exceed 450 Gt CO_2 in order to achieve – with 66% probability – a global average temperature increase by 1.5°C as required under the Paris Climate Agreement (Teske et al., 2019).[78] Some sectors of the economy are energy-intensive and therefore are considered as "hard to decarbonise." These sectors include the manufacturing of steel, aluminium and cement, the chemical industry, aviation, shipping, and heavy-duty road transport. High temperature heat for industrial processes (e.g. steel production) and fuels with high energy intensities (e.g. aviation kerosene) are currently not replaceable with electric processes. Thus, electrification is not an option according to today's knowledge and/or available technologies. To supply those energy demands, renewable hydrogen and/or synthetic fuels are required.

In the near future, an increasing number of countries support the development of a hydrogen-based industry. Large energy companies from the gas, oil and coal sector increase their investments in hydrogen projects. At the same time, governments will launch market stimulation package and work on policies to frame and support a hydrogen economy in the future.

Policy development: Hydrogen for Climate Protection continued

This research aims to provide additional guidance for policy makers to secure a sustainable, environmental and socially responsible hydrogen market. The aim is to develop a just transition from fossil fuels to a renewable energy-based hydrogen economy that avoids the mistakes of the past:

- Energy colonialism: "This extractivist system marks certain places and peoples as disposable by importing and exporting logics and materials to dominate various energy forms, ranging from humans to hydrocarbons" (de Onís, 2018)[79]
- Violation of human rights
- Fair distribution of natural resources, wealth and income from energy projects and global trade
- Community self-determination and energy justice in energy transformations

This section aims to provide guidelines for a fair and just policy for the production, transportation and use of renewable hydrogen.

5.1 Sustainability Criteria: Additionality

Hydrogen must not prolong the use of fossil fuels nor must it replicate the injustices of the fossil-fuel energy system and extractive economy. Therefore, the production of hydrogen via fossil fuels – mainly gas – is not acceptable. Hydrogen production must be based on renewable electricity and the electricity for hydrogen production must not hinder the access to energy services in the global south. Further, as noted, by using an energy justice framework, renewable hydrogen production should ensure that it is fair for all, especially for communities who are most affected by its production. Thus, one of the most critical issues in hydrogen deployment is the aspect of additionality.

The term 'additionality' means, that renewable electricity will not be diverted from energy services – especially in the global south – to fuel production for exports. The deployment of renewable electricity must prioritise the electricity supply for local communities. Consequently, it must be ensured that the electricity for any hydrogen production – both in industrialised as well as developing countries – must come from additional renewable energy capacities. However, there is still a debate how to determine "additionality" in practice and how to develop robust and adequate assessment criteria.

The following approaches characterise how additionality has been defined:

Restrictive approach: Only accept amounts of renewable electricity generation as additional for hydrogen production, which exceeds the demand in a system wide 100%+ renewable energy situation. In other words, the country (or region) must be powered by 100% renewable energy and has surplus renewable electricity that can be used for hydrogen production. It implies that the electrification of developing countries must be prioritised before any renewable hydrogen production is established. This would be the most restrictive and rigorous approach to additionality. While this approach might be a desired development under social aspects, it overlooks technical requirements to phase out fossil fuels with a limited carbon budget.

Regional approach: In a regional approach, additionality could mean to include renewable electricity that exceeds 100% of local (geographical delineated) demand and cannot or would be more cost intensive to be transported to distant (industrial) centres. This could be the case for example in countries with significant regional solar and wind resources which exceed local demand significantly such as Australia or Saudi Arabia (Figure 16). It also refers to geographically isolated areas such as islands, where 100% renewable electricity is reached, and renewable hydrogen production would be beneficial for the security of supply (= hydrogen as a storage medium for electricity supply instead of batteries).

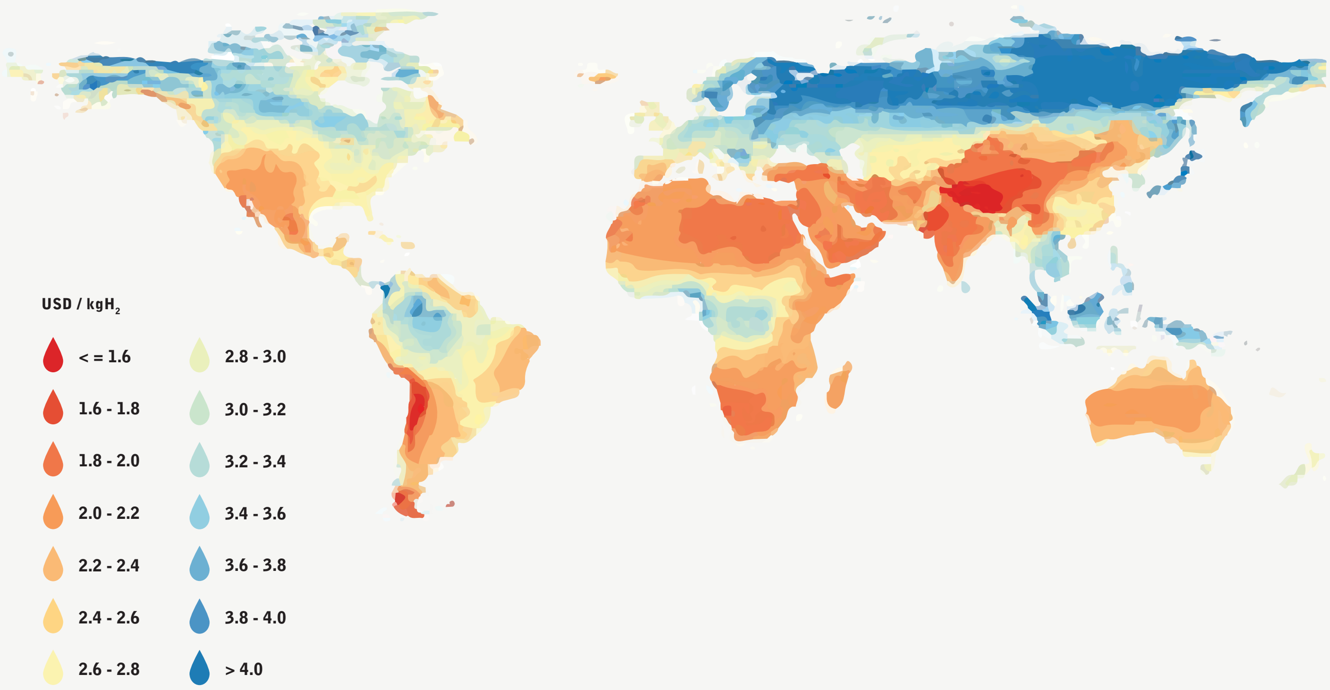
Commercialisation approach: Additionality could refer to a situation when the country's planned and policy supported renewable energy capacity is met, and additional funding/ support is provided for renewable energy projects that are purpose-built for electrolysis in a yet to reach 100% renewable system. Germany for example is interested in replacing fossil fuel imports with renewable hydrogen to comply with the Paris Climate Agreement. While Germany does not have the local resources to generate all required hydrogen from local resources, it has extensive know-how in all areas related to the hydrogen value chain. This approach can foster the technology during the commercalisation phase. Yet, it would only seem sensible to swiftly adopt a comprehensive 100% renewable energy target.

Coupling approach: Another approach could comprise a mandatory coupling of hydrogen production with the required renewable electricity generation. Therefore, the hydrogen production sector will build its own dedicated renewable generation capacity and will not compete with other (renewable) electricity production. This approach can only be implemented in regions with sufficient renewable energy potential. In northern Europe for example, this would lead to dedicated offshore wind farms for hydrogen production.

The question of additionality is crucial since there are only a limited number of countries that could export large amounts of renewable hydrogen.

The question of additionality is crucial since there are only a limited number of countries that could export large amounts of renewable hydrogen. Examples include Australia, Chile, Argentina, Saudi Arabia, Morocco, Namibia, South Africa as well as Russia and Kazakhstan (Figure 17). The role of Russia in the hydrogen economy is no longer clear, but there is increasing consensus, among the EU and US, that Russia should be excluded from future energy markets in the long-term.[80] Possible import countries have high population densities and consequently have less available land and/or solar resources and wind resources which will not allow a commercial production of renewable hydrogen. Germany is among the possible import countries.

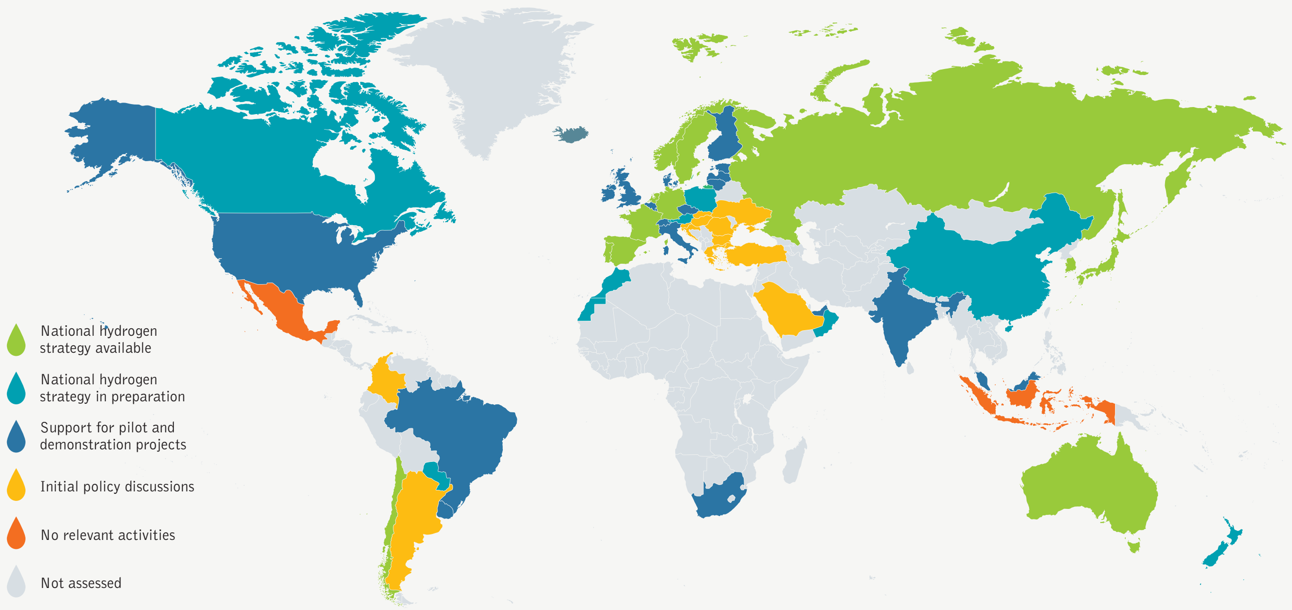
Figure 16: Examples of high potential Hydrogen producing countries worldwide (warm colours)



Source: IEA (2019).[81] **Legend:** Warm colours: high potential for hydrogen production, low costs, potential for hydrogen export. Colder colours: fewer potential for hydrogen production, higher costs, potential for hydrogen import.

Policy development: Hydrogen for Climate Protection continued

Figure 17: Examples of high potential hydrogen producing countries



Source: CarbonBrief (2020).[82] **Note:** Extent of hydrogen support in a selection of countries, including national strategies, pilot and demonstration projects and policy discussions. Based on a figure from a report by Ludwig-Bölkow-Systemtechnik GmbH (LBST) and the World Energy Council's German chapter. Map by Joe Goodman for Carbon Brief.

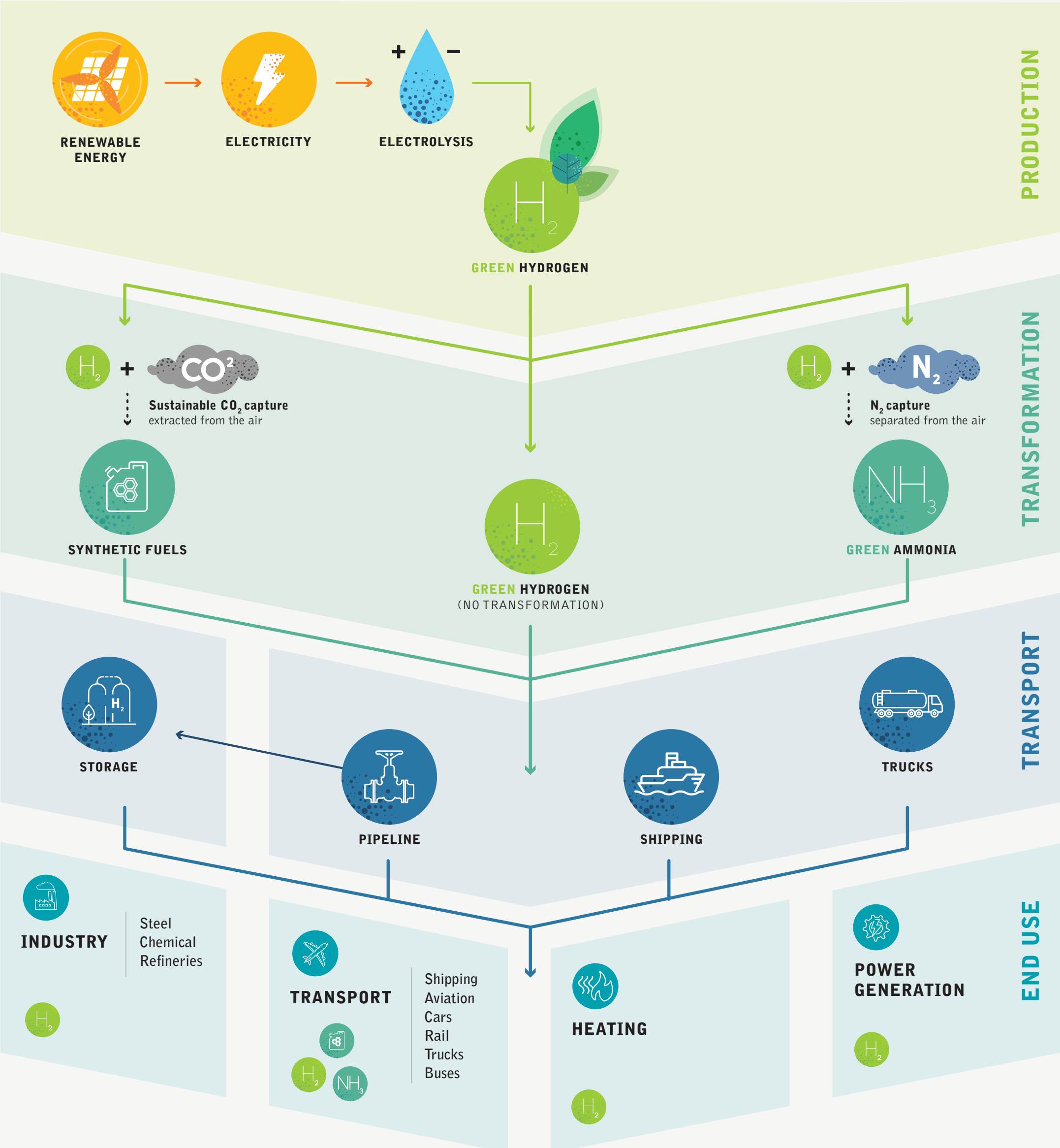
Another difficulty to account for "additionality" criteria is emphasised by Bracker et al. (2019)[83] points out another challenge to account for "additionality" and criticises the Guarantees of Origin (GO)[84] used in Europe for synthetic transport fuel production. Bracker et al. find that it does not ensure power consumption is based on additional renewable generation and thus does not justify accounting this consumption to low or zero CO_2 emissions. The same applies to long-term power purchase agreements, if the respective renewable energy production plants do not fulfil the specific additionality criteria.

Another aspect which has been discussed recently, is the lifetime of renewable energy capacity lifetime, which is used to generate renewable hydrogen. In early 2022, the EC's Delegated Act (DA), stated that "under its "additionality" rules, the commission would only allow hydrogen to be considered "green" if electrolysers are powered by renewables projects less than 24 months old" (Collins, 2022).[85] The Commission argued that the decarbonisation of the energy sector must be prioritised over hydrogen production. The criteria have been heavy criticised by the hydrogen industry.

5.2 Environmental Standards for the Hydrogen Industry

Environmental standards need to be established to support the development of a global sustainable hydrogen industry. Each step of the renewable hydrogen production value chain requires specific environmental criteria. The following figure (Figure 18) shows all steps of the renewable hydrogen value chain and table (Table 2) identifies policy goals and policy options to implement those goals.

Figure 18: Overview – Value chain of renewable hydrogen production



Source: IRENA (2020).[86]

Policy development: Hydrogen for Climate Protection continued

Table 2: Renewable hydrogen policy aims and options for different applications

PROCESS	POLICY GOAL	POLICY OPTION
H_2 Production		
• Electricity source	Renewable energy	H_2 production standard
• Electrolysis	Conserves (metal) resources	Technical standard for electrolysis
Transformation		
• Synthetic Fuels	Efficient production Sustainable source for carbon (no fossil carbon)	Technical standards Certificates for the origin of carbon
• Ammonia	Sustainable use of ammonia	Technical standards
Transport		
• Ship transport • Land-transport • Pipelines • Storage	Efficient transport and storage of H_2 to end-use sectors Conversion of natural gas infrastructure for hydrogen As much as technically possible	Just transition program for employees and natural gas infrastructure: • Research & Development • Transition benefits e.g. from CO_2 tax income
End use		
• Industries	H_2 replaces fossil fuel processes that cannot be electrified H_2 is used for new processes to reduce process emissions (e.g. for steel making)	• Production standards • CO_2 pricing
• Transport modes	Priority to replace fossil fuels to avoid the increased use of unsustainable biofuels	
• Shipping	Replacement of heavy oil as a priority	IMO standards for the use of heavy fuels at sea
• Road	Replacement of diesel for heavy duty vehicles	Road toll charges for fossil fuelled trucks
• Rail		H_2 use for tracks that cannot be electrified • Bonus for fuel switching
• Heating Residential	H_2 to support fuel switching from fossil fuels in cogeneration and for district heating systems	• CO_2 pricing • Bonus for fuel switching
• Power Generation	H_2 to support fuel switching from natural gas for dispatch power plants	• CO_2 pricing

Source: OECM model outputs (ISF, 2020).

Since renewable hydrogen will play a role in the decarbonised and 100% renewable energy future, there must be a clear link to Sustainable Development Goals (SDGs) and its guiding principle "to leave no one behind".

5.3 Social Criteria: Opportunities

Significant parts of the German and EU Hydrogen Strategies focus on renewable[87] hydrogen imports from countries most likely in the global south. Hence it is essential to evaluate the social and ecological viability, feasibility and desirability of renewable hydrogen production in these countries and consequently develop appropriate policy mechanisms built on and guided by perspectives of human rights and energy justice; one that is gender-aware and intersectional and that prioritises economic, social and cultural rights. While the technical implementation is one part, the other and certainly equally important element is its socioeconomic-political integration. However, the current public discourse largely focusses on the economic aspects, in particular the costs, scale and market competitiveness. While examples from the past, in particular renewable energy projects,[88] demonstrate ways to avoid social and ecological impacts, understanding new dependencies and navigating the process to circumvent infrastructure and institutional lock-in effects, are crucial.

This section presents opportunities and risks associated with renewable hydrogen production in the global south. It serves as a starting point for dialogue among civil society, political stakeholders and industrial project planners.

Since renewable hydrogen will play a role in the decarbonised and 100% renewable energy future, there must be a clear link to Sustainable Development Goals (SDGs) and its guiding principle "to leave no one behind" as outlined in the UN Agenda 2030, acting on on climate change, improving public health, making energy accessible (based on SDG 7 which ensures access to affordable, reliable, sustainable and modern energy for all), as well as food and water security must go hand in hand with the development of new industries for renewable hydrogen. Hence this technology bears a lot of opportunities.

Employment and economic development

The two main arguments for renewable energy deployment in the global south are the employment benefits and economic development. The decentralised nature of renewable energy enables nationwide distribution of jobs – which is less so the case for jobs within the fossil-fuel industry. Marginalised communities are often located away from economic hubs such as cities and/or industry regions. However, those regions often have very good solar and/or wind resources. An example would be the excellent solar resources in the Atacama Desert of Chile or steady winds of the Tierra del Fuego region in the south of Argentina. Large-scale wind and solar projects with hydrogen production in remote regions will be beneficial for those communities.

Hartley et al (2019)[89] found that for example South Africa can significantly boost employment by increasing the share of renewables. Employment in South Africa's renewable energy sector, can be expected to increase by an additional 40 % in the period 2018 to 2030, accounting for 580,000 job years, which is equivalent to one year of work for 580,000 workers. By following the Council for Scientific and Industrial Research least cost pathway, this number can be more than doubled to almost 1.2 million job years, if created along the renewable energy value chain. "Boom and bust" cycles of renewable energy policy support must be avoided in order to create a sustainable workforce.

There are lessons to be learned from past projects to ensure the success of the Moroccan energy transition. Evidence shows that the Noor Solar Power Plant, funded by IRENA, has failed to create local jobs (Baumann 2021). The creation of local jobs must become a priority for the renewable hydrogen sector, the set up of the industry has the potential to create 15,000 direct and indirect jobs (Fuel Cells Works 2022).[90]

Renewable energy deployment can also have a positive impact on diversifying the local economy. Ensuring local procurement (including local workers) is essential.

Education and training

The expansion of renewable energy generation requires high-skilled workers, although employment is also created in unskilled labour groups. Training and education programs to increase local skills and capacity is a great prospect for countries in the global south. This, particularly, applies to marginalised communities. Efforts are needed, both by government and industry, to ensure workers are qualified for the respective jobs. For example in South Africa 30,000 individuals in marginalised communities can benefit from access to education-related programs through the Renewable Energy Independent Power Producer Programme (REIPPPP)[91] by the year 2050. Although projects have motivations to support the local community and create new jobs, positive outcomes can be curbed by top-down governance structures and vested interests.

Upskilling takes time and so an international strategy should start with supporting the training and education capacities in targeted countries and ensure that a skilled workforce will be available when the construction and production of the technologies begins.

Policy development: Hydrogen for Climate Protection continued

Electricity access and health benefit

Universal access to electricity is an important element for creating a more equitable and democratic society. But many communities in the global south still lack this basic right. Electrification could be accelerated through international efforts to deploy renewable energy sources for hydrogen production in these countries. However, it must be ensured that renewable energy projects benefit the local community first before any electricity is used to produce hydrogen for export.

An expansion of renewably energy deployment can reduce negative health impacts and related costs for people and businesses stemming from air pollution of coal fired power plants. In South Africa, the air pollution from coal fired power stations adds to the already poor air quality. According to the World Heath Organisation (WHO), air pollution leads to 7 million premature deaths every year (WHO in Department of Science and Innovation, 2021).[77] For example, in the Mpumalanga region in eastern South Africa, 12 coal fired power stations are operating. This region has been identified as highly air polluted and is of particular concern to the Department of Environmental Affairs (Department of Science and Innovation, 2021, p. 13).[77] Scaling up renewable energy and replacing coal fired power stations with renewable energy infrastructure, will have major improvements to air quality and will reduce air pollution related health risks.

Local ownership and participation

International studies have shown that local ownership of renewable energy projects has several social and economic benefits including increased acceptance, securing local electricity supply (or access) and local economic added value. In fact, if there is a community ownership component as part of a renewable energy project, particularly (but not limited to) larger-scale renewable energy projects, the economic benefit derived from the project by the local community is 1.5-7 times greater than it would have been otherwise (Table 3).

This is because projects with a local community-ownership component typically result in:

- Greater use of local content, including more local jobs and contractors, particularly in the construction phase. This in turn increases local skill development, which can be leveraged by regional businesses into contracts in the wider renewable energy industry.
- Larger and more appropriately targeted benefit funds/programs
- More of the profits being retained locally, as local investors/owners spend their profits in the local community.

There are very few studies exploring community ownership or co-ownership of renewable energy projects in the global south. Indeed, funding of local renewable energy projects is a significant challenge. Yet, the South African example (Text box 4) shows some potential for considering local needs in renewable energy policy, such as the Renewable Energy Independent Power Producer Programme (REIPPPP). It includes community benefit requirements, which stipulates quantitative targets for socio- economic development, as well as a community shareholding threshold in new enterprises. This component of the scheme has resulted in the availability of around 11.5 billion Rand for community development (Baker & Wlokas, 2014).[96] Communities eligible for support under this scheme are those within a 50km radius of a project and due to the geographical location of the resources this means particularly marginalised communities could benefit.

Co-ownership schemes offering investment opportunities are also an option for enabling the local community to benefit from renewable energy projects. Of course, only middle to high income groups and businesses might have the resources to afford such an investment, low income and poor groups do not have the same options.

Further, studies identified more opportunities and positive impacts associated with large-scale renewable energy projects such as:

- Improved local infrastructure and services. For example, Terrapon-Paff et al. (2019)[97] show how a poor region in Morocco benefits from the construction of a solar thermal plant and demonstrate how investments made under the social development plan improve access and availability of social services.
- Community connection: if the project involves high levels of community engagement and / or community co-investment or co-ownership, then the project can increase a sense of community connection and social capital.
- Increased community resilience

Table 3: Comparison of financial benefits accrued in a community: corporate versus locally-owned wind farms

COUNTRY	CORPORATE OWNED	COMMUNITY/ LOCALLY OWNED
Germany	€7 million over life of project	€58 million over life of project
UK	£1,000-5,000 / MW / year	£200,000-250,000 / MW / year
USA	US$13,000-55,000 / MW / year	US$82,000-140,000 / MW / year
Australia	AU$500-1,200 / MW / year to community fund	AU$5,000 - 8,000 / MW / year to community fund

Sources: Gottschalk et al. (2016).[92] Cowell et al. (2011).[93] Lantz & Tegen (2009).[94] Hicks et al. (2018).[95]

Box 4

Experiences from the South African Renewable Energy Transition

There is a great opportunity to fully decarbonise the South African electricity sector. The country is endowed with an abundance of renewable energy resources. This combined with the recent drop in technology costs and the need for new power generation as coal power plants reach retirement, South Africa has the potential to produce excess renewable electricity for hydrogen production in particular from solar PV (Perner & Bothe, 2018). This is amplified by a high annual 24-hour global solar radiation average of 220 W/m^2, compared to 100 W/m^2 for Europe.

Indeed, several studies have shown huge employment potential when the share of renewable energy is significantly increased. In addition, there is tremendous prospect in rooftop solar PV which would bring cost benefits for residential and commercial consumers. Significant flow on effects are also expected in regard to education, local economic development, local ownership, reduction of air pollution and improvement of human health (IASS/CSIR, 2019 a,b,c).

However, more than 90% of the country's energy still comes from domestic coal fired power stations, while only 8.8% is generated from renewable energy sources. Since 2011, the government fosters large-scale renewable energy through the Renewable Energy Independent Producers Procurement Programme (REIPPPP), where independent power producers are invited to tender for licences to sell electricity to the Eskom grid under a 20-year purchase agreement. This policy is unique globally in its emphasis on providing benefits for communities which are often considered as "marginalised" and located in the vicinity of projects. The mechanisms include local employment quotas, community ownership renewable energy projects, as well as contributing a proportion of their revenue towards development spending, known as socio-economic development and enterprise development. The high quality regulatory framework and tough qualification criteria of this scheme have been praised internationally, although it proved complex and expensive for developers, due to high compliance costs (Essex & de Groot, 2019).

The renewable energy transition in South Africa faces complex issues regarding energy access, significant societal inequalities stemming from legacy of the Apartheid and colonial regime. In fact, there is a considerable energy underclass that cannot access or afford to use electricity for their cooking, lighting and heating needs. Instead, they rely on multiple sources of energy, including 'dirty' fuels which are harmful to human health (Musango, 2014; Knox et al., 2017). The large-scale REIPPPP projects did not deliver the anticipated significant benefits for marginalised communities (yet) since power producers have lacked an understanding of the REIPPPP mechanism and their intended role for supporting local communities. Essex and de Groot (2019) found that the renewable energy transition has yet to contribute to deliver the goals of establishing the basics of quality of life, social justice and the access and affordability of energy supply to all groups within society. Bickerstaff et al. (2013) raised concerns that the perpetuation of an 'energy underclass' appears to be a real likelihood from the sustainable energy transition (p.5). The agendas influencing the generation, distribution and consumption of electricity in South Africa are multiple and deeply conflicted. Hence the road to 100% renewables is not an ideological or spatially neutral project and will indeed be very challenging. Any interventions must consider these complexities while the imperative is that renewables improve the lives of the people in South Africa, not elsewhere first. Similar to South Africa, the transition to 100% renewable energy in other countries of the global south are fundamentally linked to questions of energy justice and poverty alleviation, and the fact, that historical legacies and influences have created ingrained cultural norms related to colonial rule, or the response to colonial rule.

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Policy development: Hydrogen for Climate Protection continued

5.4 Risks

Renewable energy and renewable hydrogen, are clear solutions to climate change, helping countries and industries move away from carbon polluting alternatives. This important role comes with human rights-based environmental and social responsibilities. For example, the Business and Human Rights Resource Centre has recorded over 200 allegations of serious human rights violations linked to renewable energy projects in the last 10 years.[98]

Renewable hydrogen projects will require large renewable energy installations which come with environmental impacts, such as land-use change, noise, water-use and resource utilisation. Considering the issues local populations in the global south face, as a result of poor accessibility, affordability and reliability of electricity supply, learnings of environmental and land use impacts related to new energy infrastructure can be challenging for local populations, in particular if these projects are benefiting energy exports. The integration of the local population early on in the planning and consultation process, can create awareness and knoweldge of potential tensions resulting of economic and social inequalities. Disregarding these issues, can give rise to local opposition and can jeopardise energy transitions.

Large infrastructure projects – whether they are in the field of renewable or non-renewable energy – can potentially have negative impacts including:

- Conflicting use of water and water scarcity
- Negative impacts on local ecosystems
- Conflicts for land-use
- Technology failures
- Project cost increase due to poor planning and/or corruption
- Financial dependence on donor countries
- Lack of inclusion of local population in the entire energy supply chain, starting from enabling access to energy to involvement in decision making processes
- Decreasing acceptance for renewable energy due to poor planning and/or corruption

This section will provide some examples and supports a discussion about the possible risks without claiming completeness.

Social and environmental NGOs highlight possible risks and argue that hydrogen production is only viable and desirable under specific conditions and for selected applications. One of the unequivocal prerequisites is that hydrogen production is based on additional renewable energy sources – only then a fully decarbonised 100% renewable energy system can be achieved. In addition, direct electrification and energy efficiency measures must go hand in hand.

Water

Water is a critical input for the hydrogen industry. There are different estimates of the amount of water needed to produce renewable hydrogen through the electrolysis process. The German Environment Agency (UBA) (2016)[99] derives the water requirement for electricity-based kerosene production from the stoichiometry of the processes and indicates the required quantity of water to be around 1.4 litres of water per litre of fuel. Additionally, there are water requirements for cleaning the solar panels of approximately 75 litres of water per kilowatt hour (kWh) to ensure their highest efficacy. According to the IEA around 9 litres of water are needed to produce 1 kg hydrogen. The National Hydrogen Strategy of Australia states that producing "enough hydrogen to satisfy Japan's projected annual imports in 2030 would require less than 1% of the water now used by Australia's mining industry each year". A study by Shi et al (2020)[100] even goes so far to claim that the water consumption footprint is much less than that reported in the literature. However, they also find that the quantity of water footprint varies significantly among different assumptions while a significant amount of water is also needed to produce the solar panels or wind turbines.

Nonetheless, there is consensus that freshwater access can be a significant issue in water stressed areas. For countries that are high on the water scarcity index (Figure 19), water is a significant consideration in the development of a renewable hydrogen industry. Yet, countries with high potential for renewable hydrogen production (for example South Africa, Australia, the MENA Region, the south-west region of the USA, China) due to very favourable sun and wind conditions are also among the most water stressed regions in the world.

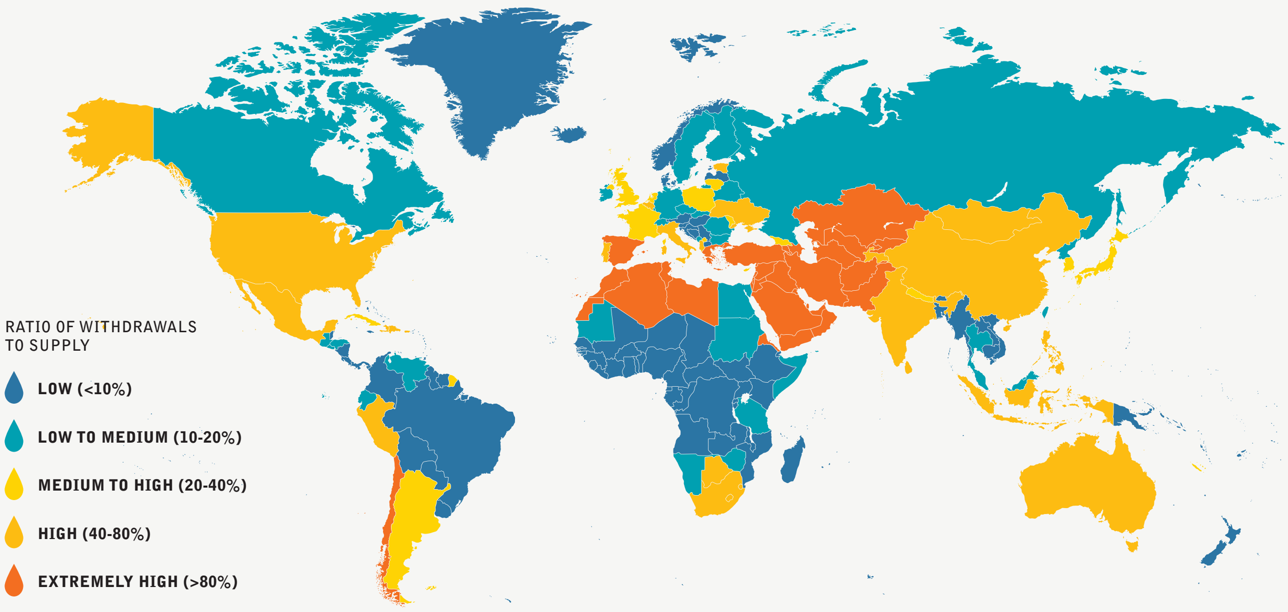
It is unquestionable that the operation of renewable hydrogen plants should not impede the drinking water supply or access of the local communities' (including agricultural water use), nor increase any financial stress with regard to water costs. Instead, the local community should benefit from the establishment of new water provision. Bracker et al (2017)[102] highlights that "The Middle East and North Africa (MENA region) is already today among the world's driest regions, and climate change will lead to a further increase in aridity in many regions of the world." Even though Malins (2017)[103] stressed that the water use for renewable hydrogen production is unlikely to be problematic at the national level, there is still potential for rapid development of hydrogen production associated with concentrating solar power to impact water availability at a more local level. Hence the slightest water extraction could have serious impacts on local communities. Water stress can have environmental impacts on ecosystems as well, only a small increase in water consumption may tip the system into a negative trajectory.

In the study by Terrapon-Pfaff et al. (2019)[104] the water issue was discussed as part of a social impact assessment for a solar thermal plant (NOORO I power plant) in Morocco. Diverging views were observed regarding the plant's water impact. On the one hand, the local community raised (as one of their major) concerns that the availability of local water resources was reduced due to the use of groundwater for construction purposes and ultimately reducing the capacity to sustain agricultural activities. On the other hand, studies indicated that the water demand of the plant will not negatively affect the local water availability. These concerns must be taken into consideration and addressed early. In an arid area, water is the most valuable resource and even a (potentially) incorrect perception can lead to significant conflicts.

However renewable hydrogen production could be an opportunity to help grow a circular economy approach for recycled water use associated with this emerging industry if it is done correctly from the beginning. Desalination is another potential water source for the hydrogen industry. While this would reduce competition for existing potable water sources, there are potential negative ecological consequences associated with highly saline water and scaling chemicals being released into marine ecosystems. Best practice environmental management and seeking opportunities to use this saline by-product (circular economy and industrial ecology options), will be essential for the development of a sustainable renewable hydrogen industry, should desalination be required (WWF Australia 2020).[105]

The Ökoinstitut (2019)[106] summarises it as follows: the development of renewable hydrogen production capacities can lead to negative (e.g. rising water costs, lack of water availability) but also to positive (e.g. increased water availability through seawater desalination plants) effects in terms of water availability in regions with water shortages at the local level. In desalination plants, local ecological effects can also occur as a result of the return of brine enriched with salt and chemicals. For plants supported by policy measures, the implementation of sustainability measures and their independent evaluation should be mandatory.

Figure 19: Water stress by Country, 2040



Note: Projects are based on a business-as-usual scenario using SSP2 and RCP8.5.

Source: World Resources Institute, 2015.[101]

Policy development: Hydrogen for Climate Protection continued

Box 5

Considerations from the failure of the Desertec project

The huge potential for solar radiation in the deserts of North Africa has inspired Europeans for many decades to supply energy, not only in the countries where it is produced, but also to countries in Europe. In the late 2000s this idea reinvigorated again as a possible way to decarbonise the European power sector until 2050. In this context, the Desertec Industrial Initiative (DII) was founded by several, predominant German enterprises in 2009. The objective of DII was to organise the conditions for the realisation of the Desertec idea, which aimed to both (a) supply Europe, in a large scale manner, with electricity produced in solar power plants in North Africa and the Arabic peninsula and (b) contribute to the self-supply of the Middle East North Africa region (MENA).

Despite significant efforts by an international network of politicians, academics and economists, publicity for the DII project vanished in 2014/2015. The main message by large media broadcasters focused on the projects failure and the DesertTech concept no longer received any further support. The majority of members left DII at the end of 2014.

The consortium came to the realisation that delivering the DII at the promised cost and within the planned time frame is practically impossible because of political, economic and social reasons.

There are several lessons which can be learned from the DII project when considering future large scale renewable energy projects in the global south.

Hermann Scheer summarised the project idea as an expression of a "new gigantomania" (Scheer 2012, p. 137, in Schmitt, 2018), specifying that the (certain) "technical feasibility", though does not imply a "social feasibility" (Scheer 2012, p. 150, in Schmitt, 2018).

Klawitter and Schinke (2011) argue that a technocratic perspective is insufficient to capture potential socio-political and socio-economic impacts that such a purposive transition could have on either the livelihoods of people in the MENA-region or the success of the concept itself. Without addressing the concept's human development dimension, it is likely to offer – besides climate benefits – only a few trickle-down effects and instead bears a high risk of generating numerous adverse impacts particularly for the most vulnerable groups of society.

Indeed, many different factors contributed to the failure of the project such as technology choices, entrepreneurial performances and political processes, which led to internal conflicts and ultimately the non-realisation. While protagonists viewed the idea as a starting point for a new trans-Mediterranean EU-MENA union, critics in contrast saw it as a neo-colonial project. Two main points deserve further discussion: firstly, the consortium lacked the understanding of local contexts, needs and political issues and secondly the omission to integrate local and community partners and deliberative participatory processes to raise awareness and acceptance of this mega-project and ensure that the local community will benefit from the project.

Certainly, an error from the onset was that most of the founding members of the DII project, had a German or European background. The risk of a quickly destabilising political situation particularly the implications of the Arab spring in North Africa and the Middle East were also underestimated. The main contract personnel vanished or did not respond to the political turmoil and hence conversations were brought to a halt. Socio-economic inequalities and other social issues are continuous challenges influencing the stability of political regimes in the Middle East countries as well as other countries in the global south.

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Acceptance, social license and land use

Although the hydrogen plants as such will take up little space, the land use of renewable energy generation will be significantly larger. As such technology is always situated in a social context and, as a result, renewable energy projects require ongoing negotiation between social, environmental, political, economic and technical factors (Bridge et al., 2013;[107] Ellis et al., 2009[108]). In this context, attention to community engagement processes and the social impacts of large-scale renewable energy projects is essential, and a key determinant of social license.[109] Important considerations are existing ecological, agricultural and heritage values and uses of the land, as well as local people's emotional, religious and historical identification with the place they live on.

In fact, despite large scale renewable energy systems are important for the transformation towards a more sustainable energy system on national and global levels, these technologies do not automatically foster sustainable development at the local level. In this regard, utility-scale renewable power plants show similarities to other large-scale infrastructure projects. Stakeholder and community engagement will be beneficial to ensuring local benefits are distributed and adverse local impacts are reduced. Engagement is most effective in developing constructive relationships and trust if it starts as early as possible. This can help to ensure acceptance of renewable hydrogen production in the short and long term. As in the example of Desertec, the involvement of local stakeholders' right from the project concept stage is important to ensure respective community support and acceptance.

The land requirements for renewable hydrogen are specifically focussed on the availability of good wind or solar resources. Since some geographic regions are hot spots of renewable energy development and there is a competition situation emerging, which has yet to be addressed. The Ökoinstitut (2019)[110] points out that renewable hydrogen can't compete with the direct electricity use which has a much lower land use intensity (for example battery electric vehicles and heat pumps). In countries where not everyone (or at least the large majority) has access to electricity, this becomes even more problematic.

Though there is a paucity of information about the land use potential for renewable hydrogen production and resulting social acceptability while also assessment criteria and standards are missing that define context specific priority uses. These criteria will be essential to ensure that imports of renewable hydrogen comply with sustainability criteria and do not impair the Sustainability Development Goals.

Similar to bioenergy production, renewable hydrogen deployment can lead to direct and indirect land use change and impact ecosystems and their biodiversity. Hence land use along the entire the value chain of renewable hydrogen must comply with criteria to protect biodiversity and ecosystems.

Energy access and new energy colonialism

Energy poverty (incl. the access and means to afford electricity) and low availability of energy services are a major issue in the global south, particularly in Sub-Sahara Africa. In fact, 68% of the continent's population lack access to electricity (Sustainable Energy For All – SE4All, 2020).[111] North African countries and South Africa are major exceptions with significantly higher levels of electrification and overall energy consumption. Meeting current and future energy demand poses a major challenge to all African countries. Hence extensive renewable energy deployment could offer multiple benefits and opportunities. However, they could also increase the issues of electricity access and affordability for local communities.

These issues are pertinent as a recent example from Congo and the Inga dams – two hydroelectric dams at one of the largest waterfalls in the world – has shown. In the context of the German push for renewable hydrogen a business delegation caused confusion in the Democratic Republic of Congo. Potential investors held talks at the highest level in Kinshasa and visited the Inga dams on the Congo River. The Congolese media reported that the Germans wanted to build a plant in the Congo to produce hydrogen promising investments of up to 50 billion Euros – more than Congo's gross domestic product. In fact, the Inga dams have been discussed for decades. The current electricity produced from Inga I and II benefit the country and a part is exported to South Africa. A third dam, Inga III, has been in planning for decades and with around 11 gigawatts of capacity is expected to increase power generation tenfold. Yet, it must be built first. But even that electricity is already sold to benefit the country itself and to South Africa. In addition, the list of other interested parties from Angola to Nigeria is long. It appears the German delegation overlooked bluntly the fact, that these countries firstly need all the electricity for themselves while Inga III may also lead to massive social and ecological impacts. Their approach very much resembles old patterns of exploitation and energy colonialism. To keep the integrity of German hydrogen plans, such activities must be avoided.

Collaboration for renewable hydrogen production with countries in the global south must become equal partnerships.

SWOT Analysis

The production of renewable hydrogen requires large scale renewable energy generation and thus will have social and ecological impacts particular in countries of the global south which are considered to hold a wealth of renewable energy sources. Public policy and government funding are essential to support the commercialisation of renewable hydrogen. Hence policy makers have a key role in designing and guiding the renewable hydrogen deployment.

The experience with the negative impacts of an extensive biofuel production needs to be taken into consideration when defining a framework for a sustainable renewable hydrogen deployment. This also includes the soft criteria of local acceptance and local participation.

The analysis of Strengths, Weaknesses, Opportunities, and Threats (SWOT) is based on the previous literature and provides a short summary of the perceived opportunities and risks associated with a renewable hydrogen production and respective expansion of renewable energy generation in the global south.

Threats and weaknesses of hydrogen projects are similar to fossil fuel-based and nuclear energy infrastructure projects. They are significant but there are not causally related to the actual technology itself. While the strength and opportunities are significantly larger for renewable hydrogen.

Policy development: Hydrogen for Climate Protection continued

However, strong and effective policies are required, to avoid the negative impacts documented from various energy infrastructure projects in the global south.

The import strategy for hydrogen of a nation, such as Germany, needs to establish hydrogen product criteria to support the strength and opportunities arising from renewable hydrogen production such as:

- Certificates of origin to guarantee the sustainable and renewable production of hydrogen
- Social standards for hydrogen production

Accompanying funding programs for training and education of local staff.

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86. IRENA (2020), Green Hydrogen: A guide to policy making, International Renewable Energy Agency, Abu Dhabi, ISBN: 978-92-9260-286-4

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110. Ökoinstitut. (2019). Kein Selbstläufer: Klimaschutz und Nachhaltigkeit durch PtX. https://www.oeko.de/publikationen/p-details/kein-selbstlaeufer-klimaschutz-und-nachhaltigkeit-durch-ptx

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FIGURE 20: SWOT for renewable hydrogen production in the global south

Strengths

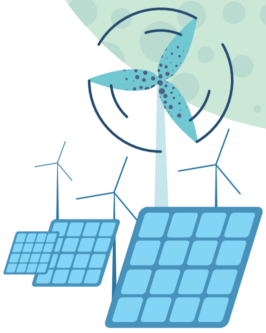
1. Use of available local resources for solar and wind (deserts, coastlines, non-arable or uninhabitable land due to mining and/or climate change)
2. Renewable energy strengthens the focus on ecological sustainability
3. Young and growing population
4. Support equitable development and bolster community livelihoods

Weaknesses

1. Political instability in form of institutional set ups and governance structures
2. Low investment capacity
3. High legal uncertainty
4. Lack of required infrastructure
5. Long distance transport required
6. Lack of technological and skills transfer by donor countries

Opportunties

1. Fast-tracked access to energy services, e.g. through electrification benefits for rural areas, industry and small to large businesses
2. Enhanced access to technology, education and training
3. Additional employment opportunities
4. Local economic development (manufacturing, profit shares from community energy)



Threats

1. Land use conflicts
2. Lack of social acceptance
   - **a.** risk of corruption and disengagement if community engagement is neglected
   - **b.** risk of project cost increase due to poor planning
   - **c.** risk of conflict over the use of local resources, related to water use, water scarcity and land use and land scarcity
3. Negative impacts on local ecosystems
4. Technology failures
5. Financial dependence on donor countries


H_2
H_2 HYDROGEN POWER
CLEAN ENERGY OF THE FUTURE
H_2

Rendering of a Hydrogen renewable energy production facility. © Audio und werbung

06

Policy Recommendations for Germany

The policy recommendations discussed in this section focus on social and environmental standards. Policies to foster the development of the renewable hydrogen technology and to establish the required economic framework have been developed by the International Renewable Energy Agency and published in their 'Green Hydrogen Policy Guide' in 2020 (IRENA 2020). While those international policy recommendations will need to be adapted to the German national context, the overall framework of the IRENA recommendations seem sufficient and comprehensive.

However, more policies are required to secure social and environmental standards and to avoid energy colonialism in the global south.

The societal context of countries in the global south is very complex and viewing the renewable hydrogen as a panacea is misleading. Questions of equity, human rights and sustainability are pertinent. In fact, the whole debate must boil down to a single question: How can renewable hydrogen improve the lives of the people in the global south, especially the most vulnerable and the most marginalised, to contribute to the paradigm of the Agenda 2030 "to leave no one behind".

Policy development: hydrogen for Climate Protection continued

It is important to take lessons from the biofuels and bioenergy use in Germany and Europe and develop a risk reduction strategy to avoid probable negative sustainability effects (Ökoinstitut, 2019). Based on the research documented in this report, we recommend including the following policies in the German National Hydrogen Strategy (BMWi 2020):

Environment and Sustainability

The German National Hydrogen Strategy states that:

"The Federal Government considers only hydrogen that has been produced using renewable energy (green hydrogen) to be sustainable in the long term." (BMWK, 2020, p. 3).

Furthermore, transparent and mandatory technical standards are required to define sustainably produced renewable hydrogen such as:

1. Renewable electricity generation for the production for imported hydrogen to Germany must meet the same environmental standards as power generation plants in Germany
2. For the production for synthetic fuels, the carbon must have a certificate of origin. The carbon must come from either biomass or air-capturing processes. Fossil carbon sources are excluded.
3. Infrastructure for transport and storage of hydrogen should prioritise to re-use and/or convert marine and land based natural gas transportation equipment and natural gas storage facilities to promote and accelerate the (technical) transition of fossil fuel infrastructure.

Social Responsibility

Germany's current National Hydrogen Strategy does not contain the word 'social' and 'responsibility' when describing the nation's requirements to reduce greenhouse gas emissions – which we of cause support. However, social responsibility is also required in the way renewable hydrogen is produced – whether it in Germany or outside Germany. In the context of hydrogen imports, the strategy clearly states hydrogen will be imported in 'substantial quantities' in the 'medium to long-term'.

Furthermore, the National Hydrogen Strategy formulates that the Germany government *'shares with other future importers an interest in the swiftest possible establishment of a global hydrogen market. In view of their potential for renewable energy, the countries currently producing and exporting fossil fuels also have attractive opportunities to convert their supply chains to the use of renewable energy and hydrogen, and thus to become potential suppliers of hydrogen. In this way, these countries will be also able to benefit in the long term from existing trade relations.'*

Suggestion for addition to the *National Hydrogen Strategy*:

- The Federal Government considers only hydrogen to be imported to Germany that is produced socially responsible in the production countries of origin. This includes that hydrogen producing companies :
- operate with non-discriminatory employment practices
- pay rates equal to or higher than the legal or regional minimum wages,
- respect freedom of association and collective bargaining rights for the workforce,
- safeguards for worker safety and health.

Transparent and mandatory technical standards are required to define sustainably produced renewable hydrogen.

Development for the Global South

Core recommendations for investors and companies operating in the global south include:

- Set a clear and urgent goal to implement human rights and environmental due diligence in operations and supply chains, alongside access to remedy, with special emphasis on land and community rights risks.
- Work towards the international standards of the United Nations Guiding Principles on Business and Human Rights (UNGPs). Ensure the approach is proactive and consults those at risk of being impacted or exploited. Reinforce related goals with a time-bound plan, resourcing commensurate to ambition, executive oversight and board approval.
- Leading green hydrogen investors and companies should cooperate to jointly call on governments and partners to demand higher social standards.
- Seek to implement both co-benefit and co-ownership models to build long term value and stable infrastructure.

Furthermore, the future of renewable hydrogen will go beyond the energy and economic dimensions, as a cross-cutting topic, it will have wide-ranging implications for foreign and security policy development. Global competition for technologies, control of supply chains and critical raw materials (CRMs) as well as supply security concerns will shape the pathway towards a renewable hydrogen world and determine the future geo-economic cooperation as well as geopolitical conflicts in the next decades.

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KATO

A refinery that uses hydrogen under construction. © Sergio Bertino

07

Conclusion

The adoption of renewable hydrogen by hard-to-mitigate sectors is crucial to keep global warming below 1.5°C by 2050. The large scale uptake of renewable hydrogen will enable energy intensive industries, such as the steel, cement, chemical and heavy transport sector, to reduce GHG emissions and operate in a net zero world. However, the transition towards renewable hydrogen must be planned and implemented in a fair and sustainable manner with human rights and environmental protection at its core, and with a significant benefit for societies in the global south.

First, it is essential that hydrogen production is generated using renewable electricity. Currently, more than 95% of hydrogen is produced from natural gas, oil, and coal – highly carbon intensive processes. The large scale uptake of hydrogen by industry sectors, must avoid prolonging the use of fossil fuels, thus hydrogen must be produced via the electrolysis route, powered by renewable energy sources, such as large scale wind and solar PV.

Conclusion continued

While industrialised nations have been leading the technological development of renewable hydrogen, developing countries have merely focussed on technology adoption and production for export markets to meet the growing electricity demand of industrialised nations. To fuel the future economy with renewable hydrogen, it will require 1.5 times the amount of electricity, which was generated worldwide in 2020.

Second, the global south has experienced energy colonialism, abuse of human rights and environmental degradation because of fossil fuel trade in the past, such experiences must be avoided at all costs. With the shift towards renewable hydrogen, the energy sector can learn from the past. Key lessons can be learned from failures caused by the extensive fossil fuel export from the global south to industrised nations. In the past, a combination of lack of political will by governments, limited governance structures, lack of monitoring by civil society and media, and fossil fuel companies benefiting from unregulated resource exploitation, left communities of the global south exposed to adverse social and environmental impacts. Particularly affected were those living near fossil fuel extraction sites.

Third, energy companies and businesses investing in hydrogen production in the global south, must ensure local communities will benefit from such major developments. Benefits can be delivered through

- early engagement e.g. in form of public consultations, the representation of local voices in formal arrangements, participation in project consortia, allows to better communicate local contexts, needs and understand political issues and developments,
- job creation, fair wages, and
- long-term benefits, here access to energy services and renewable energy is key.

Fourth, renewable hydrogen production must be considered 'additional' to essential energy services, meaning it must not restrict, but support communities' access to affordable, reliable and modern energy services (Sustainable Development Goal #7). Any conflicts between the transition to 100% renewable electricity and the production of renewable hydrogen for export markets, must be avoided.

Fifth, responsible planning and siting can avoid land use conflicts and the misuse of critical resources, including water. The production of hydrogen via the electrolysis requires fresh water as a source. There are only a limited number of countries in the global south, which have the capacities to produce hydrogen for export purposes, these include Morocco, South Africa, and Chile. It is predicted that by 2040, all three nations will be experiencing high to extreme levels of water stress. In countries of the global south that suffer water stress, the operation of renewable hydrogen plants must be carefully evaluated, in cases where restrictions of drinking water supply or irrigation of agricultural areas occur, developments must be avoided altogether. Again, the cooperation with local communities to identify and map water-related issues, is vital. Although, locations of wind and solar farm deployments are limited by a region's wind speed and sunshine potential, low impact areas for water resources and biodiversity conservation, can be best identified early on during the planning and consultation process.

Finally, the timing for the energy transition, including renewable hydrogen production, is well underway, therefore responsible decision-making and the development of ethical guidelines must not be delayed. The development of renewable hydrogen technology is progressing quickly, and technology is already available. Technology uptake by the global south will be the next step, this process must be led by guidelines, which include learnings from failures of fossil fuels projects. In this regard, the early engagement and participation of communities in the development of renewable hydrogen plants, will not only ensure community benefits occur, but will inform the provision of energy services, identify sites of high/low social, cultural and environmental value, and oversee the fair distribution of material and economic benefits.

Finally, the timing for the energy transition, including renewable hydrogen production, is well underway, therefore responsible decision-making and the development of ethical guidelines must not be delayed.

Factory emissions.
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Hydrogen Energy Project in Hastings, Victoria, Australia. Liquid hydrogen will be shipped to Japan. © Dorothy Chiron

Technical and Economic Data

A. Hydrogen and Power to X

While hydrogen is a fuel, Power-to-X (PtX) is often used as a term for the conversion processes and technologies. Power or "P" stands for the electricity or input on the production side. The "X" can stand for any resulting fuel, chemical, power or heat. PtX has received increasing public attention since these technologies can enable an indirect electrification of sectors that are (so far) dependent on fossil fuels, which include

- Power-to-Heat (PtH): Transforming electricity to heat through heat pumps, electrical resistance heating, induction, plasma process etc.
- Power-to-Gas (PtG): Transfer electricity into a gaseous, material energy carrier. This involves hydrolysis (H and O_2) and can further involve carbon (CO_2) to produce methane or ammonium
- Power-to-Liquid (PtL): Transfer electricity into fluid material energy carriers

B. Hydrogen production – Background information

Hydrogen has to be produced with renewable electricity (green hydrogen) to constitute a zero emission technology, a climate solution and involves a technology (electrolysers) that over the next decade could rapidly come down the cost curve like solar, wind and batteries, making it affordable.

A central step for renewable hydrogen production is electrolysis, in which hydrogen (H_2) and oxygen (O_2) are obtained from pure water (H_2O) by means of electricity with conversion losses.

The core equipment for this process is the electrolyser:

Electrolyser: A single fuel cell consists of a membrane electrode assembly (MEA) and two flow-field plates delivering about 0.5 and 1V voltage, which is too low for most applications. Just like batteries, individual cells are stacked to achieve higher voltage and power. This assembly of cells is called a fuel cell stack, or just a stack.[i] Basically, the main differences between those four types are the chosen materials for the membrane and the design of the 'cell stack'.

Resources for electrolyser: An Electrolyser has two electrodes or catalysts – one on the oxygen side and one on the hydrogen side. Those electrodes are made out of rare metals. Different electrolyser types use different metals such as nickel, iridium, platinum, gold and titanium.[ii] The quantities are quite low. However, with increased implementation of electrolysers, the use of rare metals must be monitored, and possible environmental impacts avoided.

Transport: Hydrogen can be used directly in various applications or stored in form of gas or liquefied hydrogen and distributed for usage where and when required, constituting the key element for 'sector coupling'. However, hydrogen must be compressed (for gas) or liquefied, which requires additional energy. Equally, it can then be converted back to electricity or used to displace demand for natural gas in the heating (and power) sector, or indeed for transport. Throughout the overall production, distribution and retail chain of compressed hydrogen about 4% losses occur (ROD 2018).[iii]

Technical and Economic Data continued

C.

Current and future costs of hydrogen production with electricity

This section focuses on the current and future costs for electrolysers to produce hydrogen, and the estimated overall production costs for renewable hydrogen. The International Renewable Energy Agency (IRENA) published a comprehensive analysis, the data presented here is largely based on the IRENA analysis (IRENA-H_2 2020A).[iv] The IRENA analysis provides a detailed cost overview of all parts of the electrolyser – such as manufacturing, costs for anodes, cathodes etc. – and a detailed breakdown of how these costs can be reduced. However, our analysis focuses on policy developments and therefore only high level results will be presented.

There are two commercially available processes for water electrolysis: alkaline electrolysis cells (AEC) and polymer electrolyte membranes (PEMEC). AEC are the incumbent technology with a 100-year history, but PEMEC are rapidly reaching maturity and are of particular interest for power-to-gas applications. PEM systems were introduced in the 1960s and were commercialised in the last decade. However, there are currently more electrolyser technologies under development.

The current investment costs for electrolysers are largely dependent on chosen technology. There are four main technology types:

1. Polymer Electrolyte Membrane (PEM) electrolyser
2. Alkaline electrolyser
3. Anion Exchange Membrane (AEM) electrolyser
4. Solid oxide electrolyser

Efficiencies: All electrolyser types have different efficiencies. The dominating technology to date is PEM. Depending on the system, between 50 and 83 kilowatt-hours are needed to produce one kilogram of hydrogen. Converting efficiency into percentage values is equal to 50% to 65% efficiency. Currently, about half of the energy is lost over the whole cycle: electricity to hydrogen, storage and transport, hydrogen combustion in power plants, and back to electricity. In energy scenarios, it is usually assumed that the full-cycle efficiency increases to 75% by 2050. Efficiencies for the four technologies are shown in Table 2.

Besides the electrolyser technology, the installed capacity – the size of the system – is of high importance for the costs. Larger system sizes are significantly cheaper than smaller ones.

Table 4 shows the costs for four different electrolyser technologies in 2020 and the cost reduction target to get below US$100 per kW for the stack and below US$ 200 per kW for the system by 2050.

Besides the investment costs for electrolysers themselves, the operating hours per year are an important parameter to reduce the production costs for each unit of hydrogen. The higher the annual utilisation, the lower the hydrogen production costs. Thus, hydrogen production with 'surplus' electricity from wind or solar farms will lead to high costs and battery storage will most likely be more economic. Therefore, electrolysers must be largely dedicated to hydrogen production as a fuel and not only as a short-term storage technology.

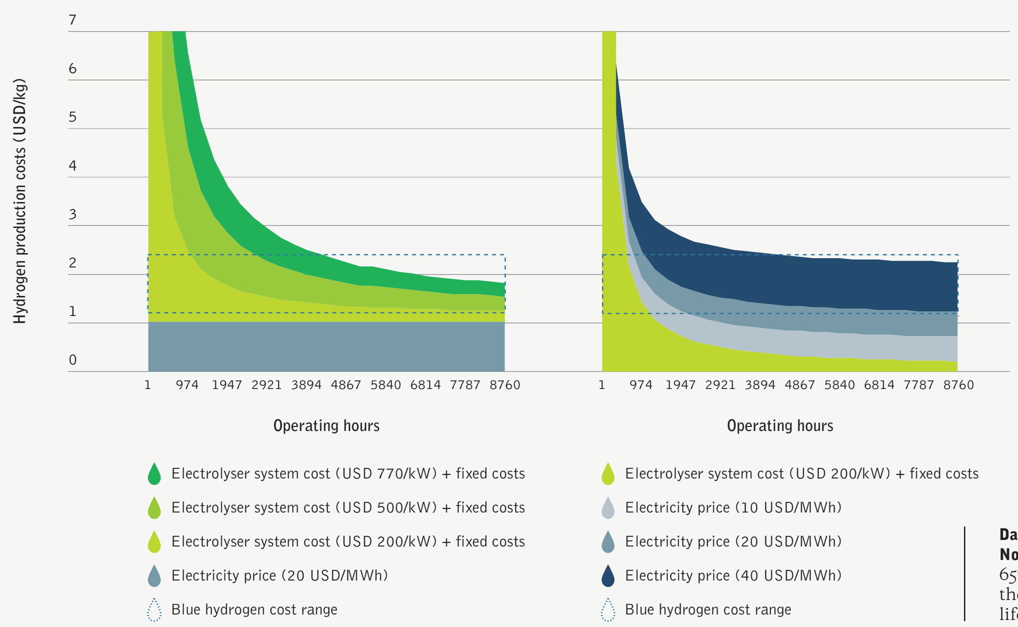
Finally, the actual electricity price per unit to operate the electrolyser is of significant importance. Figure 21 shows the production costs for one kg of hydrogen in relation to the electrolyser costs per kilowatt (right). The left figure shows the calculated production cost with a US$ 200 electrolyser system and three different electricity prices: US$ 40, US$ 20 and US$ per megawatt-hour (MWh). The dashed lines indicate the costs for fossil hydrogen.

Table 4: Current and future Efficiencies and costs of electrolysers

	2020	TARGET 2050
PEM		
System efficiency [kWh/kgH2]	50-83	<45
Capital costs (stack) - minimum 1 MW -	USD 400/kW	< USD 100/kW
Capital Costs (system) - minimum 10 MW-	700-1,400 USD/kW	< 200 USD/kW
Alkaline		
System efficiency [kWh/kgH2]	50-78	<45
Capital costs (stack) - minimum 1 MW -	USD 270/kW	< USD 100/kW
Capital Costs (system) - minimum 10 MW-	500-1,000 USD/kW	< 200 USD/kW
AEM		
System efficiency [kWh/kgH2]	57-69	<45
Capital costs (stack) - minimum 1 MW -	unknown	< USD 100/kW
Capital Costs (system) - minimum 10 MW-	unknown	< 200 USD/kW
Solide Oxide		
System efficiency [kWh/kgH2]	45-55	<40
Capital costs (stack) - minimum 1 MW -	> USD 2,000/kW	< USD 200/kW
Capital Costs (system) - minimum 10 MW-	unknown	< 300 USD/kW

Source: IRENA (2020a).[v]

Figure 21: Hydrogen production cost as a function of investment, electricity price and operating hours[vi]



Data: Based on IRENA analysis.
Note: Efficiency at nominal capacity is 65% (with an LHV of 51.2 kWh/kg H_2), the discount rate 8% and the stack lifetime 80,000 hours.

Technical and Economic Data continued

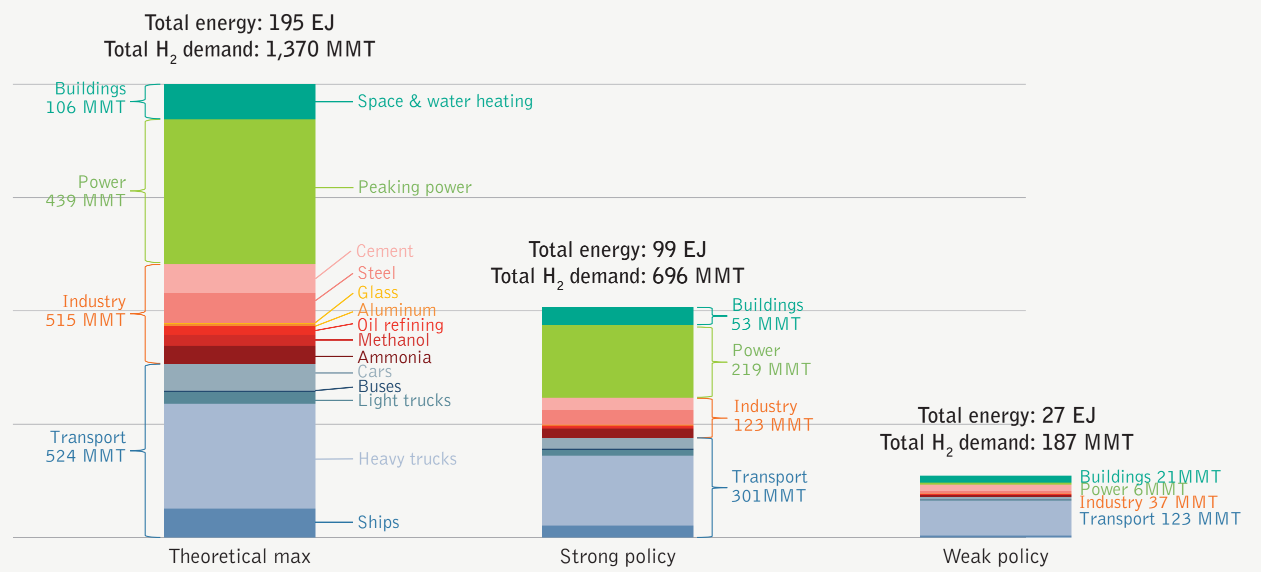
D.

The Role of Renewable Hydrogen in Climate Mitigation Pathways – energy models and net zero scenarios

The analysis considers the key technologies required for a successful energy transition and focuses on the roles and potential of renewable energies. Wind and solar energy have the highest economic potential and dominate the pathways on the supply side. However, variable renewable power from wind and photovoltaics (PV) remains limited by the need for sufficient secured capacity in energy systems. Therefore, we also consider hydro power, bio and geothermal energy as well as concentrated solar power (CSP) with high-temperature heat storage as a solar option that promises large-scale dispatchable and secured power generation.

There are various global decarbonisation scenarios with a target to keep global warming below +1.5°C published in the literature. Under the Bloomberg New Energy Finance[vii] *Weak Policy* scenario, 7% of the global energy supply would come from hydrogen, while their Strong Policy case would result in a 24% hydrogen share (see Figure 22). Bloomberg projects under the *Theoretical Maximum* case (Figure 22) that all 'unlikely to electrify' sectors would substitute fossil fuels with renewable hydrogen, which would increase global hydrogen demand to 1,370 MMT (million tons). This would require an additional 11,000 GW of wind power, and solar capacity will also be required for hydrogen production only, over the next 30 years, to generate 31,320 TWh/a. To put this in perspective, the global electricity generation in 2020 was around 22,000 TWh/a.

Figure 22: Potential demand for hydrogen in different scenarios, 2050



Source: BNEF, 2020. **Note:** Aluminum demand is for alumina production and aluminum recycling only. Cement demand is for process heat only. Oil refinig demand is for hydrogen use only. Road transport and heating demand that is unlikely to be met by electrification only: assumed to be 50% of space and water heating, 25% of light-duty vehicles, 50% of medium-duty trucks, 30% of buses and 75% of heavy-duty trucks.

D.1.

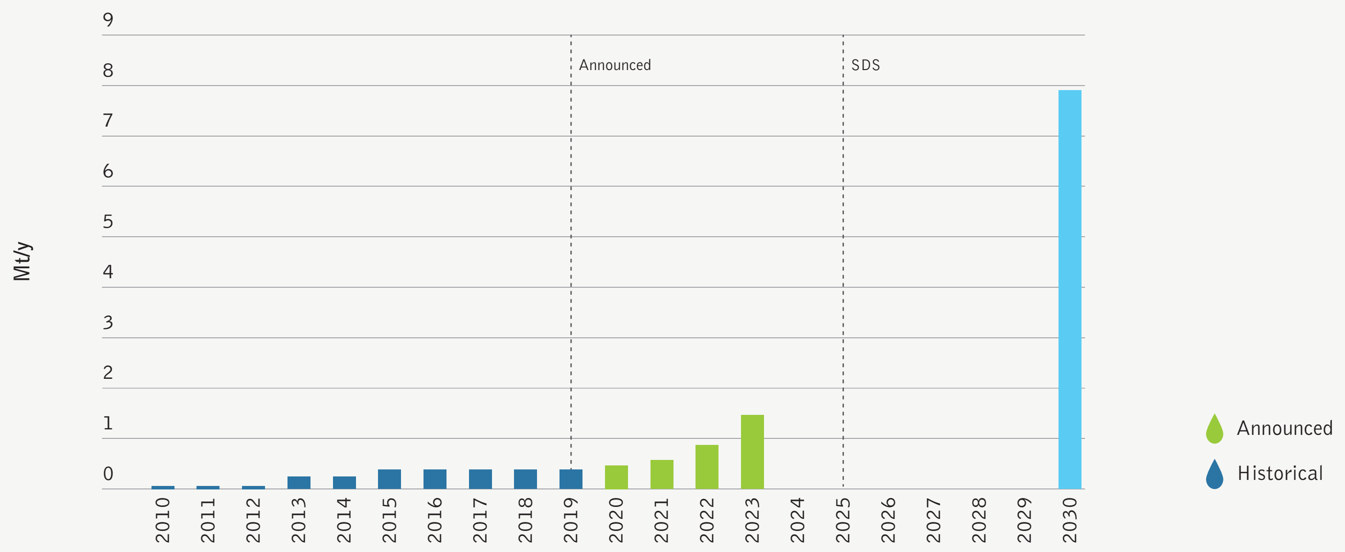
International Energy Agency – Sustainable Development Scenario

The Sustainable Development scenario of the International Energy Agency (IEA) projects an increase from 0.46 Mt hydrogen to 7.92 Mt hydrogen in 2030, an increase by factor 16 in only 10 years (Figure 23). However, this includes the production of fossil-based hydrogen as well as renewable hydrogen.

Global Energy System based on 100% Renewable Energy (University of Lappeenranta)

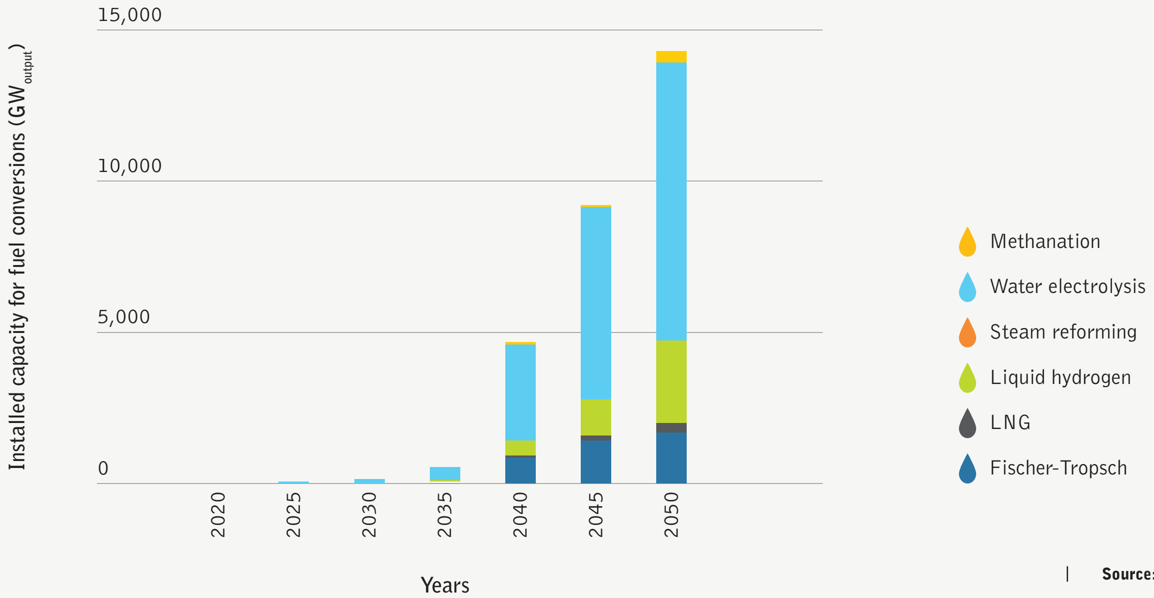
In June 2019, researchers from the University of Lappeenranta (LUT), published a 100% renewable energy scenario (Ram et al., 2019).[ix] Hydrogen and batteries represent the main storage technologies for heat, electricity and transport services. Electrolysis plays the dominating role for the hydrogen and synthetic fuel production. By 2050 almost 10,000 GW of electrolysis capacities are required globally (Figure 24).

Figure 23: Low-carbon hydrogen production, 2010-2030, historical, announced and in the Sustainable Development Scenario, 2030



Source: IEA (2020).[viii]

Figure 24: Installed capacities of fuel conversion technologies



Source: Ram et al. (2019).

Technical and Economic Data continued

D.2.1

Deep dive: The One Earth Climate Model

In order to analyse the role of hydrogen in the future CO_2-free global energy supply in more detail, we present scientific work by the University of Technology Sydney. 'Achieving the Paris Climate Agreements- Global and Regional 100% Renewable Energy Scenarios with non-energy GHG Pathways for +1.5°C and +2°C,[x] published in February 2019, the following storylines and assumptions are based on this work. The energy modelling primarily aims to achieve a transparent and consistent scenario, an ambitious but still plausible storyline from several possible techno-economic pathways. Knowledge integration is the core of this approach because we must consider different technical, economic, environmental, and societal factors. The scenario modelling follows a hybrid bottom-up/top-down approach, with no objective cost-optimisation functions.

Scenario definition

Scenario modelling was performed for three main scenarios that can be related to different overall carbon budgets between 2015 and 2050 and derived mean global temperature increases. The (around) 5.0°C Scenario was calculated based on the Current Policies scenario published by the International Energy Agency (IEA) in World Energy Outlook 2017 (IEA 2017),[xi] and the emission budget for this scenario simply uses and extrapolates from the corresponding narratives. The 2.0°C and 1.5°C Scenarios were calculated in a normative way to achieve defined emission budgets.

The Global Economy by 2050 – Socio-Economic Assumptions

- World GDP[xii] will grow on average by 3.2% per year over the period 2015–2050 although with significant regional differences (according to predications from the World Bank)
- The world population[xiii] is expected to grow by 0.8% per year on average over the period 2015–2050 although with significant regional differences (projection from UN). Global population will increase from 7.4 billion people in 2015 to nearly 9.8 billion by 2050

The 1.5°C Scenario

The optimal scenario in terms of climate outcomes is the 1.5°C scenario, which aims to achieve a global energy-related CO_2 emission budget of around 450 Gt, accumulated between 2015 and 2050. The 1.5°C Scenario requires immediate action to realise all available options. It is a technical pathway, not a political prognosis. It refers to technically possible measures and options without taking into account societal risks or barriers. Efficiency and renewable potentials must be deployed even more quickly than in the 2.0°C Scenario. Furthermore, avoiding inefficient technologies and behaviours are essential strategies for developing regions in this time period.

The scenario-building process involves many assumptions and explicit, but also implicit, narratives about how future economies and societies, and ultimately energy systems, may develop under the overall objective of 'deep and rapid decarbonisation' by 2050. These narratives depend on three main strategic pillars:

- Efficiency improvement and demand reduction leading to a continuous reduction in both final and primary energy consumption. In the 1.5 °C Scenario, these measures must be supplemented with responsible energy consumption behaviour by the consumer.
- Deployment of renewable energies: massive implementation of new technologies for the generation of power and heat in all sectors.
- Sector coupling: stringent direct electrification of heating and transport technologies in order to integrate renewable energy in the most efficient way. Because this strategy has its limitations, it will be complemented by the massive use of hydrogen (generated by electrolysis) or other synthetic energy carriers.

The 2.0°C Scenario

The second best scenario, is the 2.0°C scenario, which aims to achieve an ambitious emissions reduction to zero by 2050 and a global energy-related CO_2 emissions budget between 2015 and 2050 of around 590 Gt. The scenario is close to the assumptions and results of the Advanced E[R] scenario published in 2015 by Greenpeace (Teske et al. 2015).[xiv] However, the scenario includes an updated base year, more coherent regional developments of energy intensities, and reconsidered trajectories and shares of renewable energy resource (RES) deployment. The 2.0 °C Scenario represents a far more likely pathway than the 1.5 °C Scenario, because the 2.0 °C case takes into account unavoidable delays due to political, economic, and societal processes and stakeholders. Some alternative or probably complementary future technical options are explicitly excluded from the scenarios. In particular, those options with large uncertainties with respect to technical, economic, societal, and environmental risks, such as large hydro and nuclear power plants, unsustainable biomass use, carbon capture and storage (CCS), and geoengineering, are not considered on the supply side as mitigation measures or—in the case of hydro—not expanded in the future. The sustainable use of biomass will partly substitute for fossil fuels in all energy sectors. However, this use will be limited to an annual global energy potential of less than 100 EJ per year for sustainability reasons, according to the calculations of Seidenberger et al. (2008),[xv] Thrän et al. (2011),[xvi] and Schueler et al. (2013).[xvii]

The 5.0°C Scenario (reference scenario)

The reference case only takes into account existing international energy and environmental policies. Its assumptions include, for example, continuing progress in electricity and gas market reforms, the liberalisation of cross-border energy trade, and recent policies designed to combat environmental pollution. The scenario does not include additional policies to reduce greenhouse gas (GHG) emissions. Because the IEA's projections only extend to 2040, we have extrapolated their key macroeconomic and energy indicators forward to 2050. This provides a baseline for comparison with the 2.0°C and 1.5°C Scenarios. It is indisputably clear from climate science, including the IPCC's 1.5°C report that following such a scenario in the real world, would result in catastrophic impacts on worldwide, causing the death, displacement and loss of livelihoods of hundreds of millions globally. This scenario is included to compare the results of the 1.5°C and 2.0°C pathways.

Approach

The scenario modelling follows a hybrid bottom-up/ top-down approach, with no cost optimising objective functions. The analysis considers key technologies for successful energy transition and focuses on the role and potential utility of efficiency measures and renewable energies. Wind and solar energies have the highest economic potential and dominate the pathways on the supply side. However, the variable renewable power from wind and PV remains limited to a maximum of 65%, because sufficient secured capacity must always be maintained in the electricity system. Therefore, we also consider concentrating solar power (CSP) with high-temperature heat storage as a solar option that promises large-scale dispatchable and secured power generation.

In this section, we focus on the presentation of the role of hydrogen and synthetic fuel (= synfuels) for the supply of the transport, industry and heat sector as fuel that replaces fossil fuels, as replacement of natural gas in the power sector and the electricity required to produce these fuels.

Hydrogen and synthetic fuels are not an energy source, but a storage medium for electricity generated with renewable power technologies, predominantly solar and wind. Scenario assumptions for hydrogen and synthetic fuels. Although the energy losses in the production of synthetic fuels are significant, these fuels are expected to be mandatory in the deep decarbonisation scenarios for sectors and processes in which the direct use of other renewable sources, including renewable power, is not technically feasible. We assume an optimistic increase in the efficiency – the ratio from energy output: H_2 to energy input (electricity) of electrolytic hydrogen generation – from 66% today to 77% by 2050. The generation of synthetic fuels (such as Fischer-Tropsch fuels) from hydrogen, using CO_2 as the carbon source, is assumed to be a complementary option that will allow the decarbonisation of long-range transport, particularly aviation and international bunkers, without exceeding the defined maximum sustainable biomass use. Therefore, the assumed shares of power-to-liquid synfuels in the aggregated biofuel/synfuel fraction of all transport modes is a result of the sectoral allocation of the limited biomass potentials in each world region. The assumed efficiency of synfuel generation will increase from 35% in 2020 to 42% in 2050.

Technical and Economic Data continued

D.2.2

Power sector: The role of hydrogen and synthetic fuels

The production of hydrogen and synthetic fuels with electricity increase the overall power demand significantly. Both in the 2.0°C as well as in the 1.5°C hydrogen – and to a lesser extend synthetic fuels – production starts around 2025 and increased gradually until it reaches between 24 % respectively 29% in 2045 (Table 2). The overall electricity demand for hydrogen and synthetic fuels in 2050 under the 1.5°C case arrives at just below 20,000 TWh – equal to the total global electricity demand in the year 2012. Around 75% of this electricity will be required for hydrogen production and the remaining 25% for synthetic fuels.

The produced hydrogen will be mainly used to replace fuels in the transport and industry sector, while the use for hydrogen as a replacement of natural gas in power and co-generation plants will be the smallest fraction. Under the 1.5°C case, 5% of global electricity generation require hydrogen fuels.

D.2.3

Transport: The role of hydrogen and synthetic fuels

Table 6 shows the energy demand for the transport sector, the transport subsectors road, rail, navigation and aviation as well as the role of electricity, hydrogen and synthetic fuels for supply.

Road: Hydrogen and synthetic fuels are mainly used for heavy duty vehicles to transport freight and large vehicles for public transport such as busses. The role of hydrogen in passenger cars remains minor until 2050 as electric vehicles with battery storage are seen as a more cost competitive option.

Rail: The electrification of railways is believed to be the most cost effective option and only remote train lines will use synthetic fuels as transition fuels to replace diesel. By 2050, all trains are fully electrified under all three scenarios.

Table 5: Power Sector; The role of hydrogen and synfuels for supply and demand

	UNIT	2018	2020 estimated	2025	2030	2035	2040	2045	2050
TOTAL POWER GENERATION									
REF	[TWh/a]	26,551	25,149	30,337	34,586	38,459	42,333	45,703	49,033
2.0°C	[TWh/a]			30,482	35,672	42,378	51,037	59,637	65,905
1.5°C	[TWh/a]			30,202	36,818	45,265	54,722	61,800	65,313
HYDROGEN FOR POWER SECTOR									
REF	[TWh/a]	0	0	0	0	1	1	1	1
2.0°C	[TWh/a]			39	93	289	865	1,833	3,063
1.5°C	[TWh/a]			34	270	750	1,729	2,627	3,127
ELECTRICITY FOR HYDROGEN PRODUCTION									
REF	[TWh/a]	0	0	3	3	4	4	4	4
2.0°C	[TWh/a]			395	1,131	3,025	6,617	11,216	15,048
1.5°C	[TWh/a]			508	2,631	5,725	10,495	14,363	15,139
ELECTRICITY FOR SYNFUEL PRODUCTION									
REF	[TWh/a]	0	0	0	0	0	-1	0	0
2.0°C	[TWh/a]			3	60	344	1,678	2,974	3,730
1.5°C	[TWh/a]			4	283	1,484	3,106	3,807	4,119
SHARE OF ELECTRICITY USED FOR HYDROGEN AND SYNFUEL PRODUCTION									
REF	[%]	0%	0%	0%	0%	0%	0%	0%	0%
2.0°C	[%]			1%	3%	8%	16%	24%	28%
1.5°C	[%]			2%	8%	16%	25%	29%	29%

Aviation: Synthetic fuels to replace fossil fuel play a significant role in aviation and supply around 50% of total fuels by 2050 under the 1.5°C case, complemented by bio kerosene which supplies the remaining demand.

Navigation / Shipping: Synthetic fuels replace diesel and heavy fuel oil. By 2050, half of all fuels required for the shipping industry come synthetic fuels and the other half from bio diesel (1.5°C case).

In regard to the overall quantity, hydrogen is only used in road transport, while synthetic fuels play a significant role in aviation and shipping. The 2.0°C pathway synthetic fuels and hydrogen will supply 29% of all transport energy needs, while the 1.5C pathway will lead to 35%. The remaining transport energy for road and rail will be supplied from electricity either via on-board battery storage or via (overhead) lines.

Table 6: Transport: Final energy demand and the development of electricity, hydrogen and synfuels for supply under three scenarios

TRANSPORT		UNIT	2018	2020 (e)*	2025	2030	2035	2040	2045	2050
Road	REF	[PJ/a]			94,754	102,555	109,419	116,450	122,846	127,758
	2.0°C	[PJ/a]	89,746	84,029	79,971	68,583	56,415	46,753	40,547	35,973
	1.5°C	[PJ/a]			67,575	48,607	36,662	31,052	27,346	24,870
• synfuels	REF	[PJ/a]			0	0	1	-1	0	0
	2.0°C	[PJ/a]	0	0	4	77	403	1,897	3,229	4,117
	1.5°C	[PJ/a]			5	342	1,591	3,003	3,702	3,988
• hydrogen	REF	[PJ/a]			4	4	4	4	4	4
	2.0°C	[PJ/a]	0	0	493	1,737	3,989	6,112	7,549	8,132
	1.5°C	[PJ/a]			808	2,921	4,776	6,061	6,606	6,764
• electricity	REF	[PJ/a]			739	960	1,223	1,492	1,833	2,263
	2.0°C	[PJ/a]	238	222	2,494	7,925	14,392	18,139	19,480	19,293
	1.5°C	[PJ/a]			3,246	8,537	14,423	15,699	15,101	14,519
Rail	REF	[PJ/a]			2,708	2,814	2,922	3,024	3,116	3,199
	2.0°C	[PJ/a]	2,805	2,505	2,875	3,149	3,393	3,520	3,650	3,960
	1.5°C	[PJ/a]			2,932	3,119	3,316	3,559	3,799	4,087
• synfuels	REF	[PJ/a]			0	0	0	0	0	0
	2.0°C	[PJ/a]	0	0	0	2	11	50	41	0
	1.5°C	[PJ/a]			0	5	30	72	39	0
• electricity	REF	[PJ/a]			1,156	1,270	1,394	1,522	1,656	1,791
	2.0°C	[PJ/a]	1,165	1,104	1,330	1,665	2,108	2,671	3,297	3,960
	1.5°C	[PJ/a]			1,582	2,331	2,927	3,306	3,703	4,087
Navigation	REF	[PJ/a]			2,304	2,392	2,470	2,537	2,624	2,663
	2.0°C	[PJ/a]	2,390	2,267	2,303	2,388	2,462	2,512	2,578	2,601
	1.5°C	[PJ/a]			2,301	2,383	2,456	2,506	2,571	2,601
• synfuels	REF	[PJ/a]			0	0	0	0	0	0
	2.0°C	[PJ/a]	0	0	0	3	26	220	546	846
	1.5°C	[PJ/a]			0	20	214	754	1,045	1,369
Aviation	REF	[PJ/a]			6,544	7,745	8,518	9,080	9,247	9,176
	2.0°C	[PJ/a]	5,669	4,296	4,732	4,239	3,731	3,291	2,937	2,640
	1.5°C	[PJ/a]			4,461	3,612	2,803	2,361	2,075	1,845
• synfuels	REF	[PJ/a]			0	0	0	0	0	0
	2.0°C	[PJ/a]	0	0	0	5	49	292	613	858
	1.5°C	[PJ/a]			0	38	281	721	842	971
Total (incl. pipelines)	REF	[PJ/a]			108,914	118,170	126,062	133,893	140,702	145,726
	2.0°C	[PJ/a]	106,367	98,878	91,861	80,106	67,768	59,033	53,696	49,765
	1.5°C	[PJ/a]			79,222	59,680	48,113	43,436	40,116	37,710
• synfuels	REF	[PJ/a]			0	1	1	-1	0	0
	2.0°C	[PJ/a]	0	0	4	86	490	2,459	4,429	5,820
	1.5°C	[PJ/a]			5	404	2,115	4,551	5,629	6,328
• hydrogen	REF	[PJ/a]			4	4	4	4	4	4
	2.0°C	[PJ/a]	0	0	501	1,750	4,022	6,188	7,699	8,430
	1.5°C	[PJ/a]			827	3,029	5,130	6,308	6,764	6,849
• electricity	REF	[PJ/a]			1,985	2,320	2,709	3,106	3,582	4,149
	2.0°C	[PJ/a]	1,404	1,325	3,928	9,702	16,690	21,118	23,042	23,430
	1.5°C	[PJ/a]			4,930	11,034	17,581	19,380	19,142	18,839
Share of hydrogen and synfuels in the transport sector	REF	[%]			0%	0%	0%	0%	0%	0%
	2.0°C	[%]	0%	0%	1%	2%	7%	15%	23%	29%
	1.5°C	[%]			1%	6%	15%	25%	31%	35%

Legend: * (e) estimated.

Technical and Economic Data continued

D.2.4

Industry: The role of hydrogen and synthetic fuels

Hydrogen plays and important role in industry to provide high temperature process heat. The steel industry currently emits 8% of global carbon dioxide emissions.[xviii] Among the only possible option for the steel industry to decarbonise, is to use hydrogen for Direct Reduced Iron (DRI). Thus, hydrogen plays a significant role for some industry sectors where processes cannot be entirely electrified. However, compared to the global industry energy demand (across all sectors), hydrogen will only provide a share of 4% in 2050 under the 1.5°C pathway (Table 7).

D.2.5

Residential and buildings: The role of hydrogen and synthetic fuels

Under all scenarios, hydrogen play almost no role for space heating or any other energy demand from buildings. The only application are co-generation systems in large facilities such as airports or shopping centres which are switched from natural gas to hydrogen. By 2050, only 1% of the total global final energy needs are supplied by hydrogen for the building sector (Table 8).

Table 7: Industry: final energy demand and the development of electricity and hydrogen for supply under three scenarios

FINAL ENERGY		UNIT	2018	2020 (e)*	2025	2030	2035	2040	2045	2050
Industry	REF	[PJ/a]			138,939	152,323	163,595	174,867	184,069	191,517
	2.0°C	[PJ/a]	112,619	108,571	122,639	122,584	118,475	113,576	108,390	104,410
	1.5°C	[PJ/a]			113,509	107,188	100,844	99,248	98,263	98,572
• electricity	REF	[PJ/a]			38,193	42,746	46,650	50,554	53,851	56,939
	2.0°C	[PJ/a]	33,702	31,923	38,078	42,373	46,475	50,999	54,517	57,184
	1.5°C	[PJ/a]			38,010	43,105	47,169	50,266	53,485	56,877
• hydrogen	REF	[PJ/a]			0	0	0	0	0	0
	2.0°C	[PJ/a]	0	0	76	206	819	3,008	6,070	8,692
	1.5°C	[PJ/a]			55	868	2,291	5,750	8,921	9,331
Share of hydrogen for industry of total final energy use	REF	[%]			0%	0%	0%	0%	0%	0%
	2.0°C	[%]	0%	0%	0%	0%	0%	1%	2%	3%
	1.5°C	[%]			0%	0%	1%	2%	4%	4%

Legend: * (e) estimated.

Table 8: Residential and buildings: final energy and the development of electricity and hydrogen for supply under three scenarios

FINAL ENERGY		UNIT	2018	2020	2025	2030	2035	2040	2045	2050
Residential & other sectors	REF	[PJ/a]			148,085	159,669	170,008	180,317	189,956	199,958
	2.0°C	[PJ/a]	134,643	131,928	135,815	134,351	131,657	128,305	125,141	123,697
	1.5°C	[PJ/a]			127,737	117,277	113,742	114,165	115,334	116,868
• electricity	REF	[PJ/a]			51,812	60,206	67,974	75,743	82,531	89,328
	2.0°C	[PJ/a]	45,230	42,841	50,524	56,068	60,944	65,607	70,309	73,720
	1.5°C	[PJ/a]			49,102	52,520	57,000	62,762	68,733	74,438
• hydrogen	REF	[PJ/a]			0	0	0	0	0	0
	2.0°C	[PJ/a]	0	0	89	190	667	1,604	2,396	2,000
	1.5°C	[PJ/a]			65	667	1,441	2,392	3,099	2,927
Share of hydrogen for residential and other sector of total final energy use	REF	[%]			0%	0%	0%	0%	0%	0%
	2.0°C	[%]	0%	0%	0%	0%	0%	1%	1%	1%
	1.5°C	[%]			0%	0%	1%	1%	1%	1%

D.2.6
Hydrogen and synthetic fuels for bunker fuels

Bunker fuels for international aviation and navigation are separate categories in the energy statistics. Their use and related emissions are not usually directly allocated to the regional energy balances. However, they contribute significantly to global greenhouse gas (GHG) emissions and pose great challenges regarding their substitution with low-carbon alternatives. In 2015, the annual bunker fuels consumption was in the order of 16,000 PJ, of which 7,400 PJ was for aviation and 8 600 PJ for navigation. Between 2009 and 2015, bunker fuel consumption increased by 13% (Table 9). The annual CO_2 emissions from bunker fuels accounted for 1.3 Gt in 2015, approximately 4% of global energy-related CO_2 emissions. In the 5.0°C Scenario, the development of the final energy demand for bunker fuels is assumed to be that of the IEA World Energy Outlook 2017 Current Policies scenario. This will lead to a further increase of 120% in the demand for bunker fuels until 2050 compared with that in the base year, 2015. Because no substitution with renewable fuels is assumed, CO_2 emissions will rise by the same order of magnitude.

Although the use of hydrogen and electricity in aviation is technically feasible (at least for regional transport) and synthetic gas use in navigation is an additional option under discussion, this analysis uses a conservative approach and assumes that bunker fuels are only replaced by biofuels or synthetic liquid fuels. Text box 3 shows the 5.0°C and two alternative bunker scenarios, which are defined in consistency to the scenarios for each world region. For the 2.0°C and 1.5°C Scenarios, we assume the limited use of sustainable biomass potentials and the complementary central production of power-to-liquid synthetic fuels. In the 2.0°C Scenario, this production is assumed to take place in three world regions: Africa, the Middle East, and OECD Pacific (especially Australia), where synfuel generation for export is expected to be the most economic.

The 1.5°C Scenario requires even faster decarbonisation, and therefore follows a more ambitious low-energy pathway. This will lead to a faster build-up of the power-to-liquid infrastructure in all regions, which in the long term, will also be used for limited 'regional' bunker fuel production to maintain the utilisation of the existing infrastructure. Therefore, the production of bunker fuels is assumed to occur in more regions, with lower exports from the supply regions mentioned above, in the 2.0°C Scenario. Another assumption is that consistent with the regional 1.5°C Scenarios, the biomass consumption for energy supply will decrease in the long term, whereas power-to-liquid will continue to increase as the main option for international aviation and navigation. Finally, the expansion of the power-to-liquid infrastructure for the generation of bunker fuel will be closely associated with the assumed development of regional synthetic fuel demand and generation for transportation in each world region. Text box 3 also shows the resulting cumulative CO_2 emissions from bunker fuel consumption between 2015 and 2050, which amount to around 70 Gt in the 5.0°C case, 30 Gt in the 2.0°C Scenario, and 21 Gt in the 1.5°C Scenario. Table 9 below, provides more-detailed data for the three bunker fuel scenarios.

The production of synthetic fuels will cause significant additional electricity demand and a corresponding expansion of the renewable power-generation capacities. In the case of liquid bunker fuels, these additional renewable power-generation capacities will amount to 1 100 GW in the 2.0°C Scenario and more than 1 200 GW in the 1.5°C Scenario if a flexible utilisation rate of 4 000 full-load hours per year can be achieved. However, such a situation will require high amounts of electrolyser capacity and hydrogen storage to allow not only flexibility in the power system, but also high utilisation rates of the downstream synthesis processes (e.g., via Fischer-Tropsch plants). Other options for renewable synthetic fuel production are solar thermal chemical processes, which directly use high-temperature solar heat.

Technical and Economic Data continued

Table 9: Global projection of bunker fuel demands for aviation and navigation by fuel

	UNIT	2020	2025	2030	2035	2040	2045	2050
World bunkers 5.0°C Scenario								
Total final energy consumption	PJ/yr	17 976	20 090	22 593	25 443	28 293	31 462	34 987
thereof aviation	PJ/yr	8 385	9 431	10 674	12 097	13 537	15 148	16 950
thereof navigation	PJ/yr	9 591	10 658	11 919	13 346	14 756	16 314	18 037
fossil fuels	PJ/yr	17 976	20 090	22 593	25 443	28 293	31 462	34 987
biofuels	PJ/yr	0	0	0	0	0	0	0
synthetic liquid fuels	PJ/yr	0	0	0	0	0	0	0
Primary energy demand								
crude oil	PJ/yr	19 754	21 956	24 558	27 506	30 423	33 650	37 220
CO_2 emissions	Mt/yr	1 450	1 611	1 802	2 018	2 232	2 468	2 730
World bunkers 2.0°C Scenario								
Total final energy consumption	PJ/yr	17 538	16 836	15 274	15 053	14 826	14 483	14 014
thereof aviation	PJ/yr	8 594	8 418	7 713	7 602	7 487	7 314	7 077
thereof navigation	PJ/yr	8 944	8 418	7 561	7 451	7 339	7 169	6 937
fossil fuels	PJ/yr	17 270	16 180	13 748	10 537	5 189	3 621	0
biofuels	PJ/yr	268	657	1 526	3 146	5 417	6 381	7 430
synthetic liquid fuels	PJ/yr	0	0	0	1 370	4 220	4 481	6 584
ASSUMED REGIONAL STRUCTURE OF SYNTHETIC BUNKER PRODUCTION								
Africa	PJ/yr	0	0	0	846	2 607	2 768	4 067
Middle East	PJ/yr	0	0	0	183	564	598	879
OECD Pacific	PJ/yr	0	0	0	341	1 050	1 115	1 638
Primary energy demand								
crude oil	PJ/yr	18 978	17 683	14 943	11 391	5 580	3 872	0
biomass	PJ/yr	400	952	2 150	4 369	7 420	8 623	9 907
RES electricity demand for power-to-liquid	TWh/yr	0	0	0	961	2 880	3 058	4 375
CO_2 emissions	Mt/yr	1 391	1 296	1 095	835	409	284	0
World bunkers 1.5°C Scenario								
Total final energy consumption	PJ/yr	17 538	15 995	13 747	12 795	12 602	12 311	11 912
thereof aviation	PJ/yr	8 594	7 997	6 942	6 462	6 364	6 217	6 016
thereof navigation	PJ/yr	8 944	7 997	6 805	6 334	6 238	6 094	5 896
fossil fuels	PJ/yr	17 538	15 179	7 836	2 559	0	0	0
biofuels	PJ/yr	0	816	4 536	6 398	6 931	5 540	4 527
synthetic liquid fuels	PJ/yr	0	0	1 375	3 839	5 671	6 771	7 385
ASSUMED REGIONAL STRUCTURE OF SYNTHETIC BUNKER PRODUCTION								
Africa	PJ/yr	0	0	717	2 002	2 863	3 093	2 882
Middle East	PJ/yr	0	0	155	433	619	669	873
OECD Pacific	PJ/yr	0	0	289	836	1 265	1 622	1 697
OECD North America	PJ/yr	0	0	213	568	798	924	977
OECD Europe	PJ/yr	0	0	0	0	126	262	557
Eurasia	PJ/yr	0	0	0	0	0	200	400
Primary energy demand								
crude oil	PJ/yr	19 273	16 589	8 517	2 766	0	0	0
biomass	PJ/yr	0	1 182	6 389	8 885	9 495	7 486	6 035
RES electricity demand for power-to-liquid	TWh/yr	0	0	964	2 693	3 870	4 621	4 896
CO_2 emissions	Mt/yr	1 413	1 216	624	203	0	0	0

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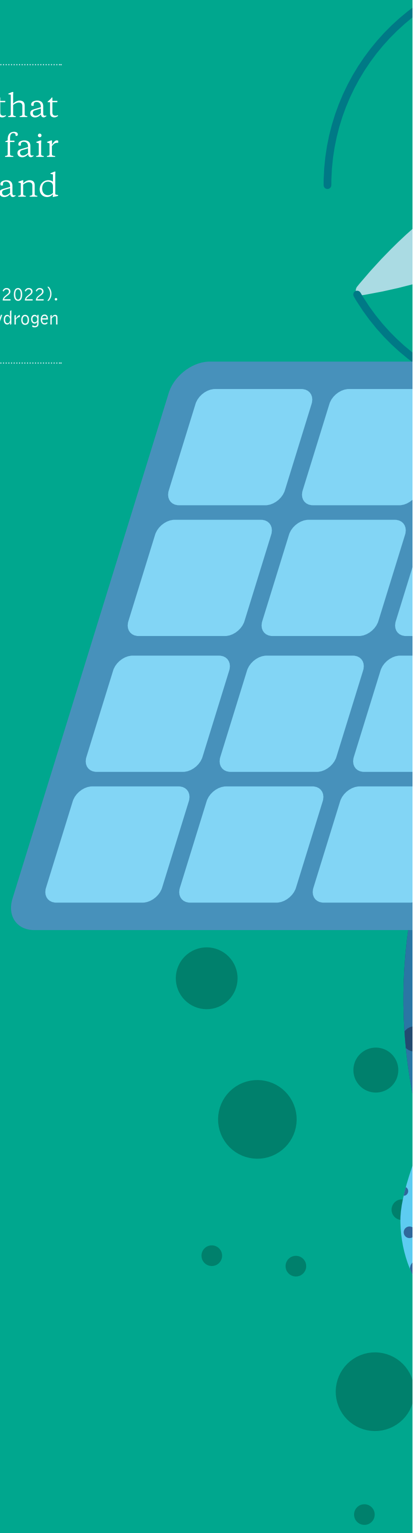
Hydrogen energy storage gas tank with solar panels, wind turbine and energy storage container unit. © petrmalinak



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