



UNECE

TECHNOLOGY BRIEF

HYDROGEN

Cover photo: aa-w, © depositphotos

The findings, interpretations and conclusions expressed herein are those of the author(s) and do not necessarily reflect the views of the United Nations, its officials or Member States. The designation employed and the presentation of material on any map in this work do not imply the expression of any opinion whatsoever on the part of the United Nations concerning the legal status of any country, territory, city or area, or of its authorities, or concerning the delimitation of its frontiers or boundaries. Mention of any firm, licensed process or commercial products does not imply endorsement by the United Nations.

This brochure is issued in English and Russian.

ACKNOWLEDGEMENTS

This technology brief is one of the outcomes of the project called “Enhancing understanding of the implications and opportunities of moving to carbon neutrality in the UNECE region across the power and energy intensive industries by 2050”. The project was managed by Iva Brkic with support from Walker Darke, Oleg Dzioubinski, Branko Milicevic, Sofiia Parent, Gianluca Sambucini and Sabina Warnell, under strategic guidance and advice of Stefanie Held, Chief of the Sustainable Energy Section and Scott Foster, Director of Sustainable Energy Division.

The project was run under the auspices of the Group of Experts on Cleaner Energy Systems with continuous support from the Group of Experts on Gas and the Group of Experts on Renewable Energy. The three UNECE Groups of Experts formed a UNECE Task Force on Hydrogen to implement hydrogen related activities across the UNECE region. The secretariat wishes to thank to James Robb, the Chair of the Group of Experts on Cleaner Electricity Systems, Francisco de la Flor Garcia, the Chair of the Group of Experts on Gas, and Kostiantyn Gura, the Chair of the Group of Experts on Renewable Energy, for their vision and continuous support in advancing UNECE work to promote sustainable hydrogen.

This brief was prepared by the UNECE Task Force on Hydrogen and a dedicated team of high-level international experts who offered quality control, advice, and validation of findings. The project team greatly thanks to James Carton, Alena Fargere, Thomas Gibon, Jon Gibbins, Rafael Guerra, David Hess, Denis Hicks, Ruud Kempener, Tom Kober, King Lee, Florian Marko, Yuriy Melnikov, Andrew Minchener, Ian Moore and Michela Morese for their expertise and continuous support. The project team and the authors wish to thank Shuyue Li for providing visual communication and design services for this technology brief.

Disclaimer

The document does not necessarily reflect the position of the reviewers and partners listed above who helped to develop this publication.

CONTENTS

Acknowledgements	ii
Key takeaways	1
1. Introduction	3
2. Production of hydrogen	5
2.1 Hydrogen from natural gas	8
2.2 Hydrogen from coal	9
2.3 Hydrogen from renewable energy	10
2.4 Hydrogen from biomass	13
2.5 Hydrogen from nuclear power	15
3. Storage and transport of hydrogen	18
3.1 Storage of hydrogen	19
3.2 Transport of hydrogen	22
3.3 The role of existing gas infrastructure	24
4. Applications of hydrogen across sectors	27
4.1 Application of hydrogen in power sector	28
4.2 Application of hydrogen in transport sector	28
4.3 Application of hydrogen in industrial sector	30
4.4 Application of hydrogen in residential & commercial sector	31
Annexes	32
Abbreviations	37
References	38

KEY TAKEAWAYS

The growing consensus that immediate action is needed to avoid the most destructive impacts of climate change translates into the reduction and ultimate elimination of all global anthropogenic greenhouse gas (GHG) emissions.

That is why sustainable hydrogen has been proposed as a backbone to a modern, decarbonised energy society. Hydrogen is already used a chemical feedstock, for example for ammonia used in fertilisers or in hydrocarbons used for plastics. In the future, hydrogen can be used as an energy carrier and energy storage medium. It has vast, viable applications across a range of sectors that need to be decarbonised, such as transport, industry, power generation and heat for buildings.

In particular, hydrogen can progress the decarbonisation of hard-to-abate sectors, such as energy intensive industries using high temperatures in their processes, or long-haul transport. These are examples of important economic activity where electrification of end-use is only partially possible, or the technology does not yet exist. Hence a rapid shift to a “hydrogen ecosystem” is consistent with the aims for Carbon Neutrality by 2050 and Agenda 2030 for Sustainable Development. It requires a deliberate, swift and extensive expansion of renewable and low-carbon hydrogen production.

The challenge to expand sustainable hydrogen production quickly enough means that policy makers should consider all options production. These include low-carbon sources, such as using fossil fuels in combination with Carbon Capture, Use and Storage (CCUS) or nuclear power, because limited time means that hydrogen capacity from electrolyzers using only renewable energy supply will not be fast enough, especially when considering the needs of energy intensive industries that will supply the materials needed for the energy transition.

The distribution of hydrogen over large distances is problematic. Pipelines will be required for long distances and so the existing natural gas infrastructure will play a significant role to ramp-up the hydrogen market. Repurposing and retrofitting existing natural gas infrastructure are practical and economic

distribution options to promote trade in hydrogen. The large-scale storage of hydrogen is still a technical challenge and will take time to develop. In the meantime, energy security in decarbonised energy systems can be enhanced by adopting a regional approach based on a hydrogen grid.

Since the feasibility of sufficient future hydrogen storage is uncertain, investments will be required to convert hydrogen into a form that is easier to store and use, such as ammonia, methanol and synfuels. These will also help to promote the adoption of a hydrogen economy because they can be internationally traded and can be easily used in many industrial processes.

The private sector, along with Public-Private Partnerships, is leading the technology development and commercialisation programmes at a variety of technical and commercial readiness levels. The scale and rate of change required to introduce the hydrogen ecosystem to support carbon neutrality by 2050 means that this must be actioned today as one of the key priorities for all Governments, involving all sectors of their economy. Policymakers and regulators can play a role in accelerating the delivery of these programmes and should:

Diversify risk by promoting all sustainable hydrogen technologies

Research and innovation in all sustainable hydrogen technologies is required to unlock all sustainable production pathways and to allow to move away from traditional hydrogen production.

Build on existing gas infrastructure to reduce distribution costs and promote trade

The natural gas transmission network can be used to integrate hydrogen in a cost-efficient way at 10-15% of the cost of a newly built hydrogen pipeline.

Build ahead of the curve and accelerate deployment of electrolyzers

The deployment of electrolyzers should not wait until 100% of the electricity is renewable. Support the deployment of electrolyzers connected to the electricity grid and low carbon generation plants.

Develop clear regulatory framework and supportive mechanisms to scale up sustainable hydrogen projects

Long-term off-take commitments for sustainable hydrogen produced for industrial, transportation, heating and synfuels projects are necessary. Clear regulatory framework and supportive mechanisms that promote, scale and de-risk investments are required.

Promote projects of common regional interest and build capacity

By 2030, investments in electrolyzers in Europe could range between €24-42bn and in retrofitting half of the existing plants with CCUS around €11bn. Share best practices and build capacity across the region to support development of regional hydrogen hubs.

HYDROGEN VALUE CHAIN

Hydrogen, an innovative solution for achieving carbon neutrality

PRODUCTION

FUEL-BASED PRODUCTION



Natural gas

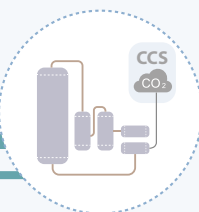
Steam methane reforming/ autothermal Reforming with or without CCS

Coal

Gasification of coal with or without CCS

Biomass

Gasification of biomass with or without CCS



Steam reforming and gasification with CCS

ELECTRICITY SYSTEM



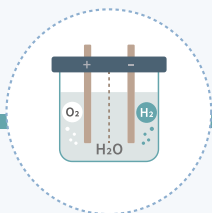
Renewable energy

Electricity from wind, solar, hydro or geothermal power



Nuclear

Electricity and heat from nuclear power



Water electrolysis

CONVERSION, PROCESSING & TRANSPORTATION

PURE H₂



PROCESSING

- Liquification and regasification of H₂
- H₂ gas compressed



CONVERSION

• Haber-Bosch process

H₂ & N₂ → ammonia; standard shipping modes



• Methanization

H₂ + CO₂ → CH₄ + H₂O
or H₂ + CO → CH₃OH (methanol)
(synthetic or substitute natural gas)



STORAGE



Liquified H₂ in storage tanks



Geological storage in underground salt caverns

USE

TRANSPORT



- Hydrogen into **fuel cells** for trucks, passenger vehicles
- **Synthetic fuels** for shipping and aviation

INDUSTRY



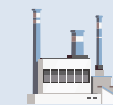
- Hydrogen as **feedstock** in refining, steel production, chemicals production
- Hydrogen for **heat generation** for industrial processes

BUILDINGS



- Hydrogen for **heating**
- Hydrogen for onsite **power** through fuel cells

POWER



- Fuel cell **electricity**, H₂ turbines and H₂ CHP
- **Energy storage** and system buffer



Awareness

Recognise hydrogen as a viable climate mitigation option



Acceptance

Develop and integrate policies to jumpstart hydrogen economy



Finance

Direct public and private investment into clean hydrogen projects

1. INTRODUCTION

Scope and Structure

This brief introduces hydrogen and the hydrogen value chain and proposes possible policy actions to allow for the faster commercialisation of new technologies and wider deployment across the region in support of the carbon neutral policy. The brief should familiarise policy makers with the role that hydrogen can play in the shift to a net-zero carbon future thanks to its low-carbon footprint and versatility to act as an energy carrier.

Before examining the details, hydrogen has two general advantages for policy makers.

- In times of rapid change, a hydrogen-led economy has the advantage that it is very flexible as it is applicable to diverse energy sources, production processes, transportation and storage models. Hydrogen is a basic chemical building block which can be transformed and used in a variety of ways.
- Hydrogen will also benefit from some general trends in the energy market - the falling prices of renewable energy, emerging technologies, increasing carbon tax, and climate and energy targets. Cheaper renewable energy, the falling costs of electrolyzers and commercialisation of carbon capture, use and storage (CCUS) for production of net-zero hydrogen could make hydrogen-powered carbon neutrality into a foreseeable future reality.

Reality check and rationale for considering hydrogen technologies

Energy is critical for ensuring quality of life and underpins the attainment of the 2030 Agenda for Sustainable Development (2030 Agenda). The role that energy plays in modern society is recognised, but there remains an important disconnect between countries' agreed energy and climate targets and the actual progress.

The analysis from the Pathways Project (2020) indicated that the countries from the UNECE region will need both to reduce their dependence on fossil fuels from over 80% to around 50% by 2050 and to achieve significant negative carbon emissions to stay on a pathway consistent with the Paris Agreement and to maintain its economic trajectory. The amount of cumulative negative carbon emissions is immense - at least 90Gt of CO₂ by 2050 to ensure delivery of the 2°C target (see Figure 1).

Fossil fuels are likely to continue playing an important role in UNECE member States, in the short and medium term, during a transition to carbon neutrality. Hydrogen is widely recognised as a key to either decarbonise sectors where full penetration of renewable electricity is not possible or where the deployment of CCUS is difficult (for example, in some hard-to-abate sectors, such as some heavy industry and long-haul transport).

Hydrogen has been produced and used in huge quantities for many years. However, hydrogen as an energy vector is a recent development. An energy vector is a tool that can be used to transport and store energy before it is converted into electricity, heat or used as raw material to supply the industry. Unlike fossil fuels, geological resources of hydrogen are rarely exploited or widely mapped and so hydrogen must be produced directly.

Currently, hydrogen is mostly used as a feedstock to produce chemicals, such as fertilisers and plastics, while its energy

vector feature remains limited. In this context, about 95% of hydrogen is produced from natural gas or other hydrocarbons and results in CO₂ emissions between 70 – 100 Mt CO₂ annually solely in EU countries.

Currently, clean hydrogen from fossil fuels with CCUS, nuclear power and renewable energy is 2-3 times more expensive to produce compared to traditionally hydrogen production methods, such as from natural gas and coal without CCUS. Investment into clean hydrogen research and development has been growing over the past 4 years to address this issue. However, significant challenges still must be overcome.

Today, most hydrogen is used locally to where it is produced. Hydrogen, compared to other energy vectors, is expensive and technically difficult to store and transport safely other than by pipeline. It is often cheaper to move the user of hydrogen to the source of hydrogen, rather than transport it. This constraint will have to be removed for hydrogen to be adopted as the main energy vector contributing to carbon neutrality.

Hydrogen is made in processes that need to operate continuously under stable conditions to be both safe and economic. As hydrogen demand grows, these processes will increase the 'baseload' energy demand in the energy system.

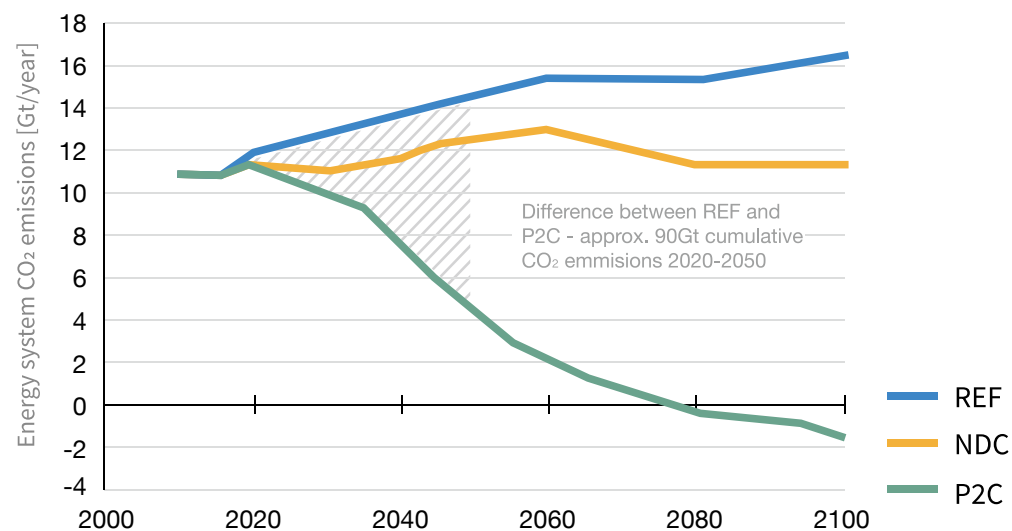
Producing sufficient hydrogen to replace our current energy vectors requires investment. According to the EU Hydrogen Strategy, cumulative investments in renewable hydrogen in Europe could be in the range from €180-470bn and, for low-carbon fossil-based hydrogen (coal with CCUS or natural gas with CCUS), in the range from €3-18bn.

In policy circles, hydrogen production from natural gas and other hydrocarbons produce so-called 'brown or grey' hydrogen (significant quantities of CO₂ are released in the process). If the CO₂ emissions are addressed through CCUS, hydrogen is considered as 'blue'. Hydrogen can also be produced via electrolysis of water. If the electricity used for the electrolysis is produced from renewable energy, then such hydrogen is

considered as 'green'. There is also 'black' (produced from coal) and 'yellow' hydrogen (from nuclear power electricity or heat).

This colour coding of hydrogen production tends to impede progress on policy discussion on hydrogen. In the context of this brief we will be referring to "traditional hydrogen" – hydrogen from fossil fuels, and "clean hydrogen" – hydrogen from fossil fuels with CCUS technology that includes CCUS with the minimum of 90% of CO₂ captured, hydrogen from biomass with CCUS, hydrogen from renewable energy electricity and hydrogen from nuclear power electricity and heat.

Figure 1 CO₂ emissions in the ECE region by policy scenario



Source: UNECE Pathways Project

The reference scenario is based on a shared socio-economic pathway (SSP2) a "Middle of the Road" or Business-as-Usual Pathway, as a point of departure. Its socio-economic, market and technology assumptions represent middle-of-the-road developments. SSPs do not include climate mitigations policies or measures (other than those existing in 2010). SSP2 provides an appropriate 'base case' for the exploration of multiple (alternative) pathways and is also the basis for the IPCC work. The **NDC scenario** assumes the implementation of the Nationally Determined Contributions (NDCs) under the Paris Agreement up to 2030 and then maintains them effectively forever. The **P2C scenario** is a techno-economic scenario, where regional CO₂ constraints, consistent with NDC through 2030, are assumed to continue reduction beyond 2030 and thus allows to stay below 2°C by the end of the century.

2. PRODUCTION OF HYDROGEN

Hydrogen is the most abundant element of the universe. It accounts for roughly 75% of all mass on the planet. However, in nature, it normally reacts with other elements. Hydrogen (chemically H_2) is a bulk chemical that is produced in large quantities — around 70 million tons per year — and used primarily in petroleum refining and in the production of ammonia (for fertilisers) and methanol. The value of the hydrogen production market is around US\$120 billion.

The move to a hydrogen economy will increase hydrogen demand. Annual hydrogen global demand in 2050 is forecast to increase to some 650 Mt, representing around 14% of the expected world total energy demand. The range of commercial uses will expand from industrial feedstocks production and include hydrogen as an energy source, together with transportation, heating and power in buildings and power generation.

Most hydrogen production is currently carbon-intensive. About 6% of global natural gas and 2% of global coal consumption is used to make hydrogen with the carbon in the feedstock emitted as CO_2 to the atmosphere. Natural gas is the primary feedstock for hydrogen production (almost 80% of global hydrogen production), followed by coal. Today, less than 5% of hydrogen is produced from renewable and low-carbon energy sources via electrolysis. If generated through electrolysis only, the current hydrogen demand would require an additional 400 GW of baseload electricity supply. Satisfying expected clean hydrogen demand in 2050 through electricity only, would require an increase in baseload electricity in the amount of 3700GW.

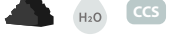
For hydrogen technologies to contribute to carbon neutrality, the current production of hydrogen needs to shift from fossil-fuel methods to fossil fuels with CCUS, renewable electricity, nuclear power or grid-connected electricity through electrolysis using low-carbon electricity.

The advantage of fossil fuel-based hydrogen production with CCUS is that this can be implemented quickly to unlock the hydrogen economy unconstrained by the development of electrolysis using renewable or low-carbon electricity capacity. The resulting CO_2 emissions will be concentrated and therefore simpler to capture compared to alternative energy vectors, such as methane, oil or coal, which result in CO_2 emissions geographically spread across all the points of use.

The only other commercialised hydrogen production method today is electrolysis based on grid electricity. This has a niche position in the market where local fossil-fuel production of hydrogen is not feasible and the high transportation cost of hydrogen makes electrolysis economically viable.

The other hydrogen production routes are not yet commercialised due to high capital expenditure required for CCUS technology and electrolyzers, significant variable costs associated with low conversion efficiency and, in the case of hydrogen from renewable energy, price for electricity and its availability.

Table 1 Overview of hydrogen production routes

		INPUT	PROCESS	OUTPUT	LIFE CYCLE EMISSIONS [kg CO ₂ . eq/ kg H ₂]	COST [\$/kg]	TECHNOLOGY MATURITY	COMMERCIAL READINESS	MAJOR ADVANTAGE	MAIN CONCERN	SOCIAL READINESS	
FOSSIL-FUEL BASED HYDROGEN		Natural gas & steam reforming		Steam reforming hydrocarbons into hydrogen and carbon monoxide		9.0-11.0	0.7 - 2.1			Low cost, proven reliability	CO ₂ emissions; methane is non-renewable	
		Natural gas & partial oxidation		Methane reacts with limited amount of oxygen		9.0-11.0	0.7 - 2.1			Low cost, proven reliability	CO emissions; methane is non-renewable; produces less hydrogen per unit of input fuel compared to SMR	
		Natural gas & steam reforming with CCS		Steam reforming hydrocarbons into hydrogen and carbon monoxide		3.0-7.0	1.2 - 2.3			Low cost, proven reliability, low CO ₂ emissions	Methane is none-renewable; needs access to carbon storage	
		Natural gas & partial oxidation with CCS		High temperature reaction between coal and oxygen		3.0-7.0	1.2 - 2.3			Low cost, proven reliability, low CO ₂ emissions	Methane is none-renewable; needs access to carbon storage	
		Coal gasification		High temperature reaction between coal and oxygen		18.0-20.0	1.3 – 2.5			Low cost, proven reliability, synergy with chemicals industry	CO ₂ emissions; coal is non-renewable	
		Coal gasification with CCS		High temperature reaction between coal and oxygen		11.8	1.6 – 2.6			Low cost, proven reliability, low CO ₂ emissions	Coal is non-renewable; needs access to carbon storage	
		Methane pyrolysis		Splitting natural gas into hydrogen and solid carbon		1.9-4.8	1.6 – 3.4			Low cost, low CO ₂ emissions	Use/disposal of carbon	
RENEWABLE ENERGY- BASED HYDROGEN		Electricity from renewable energy		Electrolysis - splitting water into hydrogen		0.7-2.8	2.6 – 23.0			Low carbon technology, flexible location	Seasonable intermittent supply Capacity linked renewable energy deployment. Dependent on rare earth metals for electrolyzers	
		Biomass gasification with CCS		High temperature reaction between oxygen and biomass (e.g., wood logs)		-14.6-0.4	1.9-8.4			Potentially negative emissions. Synergies with waste industry	Quantity of waste versus H ₂ demand. Sustainability of biomass. Needs access to carbon storage	
		Biomass & pyrolysis		High temperature reaction of biomass (e.g., wood logs) with no oxygen		-14.6-0.4	1.3-2.2			Potentially negative emissions. Synergies with waste industry	Quantity of waste versus H ₂ demand. Sustainability of biomass. Use of non-hydrogen products of pyrolysis	
NUCLEAR POWER- BASED HYDROGEN		Electricity from nuclear power		Electrolysis – splitting water into hydrogen		0.3-0.6	4.2 - 7.0			Baseload low-carbon supply of electricity	A controversial technology that requires capacity ramp up. Dependent on rare earth metals for electrolyzers	
		Heat from nuclear power		Heat from nuclear power and water through thermochemical process. Heat for Steam reforming hydrocarbons		~0.1	2.2–2.6			Baseload low-carbon supply of heat	A controversial technology with potentially high development investment costs	

* More information about comparative analysis focus on technology, commercial and social readiness see Annex I page 32.
* Depending on capture rate and methane fugitive emissions. Lower range: 93% capture, 0.2% methane emission rate -> ~3kg CO₂ eq/kg H₂. Higher range: 55% capture, 1.5% emission rate -> ~7kg CO₂ eq/kg H₂.
* Life cycle emissions without additional Carbon Dioxide Removal using BECCS or DACCS to deliver net zero GHG impact.

Source: data collected from various sources and vetted by UNECE experts

2.1 Hydrogen from natural gas

Today, natural gas is the **primary source of hydrogen** accounting for about 70% of total hydrogen manufactured. Less than 5% of the hydrogen produced is generated from low-carbon sources.

According to BloombergNEF, the levelised cost of hydrogen from natural gas without CCS ranges from \$0.7/kg – \$2.3/kg, and from natural gas with CCS from \$1.4/kg - \$2.9/kg.

Technology overview

There are **three key methods of producing hydrogen** from gas. Steam Methane Reforming is considered as the most mature method of hydrogen manufacturing from natural gas. Methane pyrolysis and partial oxidation are the promising emerging techniques of hydrogen production from natural gas that are currently passing a pilot phase.

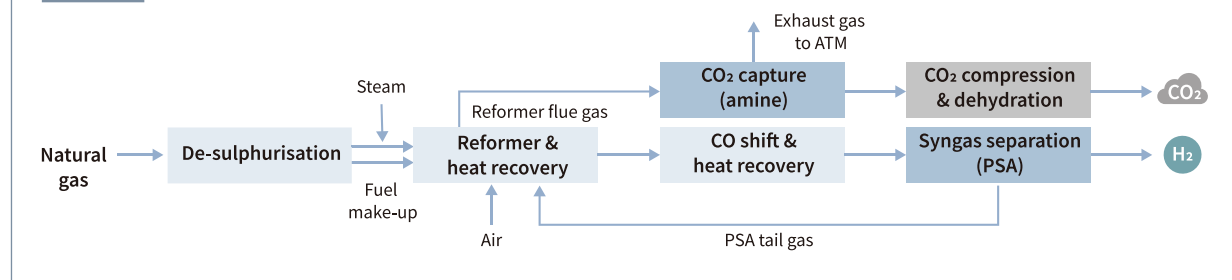
Steam methane reforming (SMR) is a mature, carbon and energy-intensive process that produces syngas (hydrogen and carbon monoxide) through the reaction of light hydrocarbons (typically methane) with water. In SMR, carbon dioxide (CO₂) is generated and released into the atmosphere. Currently, around 96% of hydrogen is produced via SMR of fossil fuels 49% from natural gas, 29% from liquid hydrocarbons, and 18% from coal.

Partial oxidation is the process in which methane and other hydrocarbons in natural gas react with a limited amount of oxygen (not enough to completely oxidize the hydrocarbons to carbon dioxide and water). The reaction produces mainly hydrogen and carbon monoxide (and nitrogen, if the reaction is carried out with air rather than pure oxygen) and a small amount of carbon dioxide and other compounds. The process is, typically, much faster than steam reforming and requires a smaller reactor vessel but produces less hydrogen per unit of the input fuel than is obtained by steam reforming.

Methane pyrolysis, a highly endothermic (requiring a lot of energy) process. Methane is split into gaseous hydrogen and solid carbon. This solid carbon means that no CO₂ is produced in this process. The heat needed to drive the process may come from various sources—combustion of hydrocarbons, concentrated solar heat, electricity or another heat source. Metal or carbon-based catalysts are used to accelerate the process.

All of these methods are energy-intensive, still they require much less energy input to create hydrogen than electrolysis (Figure 3). This explains why industry has historically adopted this fossils-reliant route.

Figure 2 Steam methane reforming with CCS (Wood, 2008)



Implications for carbon neutrality

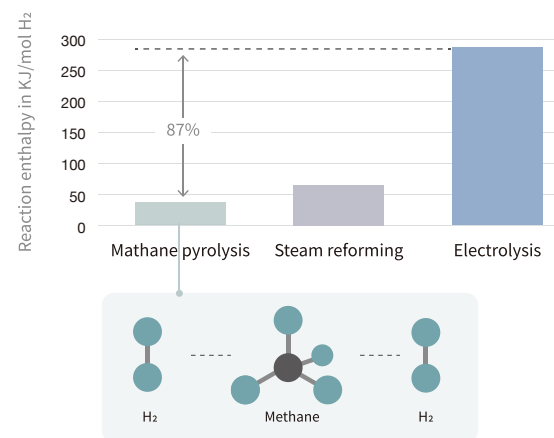
Global warming has focused attention on different hydrogen production processes and their environmental impacts.

When making hydrogen from natural gas, the global warming impact of producing and transporting the natural gas to the conversion facilities needs to be considered. Methane, the main constituent of natural gas, is a powerful greenhouse gas and it is therefore important to minimize its upstream emissions, as discussed in a previous study by the UNECE.

CCS can cut CO₂ emissions at the point of hydrogen production by 90% to 97% or more, but obviously this has no effect on upstream GHG emissions. To date, there are four large-scale hydrogen production facilities with CCS in operation globally, although not at the highest possible capture levels for economic reasons. Three of these capture carbon dioxide for enhanced oil recovery (EOR), a

Methane pyrolysis produces hydrogen from natural gas without direct CO₂ emissions. Prerequisites for the CO₂ neutrality of the process are the heat supply of the high-temperature reactor from zero- and low-carbon

Figure 3 Comparison energy needs for hydrogen production pathways



energy sources, as well as the permanent binding of the carbon produced as a by-product. This emerging hydrogen production pathway is attracting attention as it could potentially use 3-5 times less electricity for the same quantity of hydrogen compared to renewable energy-based electrolysis.

For all hydrogen routes based on methane, strict control of methane emissions from production to use is required as methane is also a powerful GHG. Methane leaks of a few percent can severely impact the environmental benefits of these routes.

Policy actions

- Create energy targets for gas suppliers to include hydrogen in the gas supply.
- Invest into carbon capture and storage infrastructure at scale to bring down costs and encourage CCUS uptake by industries.
- Retrofit and repurpose existing gas infrastructure and create supportive frameworks and regulations in order to stimulate and foster the deployment of the hydrogen market.

2.2 Hydrogen from coal

Coal produced hydrogen currently accounts for around 25% of the hydrogen production.

Hydrogen from coal via gasification is a well-established technology, which has been used for many decades by the chemical and fertiliser industries to produce ammonia, especially in areas where coal is abundant and methane is not. The techniques have been advanced in China and deployed at a large scale for the commercial production of a wide range of chemicals and future fuels. Globally around 130 coal gasification plants are in operation with more than 80% of these in China, making it the current largest hydrogen producer in the world.

Hydrogen production through coal gasification with CCUS (and the natural gas steam methane reforming with CCUS) has about three times lower cost than hydrogen production based on water electrolysis. Coal gasification with CCUS costs typically 1.9-2.4 US\$/kg H₂ with costs as low as US\$ 1.6/kg H₂ in China. Economies of scale obtained through extensive commercial roll-

out and technology innovations could reduce the expenditures further by 2050.

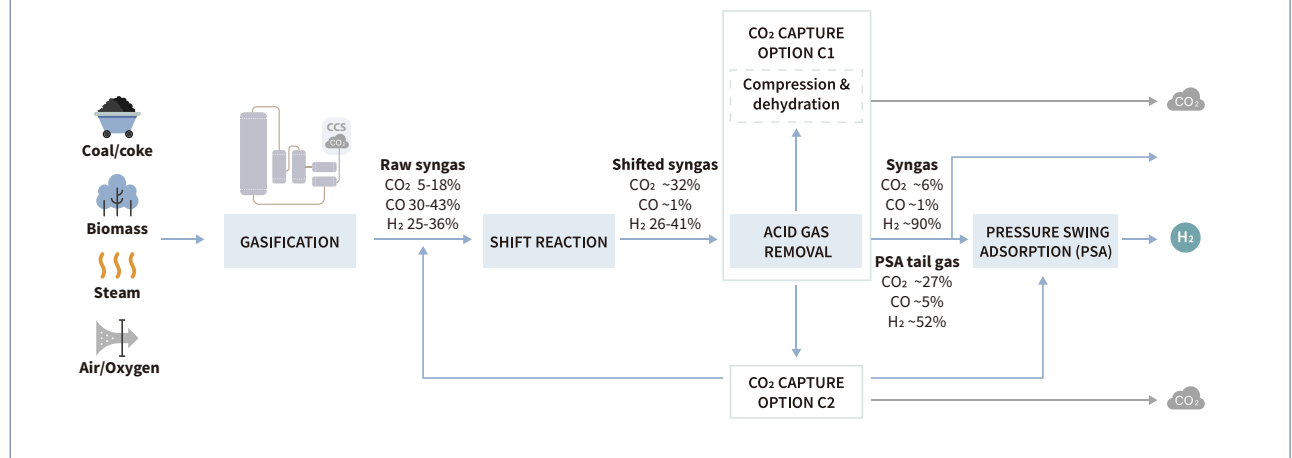
Technology overview

Coal gasification is an established technique whereby coal gets reacts with pressurised steam and air/oxygen under controlled conditions to produce syngas. Syngas is a mixture of carbon monoxide and hydrogen, together with impurities, such as carbon dioxide, methane, sulphur compounds and

water vapour. After removal of these impurities, the syngas can either be fired directly in a gas turbine or passed with additional steam through a catalytic reactor to convert the CO to CO₂ while producing more hydrogen via the water gas shift (WGS) reaction. The hydrogen and CO₂ can then be separated via membranes to provide two near pure gas streams and CO₂ can be captured and stored.

The gasification process with a catalytic reactor can produce a stream of hydrogen of around 99.8 % purity (similar purity to that from a Steam Methane Reforming Process).

Figure 4 Hydrogen production via coal / biomass gasification with carbon capture and storage



Implications for carbon neutrality

In terms of emissions, the addition of CCUS at a 90% capture rate can reduce the carbon intensity of this process to below 3 kgCO₂/kg H₂. Whilst this is good, it is not consistent with the net-zero emissions goal, so capture technology with increased capture rates approaching 100% needs to be developed and deployed. Co-processing a portion of either biomass or waste with the coal feedstock coupled with CCUS could help in attaining net-zero or even negative CO₂ /kg H₂ which would help to 'future proof' the gasification plant.

In terms of gasification with carbon capture, there are currently three facilities producing hydrogen from coal, coke or asphaltene with a combined annual capacity of around 0.6 Mt H₂ globally. The growing deployment of such facilities indicates that large scale production of low emissions hydrogen using gasification with carbon capture can already be considered technically and commercially feasible.

Gasification is an established technique that can produce clean syngas with established techniques for removal of

impurities, such as sulphur compounds and nitrogen-based compounds. Current operations mostly do not limit CO₂ emissions, but the technique for producing a concentrated stream of CO₂ is proven. As such, the overall environmental impact due to the release to the atmosphere of various gas-based conventional pollutants is low while significant reductions in CO₂ emissions is proven if not yet readily adopted.

Policy actions

- Stimulate demand for clean hydrogen, including from coal with CCS, in existing and new markets, especially in hard to de-carbonise industries.
- Invest into carbon capture and storage infrastructure at scale to bring down costs and deploy hydrogen production from fossil fuels with CCUS at scale.

2.3 Hydrogen from renewable energy

Hydrogen from renewable power has a potential to highly contribute to the global energy system decarbonization. Renewable hydrogen is obtained through the process of electrolysis where electricity is used to split water into its components – oxygen and hydrogen. At present, its market share remains low - accounting for less than 5% of total hydrogen production.

Today there is about 60MW of electrolyser capacity installed worldwide. To meet the current objectives of the European Union, this needs to increase to 6GW by 2024 and to 40GW by 2030. Expanding the electrolyser capacity is expected to cost between 24-42 billion euro. Under the assumption that these electrolyzers will run on renewable energy, this will further require additional expansion of solar and wind capacity in the order of 80-120GW what would cost additional 220-340 billion euros to the cost of infrastructure for hydrogen production from renewable energy.

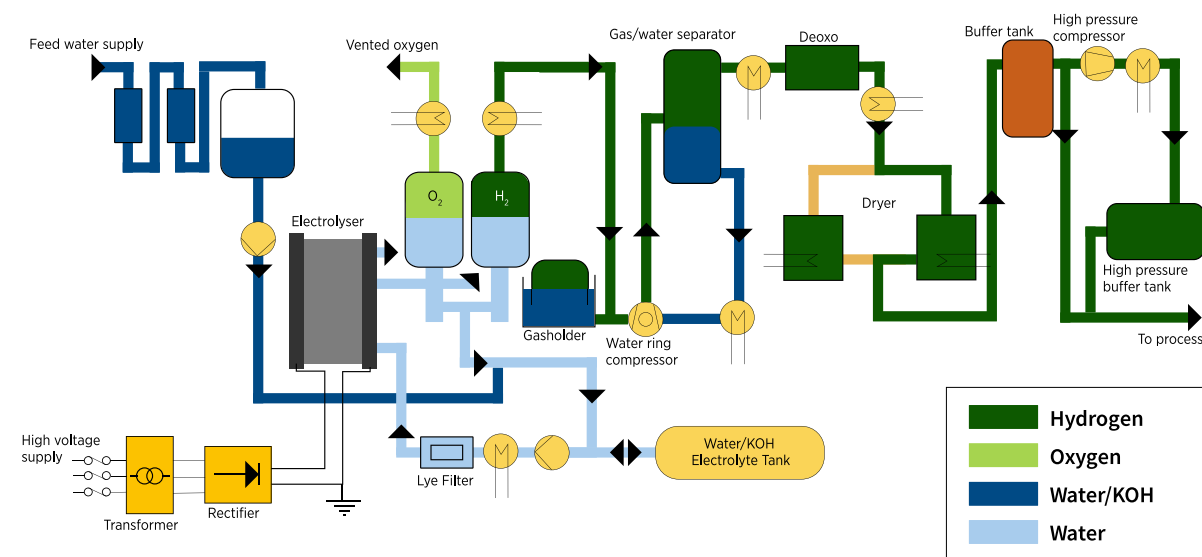
Technology overview

Electricity from renewable energy splits water through electrolysis into its components – oxygen and hydrogen.

- **Alkaline Electrolysis:** The most common electrolyser technology on the market today. This technology applies a solution that requires recirculating of the electrolyte (potassium hydroxide KOH) into and out the stack components to separate hydrogen from water molecules by applying electricity. This technology requires the constant flow of power, so it

might be less efficient with variable renewable energy sources.

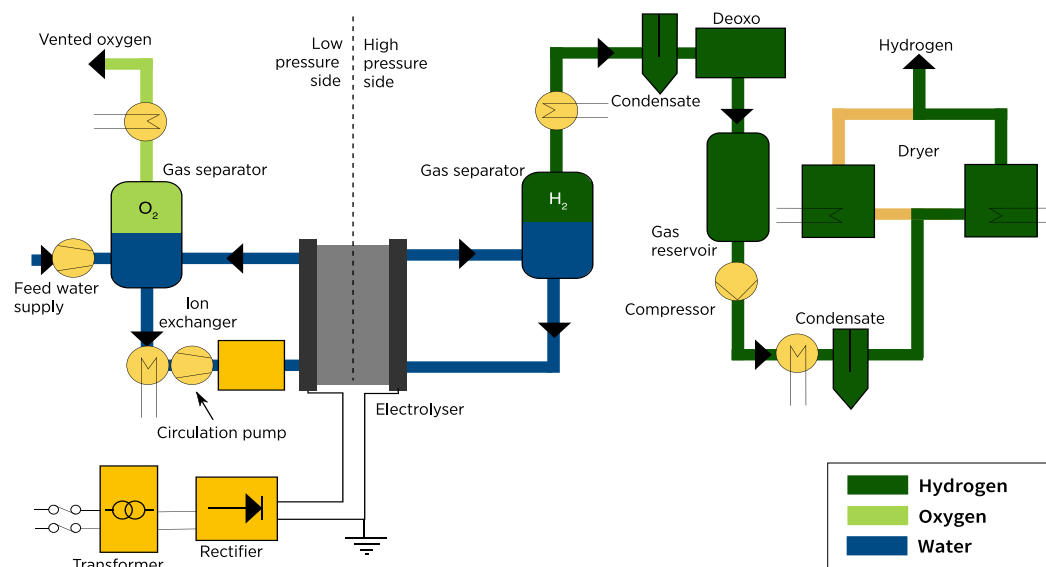
Figure 5 Alkaline electrolyser - typical system design and balance of plant



Source: IRENA 2020

- **Proton-exchange membrane:** A modern electrolyser technology known for higher efficiency and production rates. In this technology, a solid membrane is used to separate hydrogen. This technology is more simple and agile compared to alkaline electrolysis and allows for operation under differential pressures, typically 30bar – 70 bar.

Figure 6 Proton-exchange membrane electrolyser - typical system design and balance of plant



Source: IRENA 2020

- **Solid Oxide Electrolysers:** The latest generation of electrolyzers that is still in the demonstration phase but with great future prospects. This technology produces hydrogen through high-temperature electrolysis of steam.

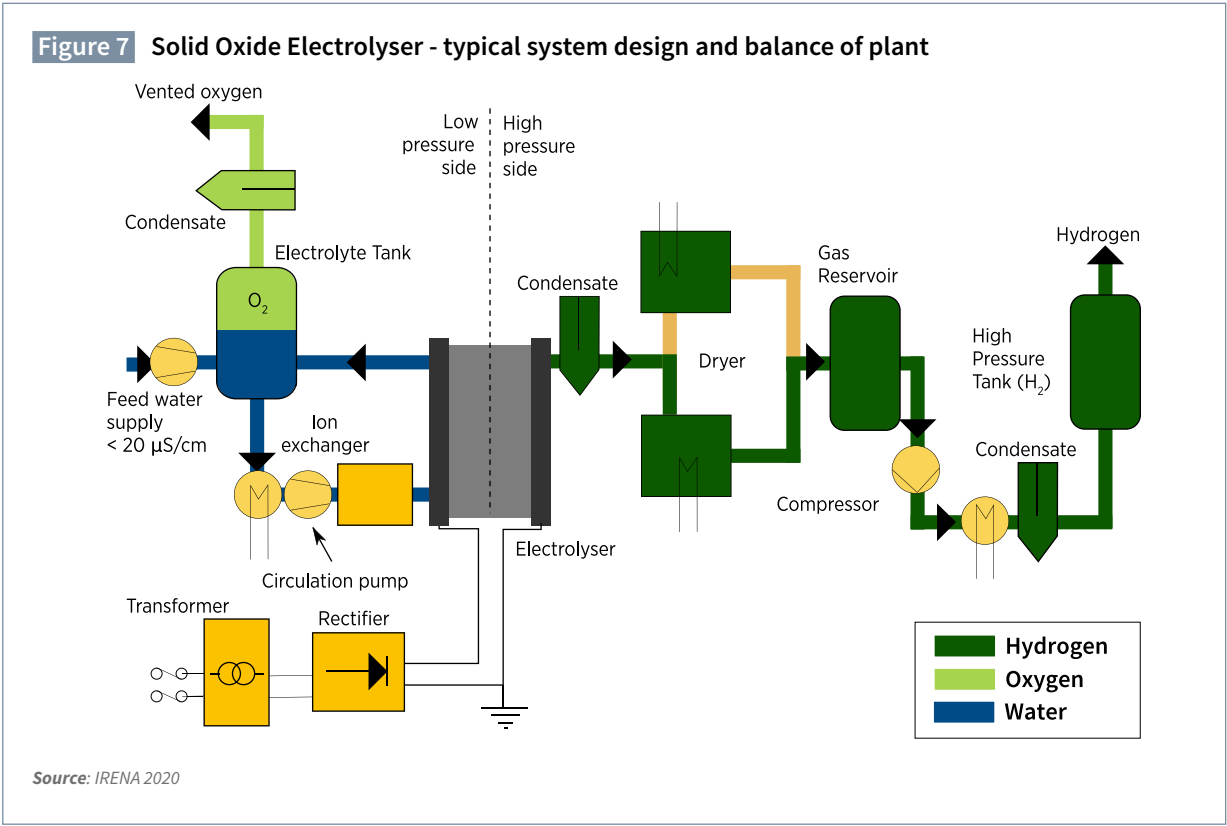


Table 2 Comparison of Electrolyser Technologies

	Alkaline Electrolysis	Proton-exchange membrane	Solid Oxide Electrolysers
Commercial status	mature	commercial	demonstration
Capex range estimate for >10 MW [US\$/kWe]	500 - 1000	700 - 1400	>2300
Lifetime [thousand hours]	60	50-80	<20
Electrical efficiency	60-70%	65-75%	>70%
Operating temperature [°C]	60-80	50 - 80	700-1000
Stack Electricity Demand [MWhr/tonne H ₂]	50-55	45	-

Source: GoldmanSachs 2020, IRENA 2020, Energy Transition Commission 2021

Stack Electricity Demand is the electrical power fed to the electrolyser stack to produce hydrogen. It excludes the electricity required for other plant operations, such as pumping, compressors, heating and cooling. The theoretical minimum is 39.4 MWhr/tonne H₂.

Implications for carbon neutrality

Utilisation of renewable energy for the generation of clean hydrogen has a positive environmental impact as the process is not associated with atmospheric emissions. In this context, an ambitious energy transition target, in conjunction with key international climate goals, could play an important role – by stimulating significant cost reduction for renewable hydrogen.

Electrolysers have a large cost reduction potential. Accelerated development of the market for electrolysers, along with the demonstration of low-carbon projects and further reduction in renewable energy prices will drive further cost reductions.

However, the development of electrolysers cannot wait until 100% of the electricity is renewable. Electrolysers need to be deployed earlier to promote sector coupling and sectoral integration. For example, coupling it with existing nuclear power plants to improve efficiencies and maximise grid integration with renewable energy.

Policy actions

- Ensure renewable energy capacity targets include the potential demand from electrolysers including the fact that this demand is 'baseload'.
- Invest into renewable energy infrastructure. Increased share of renewables will reduce the energy prices and consequently will boost green hydrogen development.
- Accelerate electrolyser development and deployment. This is the critical technical step in the transition towards a hydrogen economy.
- Expand collaboration on renewable hydrogen production across the UNECE region and foster trans-Atlantic collaboration on renewable and low-carbon hydrogen production.
- Encourage harmonised system of standards, such as Guarantees of Origin framework, to ensure traceability of hydrogen production pathways.

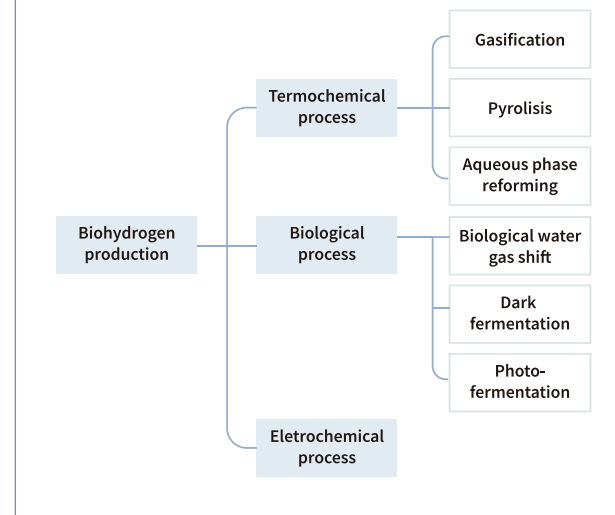
2.4 Hydrogen from biomass

Biohydrogen is the source of energy that uses living microorganisms to make hydrogen via biological processes. A novel option, hydrogen production from lignocellulosic biomass based on renewable resources, is currently in a pilot-scale demonstration stage with few applications entering the commercialisation phase. Lignocellulosic biomass is derived from agri-food residues, energy crops, marine residues, and forest by-products.

Technology overview

Currently, several types of technology are underway for the production of H₂ utilising (lignocellulosic) biomass, such as thermochemical processes, biological conversions, and electrochemically-assisted production.

Figure 8 Biohydrogen production processes



2.4.1 Thermochemical processes

Thermochemical conversion is the most advanced technology for hydrogen production from biomass. The three primary thermochemical routes are gasification, pyrolysis, and aqueous phase reforming.

Gasification is a mature technology that uses a controlled process involving heat, oxygen and steam to convert biomass to hydrogen and other products, without combustion, at approximately 1000°C.

From an operational point of view, we may have three different processes for gasification: air gasification, oxygen gasification and steam gasification. Starting with the first, the moist feedstock is introduced in the gasifier to dry, releasing water. Then, the feedstock undergoes a pyrolysis reaction liberating the gaseous compounds (CO, CO₂, LHC) and tar. Reduction reactions finally occur, and the combustion of the resulting solid from the biomass (called char) produces hydrogen. The unconverted char is transported to the combustor to form CO₂ and provide heat for the process (see Figure 4).

As an alternative, gasification can be achieved using oxygen or steam instead of air. Oxygen gasification produces gas of greater purity containing a higher level of hydrogen, no nitrogen and less tar and char.

Steam gasification is used as a compromise between air and oxygen gasification abovementioned. The hydrogen content in the gas is similar to that from oxygen gasification, whereas the process is cheaper. Nevertheless, tar, char and a minor amount of N₂ are present. Steam reforming is a concomitant purification reaction that improves the syngas composition during steam gasification by reducing the carbon-to-hydrogen mass ratio.

Pyrolysis is another process for biomass thermochemical conversion. Pyrolysis is similar to gasification but can be performed at lower temperatures and without an oxidising agent. Pyrolysis typically occurs at temperatures ranging between 400 and 800°C, under a pressure of up to 5 bar. According to the operating temperature, pyrolysis can be divided into three classes: conventional (or slow) pyrolysis, fast pyrolysis, and flash pyrolysis. Conventional pyrolysis is carried out at temperatures below 450°C and results in a high charcoal content. Fast

pyrolysis produces a bio-oil yield at medium temperatures (450–600°C) with a fast heating rate (approximately 300°C/min). Flash pyrolysis is similar to fast pyrolysis but at higher temperatures (above 600°C) and bigger heating rates (>1000°C/s) and is used to maximise the gas yield. However, the fast and flash pyrolysis yield less gas compared to the gasification, principally due to lower operating temperatures.

Aqueous phase reforming is the third thermochemical approach used for H₂ production from biomass. It converts mainly oxygenated compounds into hydrogen. Feedstock molecules are dissolved during the aqueous phase and react with water molecules at low temperatures (<270°C) and high pressures (up to 50 bar).

2.4.2 Biological processes

Biological conversion can be divided into three categories: biological water gas shift reaction, dark fermentation, and photo-fermentation. Each process depends on the nature of the enzymes used to catalyse H₂ formation.

The **biological water gas shift** reaction depends on the capacity of photoheterotrophic bacteria, using carbon monoxide as the carbon source. These microorganisms placed in water can produce H₂ in the dark by oxidising CO and reducing H₂O through an enzymatic pathway.

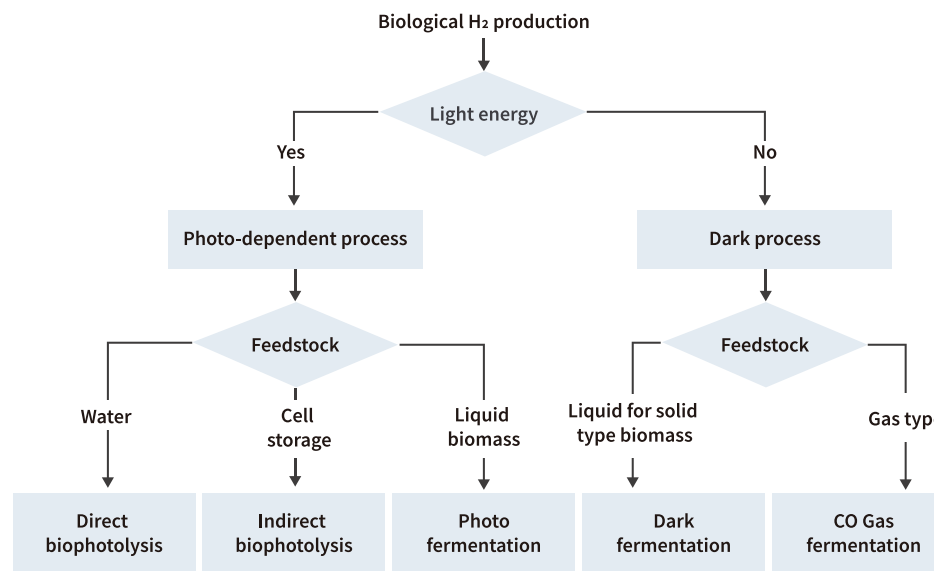
Dark fermentation occurs when anaerobic microorganisms, such as micro-algae or specific bacteria, are sustained in the dark at temperatures between 25 and 80°C or even at hyperthermophilic (>80°C) temperatures, depending on the strains.

Photo-fermentation is catalysed by nitrogenases in purple non-sulphur bacteria to convert organic acids or biomass into hydrogen from solar energy in a nitrogen-deficient medium.

2.4.3 Electrochemical processes

Electrolysis is an electrochemical process widely investigated for hydrogen production by splitting water molecules. The mechanism occurs in an electrolyser (containing a cathode and an anode) and relies on the flow of an electric current through a conductive electrolyte (alkali or polymer) in water.

Figure 9 Biological Hydrogen Production



Source: Ed W. J. Niel, 2016, *Biological Processes for Hydrogen Production, Anaerobes in Biotechnology, 2016, Volume 156*

This results in the splitting of water into O₂ and H₂.

Electrochemical conversion is also possible for biomass. The difference between water and biomass electrolysis lies in the reaction occurring at the anode. The feedstock is oxidised instead of producing gaseous oxygen from the water.

Implications for carbon neutrality

Hydrogen from biomass can help to decarbonise a range of sectors, contribute to improving air quality in cities and to strengthening energy security. Production and use of bio-hydrogens is thus an important development stream in the context of energy system decarbonisation, and meeting the world's future energy demand.

Policy actions

- Biomass "recycles" carbon dioxide. Invest into research and development to accelerate hydrogen production from biomass energy.
- Invest into carbon capture and storage infrastructure at scale to cut costs and increase deployment of biomass with CCS projects.
- Improve agricultural practices to drive down feedstock costs.

2.5 Hydrogen from nuclear power

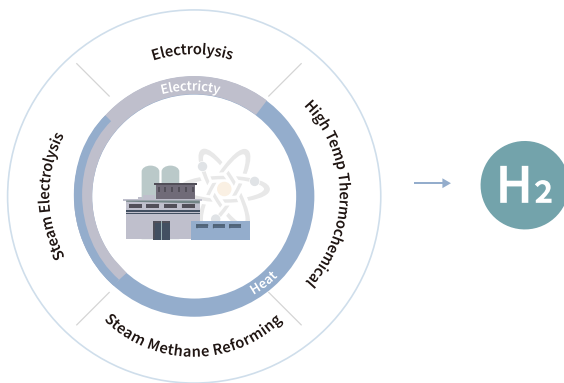
Nuclear power is an important source of low-carbon electricity and heat. In the future nuclear power can also be used to produce hydrogen via several low-carbon processes. About 100-130 new nuclear reactors of the scale of Hinkley Point C could provide sufficient electricity to meet the forecast hydrogen demand of 650 million tonnes/year in 2050. This implies a doubling of the world's installed nuclear capacity.

Nuclear power heat and electricity are attractive for hydrogen production as they provide continuous, low-carbon baseload electricity and heat suited for industrial hydrogen production. This reduces the need for energy storage that can help integrate variable renewable energy sources into energy system.

Technology overview

There are several methods of producing hydrogen with nuclear power and all are utilizing heat or electricity provided by nuclear reactors.

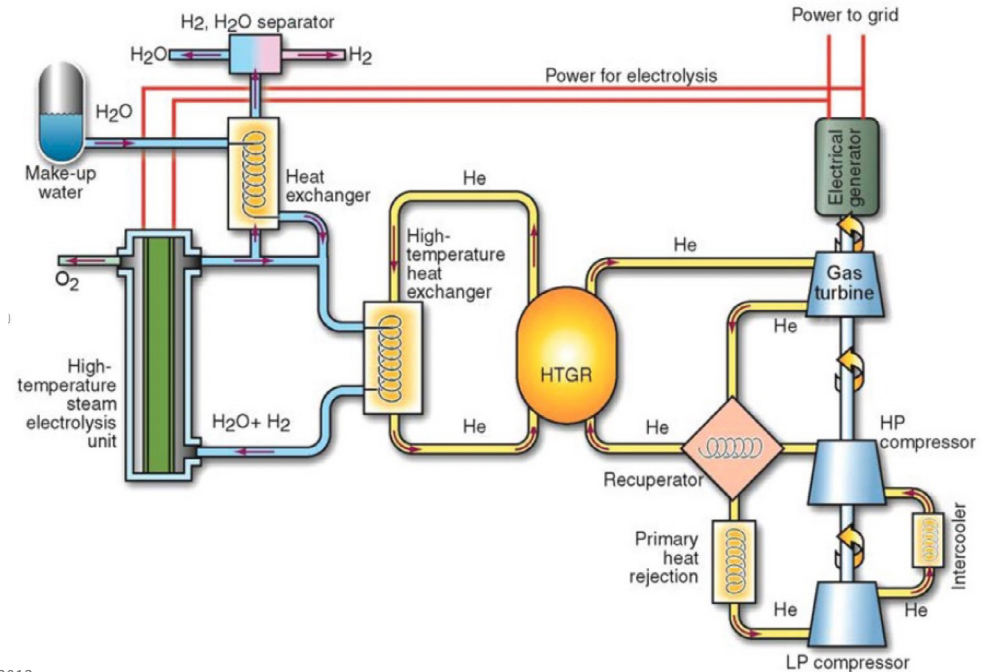
Figure 10 Hydrogen production pathways from nuclear power



Low-temperature electrolysis of water is the approach based on using current nuclear reactors producing electricity. The low-carbon electricity is used to power electrolysis that generates emissions-free hydrogen at ambient temperatures. Electrolysers are most effective when working continually at a high capacity factor rather than intermittently to diminish costs (see section 2.3).

High-temperature steam electrolysis applies low-carbon heat and electricity from nuclear reactors to power steam electrolysis, which is more efficient in producing hydrogen than electrolysis via renewable energy. While this process is more efficient at temperature range (550 – 750°C), it is also possible at temperature (<200°C).

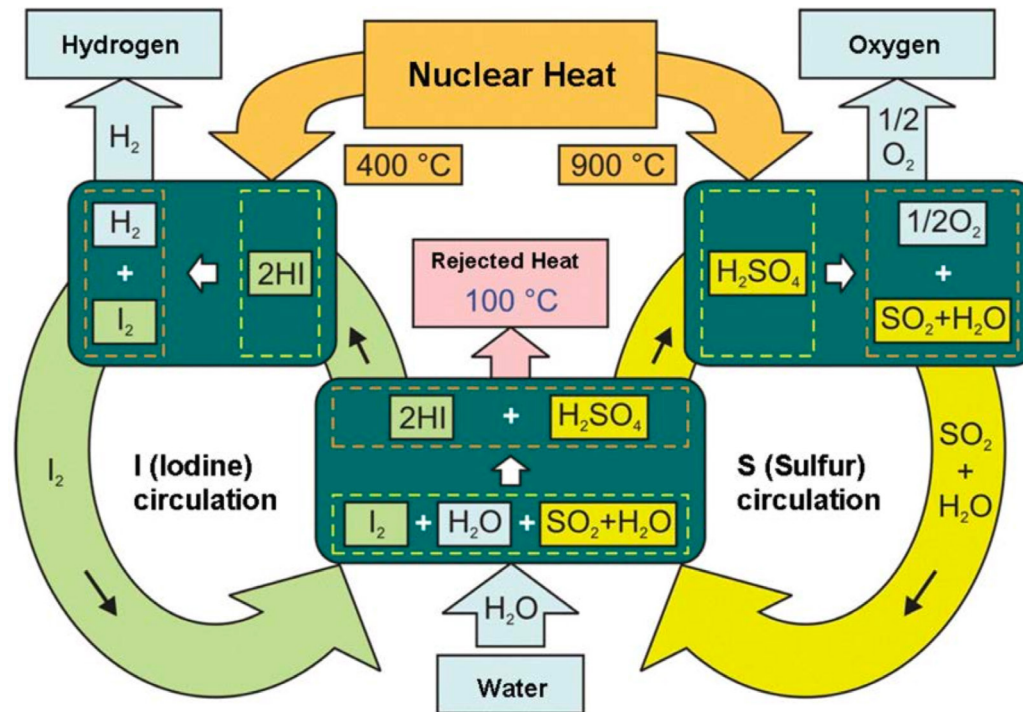
Figure 11 High-temperature steam electrolysis



Source: IAEA, 2013

High-temperature thermochemical production utilises energy from advanced reactors operating between 600-900°C. This is an emerging technology that is currently under development. At such temperatures and with the chemical environment, water splits into hydrogen and oxygen without needing electrolysis.

Figure 12 High-temperature thermochemical production of hydrogen



Source: IAEA, 2013

Nuclear energy for steam methane reforming applies nuclear heat in SMR process. This could reduce natural gas consumption and CO_2 emissions by 30% and greatly improve the thermal efficiency of the process (see Figure 2).

Industry analysis indicates that using low-temperature heat (150-200°C) to support steam electrolysis is technically feasible and offers efficiency benefits over cold water electrolysis. Steam electrolysis is readily available technology.

Global projects – Hydrogen from nuclear power

- In Asia, a high-temperature gas-cooled reactor (HTR-PM), demonstration plant for hydrogen production, expected to start operation end of 2021 in China. In Japan, a high-temperature gas-cooled reactors demonstrated hydrogen production method based on iodine-sulphur thermochemical processes.
- In the UK, the EDF Energy Hydrogen to Heysham (H2H) project demonstrated technical and commercial feasibility of producing hydrogen by electrolysis using electricity directly from nuclear with a significantly reduced carbon footprint (24 gCO₂/kWh H₂, compared to 509 gCO₂/kWh H₂). A 2020 report on the trial estimated that future electrolyser capacity of about 550MW across its UK nuclear fleet could produce about 220 tonnes of hydrogen per day by 2035, with the levelised cost of hydrogen as low as £1.89/kg (\$2.44/kg).
- In the US, the Department of Energy is to fund two projects to advance flexible operation of light water reactors with integrated hydrogen production systems. Two other projects are already underway: i) solid oxide electrolysis cell at high temperatures; ii) high-temperature steam electrolysis (HTSE) technology. The necessary heat and electricity will be supplied by one of Xcel Energy's nuclear plants.
- In Poland, the National Centre for Nuclear Research in cooperation with Japan initiated a project to develop HTGR reactors. The government plan to build a 10 MW experimental HTGR at Swierk followed by a cogeneration HTGR of 200-350 MW for heat processing. The reactor is intended primarily to produce heat and hydrogen for industrial applications.

Implications for carbon neutrality

Nuclear power, as a low carbon energy source of electricity and heat, can contribute to carbon neutrality. Long-term operation of existing nuclear plants offers the competitive generation cost for low-carbon electricity option. Nuclear power assisted SMR can reduce the amount of GHG associated with pure natural gas SMR.

Nuclear power presents specific risks such as radiological accidents and radioactive waste management that must be properly anticipated and handled. Some countries choose not to pursue nuclear power because they consider the risks of nuclear incidents and accidents to be unacceptable or because of issues linked to long-term disposal of radioactive wastes.

Policy actions

- Recognise the role that nuclear energy can play in clean hydrogen production.
- Recognise nuclear hydrogen production as one of the plausible low-carbon hydrogen pathways in “Guarantee of origin” schemes.
- Support commercialisation of hydrogen production with existing large-scale nuclear reactors. A pathway for large-scale commercial hydrogen production powered by the existing reactors should be demonstrated within the next 3-5 years.
- Support R&D of advanced modular reactors for efficient steam electrolysis and thermochemical production of hydrogen.

3. STORAGE AND TRANSPORT OF HYDROGEN

Storage and transport of hydrogen are the most significant barriers to the unfolding of a full hydrogen economy. To date, it is more economical to move big hydrogen users to hydrogen producers' locations than to ship hydrogen across distances. In addition, it is still a challenge to store millions of tonnes of hydrogen to meet anticipated hydrogen demand by 2050. Ambitious policies and investments are needed today to support hydrogen storage, transport and conversion infrastructure that is required a future hydrogen market to function.

The methods to transport and store hydrogen are defined by the physical properties of hydrogen, relative to other fuels, as illustrated in Table 3.

Difficulties in hydrogen storage and transport stem from its relatively low volumetric density (ten times less than LNG) and low energy density (ten times lower than that of petrol or diesel). To reduce the storage volume needed to contain a given amount of hydrogen, more extreme conditions – high pressures, low temperatures, or both – are required.

To withstand higher storage pressures, we need specially constructed vessels that are many times heavier and more expensive compared to rather simple tanks needed for liquid fuels (petrol and diesel). The construction of hydrogen tanks is also technologically more challenging than the one for Liquefied Natural Gas (LNG) tanks.

Maintaining low temperatures comes with an energy penalty, due to refrigeration costs, fugitive energy losses and boil off.

Table 3 Physical properties of selected energy carriers

ENERGY SOURCE/CARRIER	PHYSICAL DENSITY (kg/m ³)	SPECIFIC ENERGY (MJ/kg)	ENERGY DENSITY (MJ/litre)
Petrol	750	42	31
Diesel	900	43	37
Liquid petroleum gas (LPG)	550	46	23
Methane (STP)	1	50	0.0099
Liquid methane - LNG (111 K)	450	50	21
Compressed methane (250 bar)	215	50	9
Hydrogen (liquid, 20 K)	71	120	9
Hydrogen (STP)	0.09	120	0.0099
Hydrogen (compressed, 350 bar)	23	120	3

STP = Standard Temperature and Pressure (0°C and 1 atm pressure)

Source: Bloomberg NEF 2020c

3.1 Storage of hydrogen

State of play

Hydrogen is notoriously difficult to contain. Storage of hydrogen in gaseous form requires high pressures of over 300 bar. Such pressure is necessary because of hydrogen's low density – it is 10 times lighter than methane. To store hydrogen as a liquid, at any pressure, it must be cooled below –250 C. This is 80 degrees lower than LNG. Such high pressures and low temperatures pose enormous technical challenges and require a lot of practical experience.

In principle, hydrogen can be stored in pure form as compressed gas or liquid, or in various hydrogen carriers, such as ammonia or methanol. Production and transport of ammonia is commercialised globally, the technology and commercial readiness of methanol directly from hydrogen, rather than natural gas is still limited and will need to develop further before becoming fully commercialised. It is important to note that conversion requires significant energy input with energy losses of up to 11% for compression and decompression processes and of up to 75% if converted to ammonia and then to hydrogen.

Geologic storage of hydrogen, in salt caverns, saline aquifers, depleted oil & gas reservoirs or engineered hard rock reservoirs, is the best option for large-scale and long-term storage. Tanks, on the contrary, are more suitable for short-term and small-scale storage.

Storage technology properties

Physical storage - Physical storage deals with hydrogen in its pure form –molecular hydrogen. It is then contained at different pressures, temperatures, and phases (gaseous or liquid).

Compressed gas - The current technology for compressed hydrogen, primarily in vehicle on-board storage, uses pressure vessels operating at 350 - 700 bar. Four standard types of cylinders are used for hydrogen storage:

- Type I—all-metal cylinders
- Type II—all-metal hoop-wrapped composite cylinders
- Type III—fully wrapped composite cylinders with metallic liners
- Type IV—fully wrapped composite cylinders (non-load bearing is non-metallic)

Compressed gas vessels provide storage for relatively small quantities. For large-scale storage, we must rely on underground and underwater reservoirs. According to some estimations salt caverns are among the most cost-effective storage options: for a competitive price (around 0,23 \$/kg) it allows for large volumes of hydrogen to be stored on a long-term basis (months-weeks).

Liquefied hydrogen - To become liquid at any pressure, hydrogen must be cooled below its critical temperature (–250 C). Once liquefied, hydrogen requires energy to be kept in thermally insulated containers. Liquefied hydrogen is several times more dense than compressed hydrogen; yet, it is significantly less dense than LNG.

Storage in materials - As mentioned above, some hydrogen carriers include methane, methanol, ammonia, methylcyclohexane, sodium borohydride. A chemical reaction is needed to convert these products and release gaseous hydrogen. There are also metal powders that can absorb and release hydrogen (metal hydrides). They can store significant amounts of hydrogen at atmospheric pressure and room temperature, due to forces acting inside the metal crystal lattice. Metal hydrides are the most compact way to store hydrogen. They are more dense than liquid hydrogen.

Table 4 Hydrogen storage options and costs

	GASEOUS STATE				LIQUID STATE			SOLID STATE
	Salt caverns	Depleted gas fields	Rock caverns	Pressurized containers	Liquid hydrogen	Ammonia	Liquid organic hydrogen carriers	Metal hydrides
Main usage (volume and cycling)	Large volumes months-weeks	Large volumes seasonal	Medium volumes, months-weeks	Small volumes daily	Small-medium volumes, days-weeks	Large volumes, months-weeks	Large volumes, months-weeks	Small volumes, days-weeks
Benchmark LCOS [\$ /kg]	\$ 0.23	\$ 1.90	\$ 0.71	\$ 0.19	\$ 4.57	\$ 2.83	\$ 4.50	Not evaluated
Possible future LCOS	\$ 0.11	\$ 1.07	\$ 0.23	\$ 0.17	\$ 0.95	\$ 0.87	\$ 1.86	Not evaluated
Geographical availability	Limited	Limited	Limited	Not limited	Not limited	Not limited	Not limited	Not limited

Source: Bloomberg NEF. (2020). Hydrogen economy outlook. URL: <https://data.bloomberglp.com/professional/sites/24/BNEF-Hydrogen-Economy-Outlook-Key-Messages-30-Mar-2020.pdf>

There are two main drivers of hydrogen storage demand:

- **Inter-regional hydrogen trade.** Interregional exports and imports to balance demand and supply of hydrogen. An example in Europe: RAG Austria is involved in a project for importing hydrogen from Ukraine that implies a significant increase of storage capacities for hydrogen in Central Europe.
- **Inter-seasonal energy storage.** Through the power-to-hydrogen and electrolysis method, renewable energy can be stored in the form of energy carrier hydrogen and provide balance to the energy system.

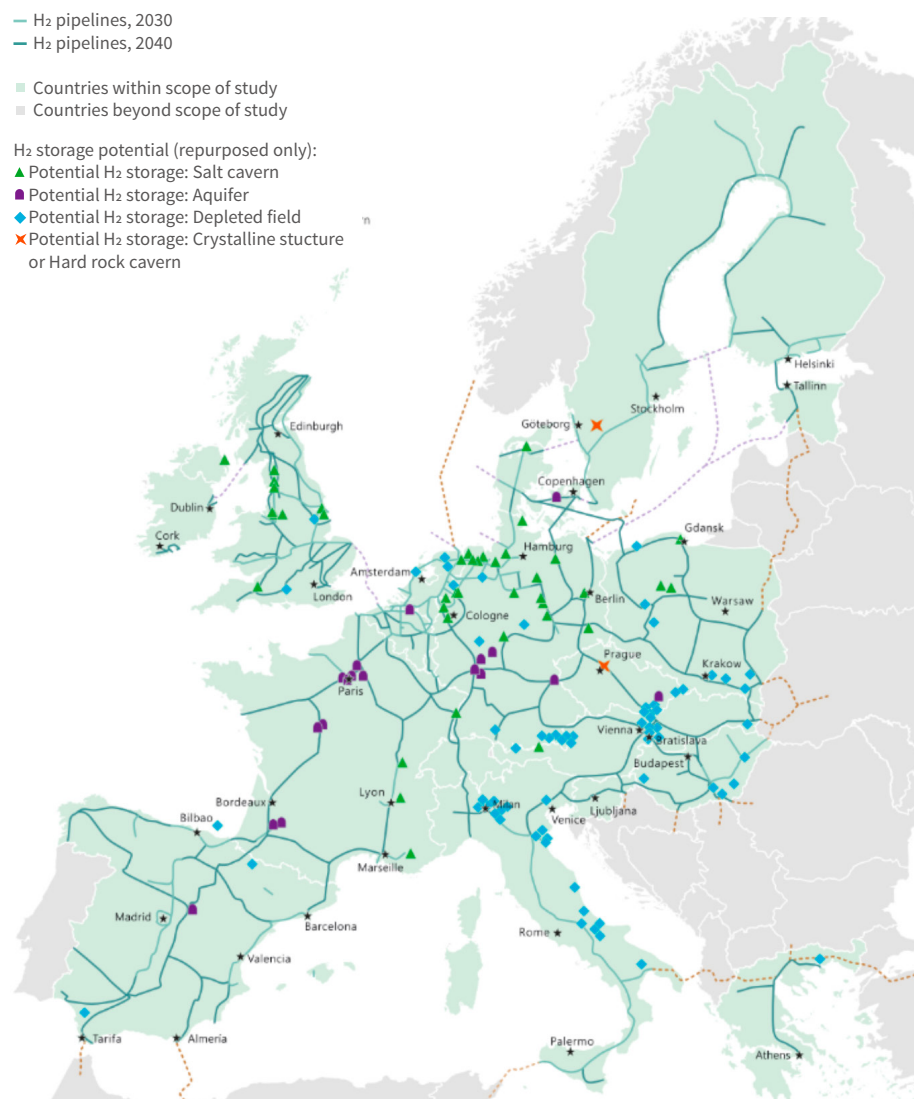
To put it in the context, the global natural gas demand in 2019 was approximately 4000 bcm, or 40,000 TWh, while the global gas storage demand was 424 bcm, or about 4000 TWh. We have a relation of 10 to one, and this proportion applies across the globe. The global hydrogen demand for 2050, as estimated by World Hydrogen Council, is 27,500 TWh a year or about 18% of the final energy demand. A more ambitious new energy outlook climate scenario provided by the BloombergNEF expects hydrogen demand to surge to about 41,000 TWh by 2050, or to 24% of the total final energy demand; a more conservative sustainable development scenario by IEA expects hydrogen to account for about 6% of the total final energy demand by 2050.

Based on the Hydrogen Council 2-degree scenario, if excluding hydrogen needed for transport, we end up with 20,000 TWh/year for hydrogen demand in 2050. If applying the same relation “10 to one”, we come up with 2,000 TWh of gas storage demand. But one cube of natural gas has approximately 10 KWh per cube and one cubic meter of hydrogen has 3.3 KWh of energy content. The latter means that hydrogen storage demand will be 600 bcm and - a 55% increase.

Other estimations (HyDeal) calculate expected hydrogen storage capacities based on the anticipated hydrogen demand and transmission needs. As such, to get 3.6 million tons of hydrogen delivered by 2030 one needs 7700 km of transmission and a storage capacity of no less than 50 TWh. And this again should consider differences in volume between hydrogen and natural gas, as well as the issue of porosity (some hydrogen will be lost in the process of storing).

The numbers imply that to achieve hydrogen economy vast expansion of existing storage capacities is crucial, and this increase is expected to be in the factor of five to ten over current capacities in the next 10 to 15 years. Simple conversion of the existing underground storage will not be enough and new hydrogen storage facilities will be necessary (see Figure 13).

Figure 13 The European Hydrogen Backbone and underground hydrogen storage analysis 2030 - 2050



Source: Gas Infrastructure Europe

Policy actions

- Encourage business models for deployment and scaling of geological physical hydrogen storage.
- Recognise the potential of chemicals, such as ammonia and methanol, to store hydrogen at high density and low maintenance cost.
- Invest into R&D of all hydrogen storage solutions. Hydrogen storage is the key technology barrier to scaling of fuel cell applications in transport sector and stationary applications.

RAG Austria Underground storage projects

In 2013 RAG Austria started a research project called underground Sun storage. The first in the world, they **injected 10% of hydrogen admixture** in a sandstone reservoir and investigated the integrity of the whole storage system. In a follow-up project - underground Sun conversion - RAG investigated **the injection of hydrogen plus CO₂ in a reservoir** where it **is converted into methane** by microbiological processes. RAG most recent project is underground Sun storage 2030 where they investigate 100% hydrogen content for storage.

(Kiss, 2021, Hydrogen Workshop)

Table 5 Overview of hydrogen storage solutions

	GASEOUS STATE				LIQUID STATE		
Type	Salt caverns	Rock caverns	Depleted oil & gas fields	Pressurised containers	Liquid hydrogen	Ammonia	Liquid organic hydrogen carriers
Capacity [tH ₂]	300 - 10,000	300 - 2,500	300 - 100,000	< 1.1	< 0.2	< 10,000	<4,500
Cost [\$/ kg H ₂]	0.23	0.71	1.9	0.2	4.5	2.8	4.5
Major advantage	Large volume over mid-term	Large volume over mid-term	Large volume over long-term	Suitable for short-distance transport	Suitable for long-distance transport	Suitable for long-distance transport	Suitable for long-distance transport
Major disadvantage	Depends on geographical availability	Depends on geographical availability	Depends on geographical availability	Low efficiency	Low efficiency	Low efficiency	Low efficiency
Technology maturity	●●●●●	●●●○○	●●●○○	●●●●●	●●●●●	●●●●●	●●●●●
Commercial readiness	●●●○○○	●●●○○○	●●○○○○○	●●○○○○○	●●○○○○○	●●○○○○○	●●○○○○○
Social readiness	●●●●○	●●○○○○	●●○○○○	●●●●○	●●●○○○	●●●●○	●●●○○○

Source: IEA 2019 Future of Hydrogen, Energy Transitions Commission 2021

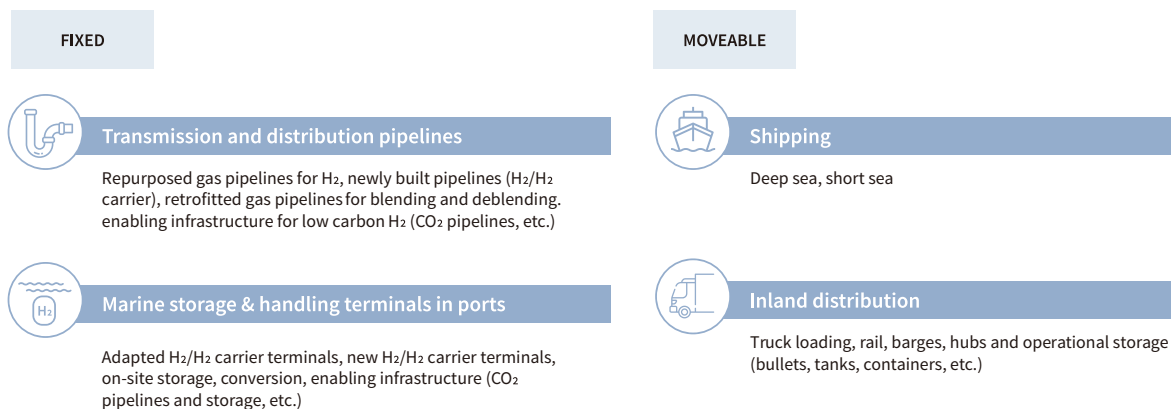
3.2 Transport of hydrogen

To be transportable hydrogen needs to be compressed, liquefied or chemically combined. Safe and cost-efficient transport and distribution of hydrogen is critical for its large-scale deployment. Hydrogen's low energy density, high diffusivity, and high flammability imply important technological and infrastructural challenges associated with the transport of hydrogen and large-scale adoption in end-markets, such as heating or transport. It is likely that the initial adoption and use will be locally concentrated in so-called hydrogen hubs or hydrogen valleys, while for global large-scale integrated value chains it will take longer to happen.

In terms of transport modes, hydrogen can be transported by:

- Road and rail, as gaseous or liquid, in special vessels, tubes, and containers
- Marine transportation, primarily by specialized cryogenic tankers
- Pipelines, which can carry either pure methane, pure hydrogen or a blended product

Figure 14 An overview of hydrogen transmission and distribution methods



Source: Enriquez, 2021. UNECE Hydrogen Workshop

3.2.1 Transport by road and railway



As mentioned in the section on storage, a common method of hydrogen transport is in pressure-proof filled cylinders on a truck. These vessels can be either of industrial standard size (up to 150 litres volume), or larger tubes. The handling of such vessels is regulated by the ECOSOC Committee of Experts

on the Transport of Dangerous Goods, managed by UNECE. In addition, in 2013 UNECE's World Forum for Harmonization of Vehicle Regulations (WP.29) adopted technical regulations on the safety of hydrogen and fuel cell vehicles that, among other things, deals with on-board hydrogen vessels.

3.2.2 Marine transportation



The transport of hydrogen across the oceans has been studied for over 40 years, primarily in the form of liquid hydrogen or as methylcyclohexane. However, the developments of this technology are still at very early stage with small demonstration projects ongoing. The first hydrogen cargo ship – Suiso Frontier – was

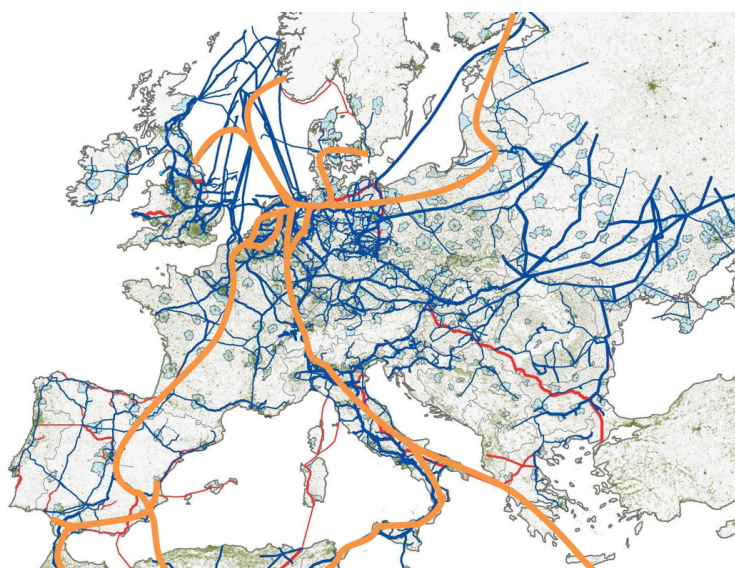
commissioned in 2019 to transport hydrogen from Australia to Japan in one 1250m³ (=88 tonnes H₂) vacuum insulated tank at -253C/1 atm. South Korea is commissioning a 20,000 m³ (=1420 tonnes H₂) cargo ship also using vacuum insulated vessels. The economics of liquid hydrogen transport contain many hidden costs, so this technology is still under development and it is unlikely that large-scale maritime hydrogen transport will scale before 2040.

3.2.3 Pipelines

Hydrogen blending into the existing gas network has multiple advantages and can be a cost-effective transitional option in the short term in regions without parallel or duplicated networks or without (potentially) available gas infrastructure capacity. The retrofitting and repurposing of existing gas networks can be combined and complemented with the construction of new dedicated hydrogen infrastructure.

Hydrogen pipelines are already used to supply single users (typically, a petrochemical plant) with hydrogen. At present a hydrogen pipeline network is built along the Gulf coast of the United States (between Baton Rouge, LA, and Corpus Christi, TX, around 900 km of pipelines). In Europe, there are various initiatives, the European Hydrogen Backbone and the Re-Stream study; the latter assesses the potential of the existing European oil and gas infrastructure to carry hydrogen and/or CO₂. There are industrial hydrogen pipelines centred at the ports of Rotterdam and Antwerp (around 1,500 km of pipelines).

Figure 15 A future trans-European hydrogen transmission and distribution pipeline network



Source: Hydrogen Europe 2019

Natural gas infrastructure in Europe (blue and red lines) and first outline for a hydrogen backbone infrastructure (orange lines)

Transport of hydrogen demand estimates and cost

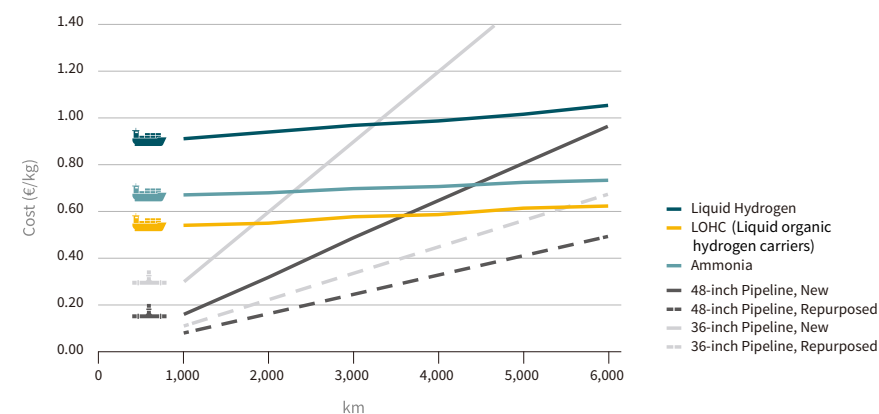
Hydrogen experts have widely agreed that the price of hydrogen produced should be no higher than 1.5 euro/kg. 1kg of hydrogen provides 120MJ of energy. In comparison, 1kg of diesel is 50 cents and provides 40MJ of energy. To be cost-efficient and compete with incumbent fuels the cost of 1kg of hydrogen should be below 1.5euro/kg. This comparison excludes the effects of the carbon pricing mechanism. Cost is the key challenge for large-scale implementation of the many technically feasible options for hydrogen transport and storage.

This implies that local hydrogen hub developments will be needed across the UNECE region. Given relatively high costs of hydrogen transportation, in particular over long distances, the locally produced hydrogen is often more cost-effective than transported hydrogen from far away, even if its production costs are lower.

Hydrogen can be transported by pipelines as pure compressed hydrogen or as ammonia. Transporting pure hydrogen makes economic sense for a distance of less than 3,500 km; for longer distances ammonia route is a more economically viable option.

According to recent researches, hydrogen pipelines are the most cost-efficient option for long-distance, high-volume transport. The corresponding expenditures range from €0.11 to 0.21/kg per 1,000 km, thus outcompeting the costs of transport by ship for all reasonable distances within Europe and neighbouring regions.

Figure 16 Comparison of hydrogen transport options over various distances



Source: European Hydrogen Backbone

By 2050, significant volumes of hydrogen will need to be transported. Substantial scaling-up of the existing distribution network capacities is among the core prerequisites to sustaining the hydrogen momentum. In a future hydrogen economy, the centres of hydrogen production and the centres of hydrogen demand will likely be relatively far from each other (e.g. offshore developments, development of hydrogen supply markets in North Africa, Sahara or the Middle East and demand markets in Europe and East Asia).

Hydrogen carriers (e.g., ammonia, synthetic methane, LOHC, kerosene, etc.) may be used to effectively transport and dis-

tribute renewable energy over large distances without having to handle large quantities of hydrogen. Therefore, countries will be able to import renewable energy from the best wind and solar spots worldwide to meet their own decarbonisation target. This production method requires a further conversion but potentially offers advantages, such as higher energy density, better compatibility with end-use applications and lower costs.

European Green Deal and Hydrogen Strategy

On 8 July 2020, the European Commission adopted a new dedicated [Strategy on hydrogen](#) in Europe, in parallel with the [Strategy on energy system integration](#). This aims to bring together different strands of action, from research and innovation over production and infrastructure to the international dimension. On 15 December 2020 the EC's adopted a proposal for a [revised TEN-E](#) rules (Trans-European Networks for Energy) to reflect the EU climate and energy priorities in energy infrastructure planning. The European Network of Transmission System Operators for Gas (ENTSO-G) 2050 Action Plan targets investments towards renewables, low-carbon and decarbonised gases, including Energy Transition Related projects to convert gas grids to accept hydrogen blends, as well as pure hydrogen under European Hydrogen Backbone, and CO₂ grids.

The [EC's Executive Vice-President for the Green Deal Frans Timmermans](#) said: "Now is the time to invest in the energy infrastructure of the future. The revised TEN-E rules will allow clean technologies to be plugged in to our energy system – including offshore wind and hydrogen. We need to update and upgrade now to achieve the Green Deal's goal of climate neutrality by 2050".

Hydrogen transport - specific policy actions

- Foster R&D for innovative clean hydrogen carriers and reconversion
- Incentivise regional clean hydrogen supply and demand (H₂ valley approach)
- Include mapping of future clean hydrogen demand centres in infrastructure planning instruments (e.g. industry)
- Consider the possibility that low-carbon hydrogen imports may be cheaper than domestic production
- The legislation should be flexible enough as not to prevent various actors, including gas transmission system operators (TSOs), from owning and operating hydrogen network

3.3 The role of existing gas infrastructure

On the European continent, a mature developed and regulated network of gas infrastructure is already in place. The European transmission grid for natural gas is approximately 200,000km long. Adding to that a distribution grid that is double the size of the current transmission grid implies that the gas infrastructure is the key enabler for the deployment of a hydrogen economy. The UNECE Group of Experts on Gas recognised the key role of gas operators, gas industry and gas infrastructure in the transition to a hydrogen economy through the energy system integration.

Even though pipelines and gas storage facilities today are being considered as the most cost-competitive solution for hydrogen distribution, numerous challenges remain unsolved. One of them is an increasing difficulty of building new pipelines - with the NIMBY effect ("not in my back yard") being among the core issues. It is in the best interest of actors in the hydrogen value chain to find ways to extensively reuse existing gas infrastructure instead of constructing bespoke hydrogen infrastructure. It is thus necessary to start immediate retrofitting and repurposing of current gas infrastructure.

Given TSOs know-how in operating gas transmission infrastructure, the gas TSOs should be among those certified as owners and operators of future hydrogen networks.

Authorising gas TSOs to carry out activities related to the development, integration and operation of hydrogen infrastructure would facilitate an efficient way forward due to their experience in planning, financing, constructing, operating and maintaining gas infrastructure, since existing gas grids will be retrofitted and repurposed for hydrogen.

Estimating hydrogen storage demand by linking hydrogen demand to existing gas grid

If you want to compare **hydrogen storage demand** with the natural gas situation, you have to clearly understand the context specifics of each given country. If you get LNG, for instance, you have a different approach and different necessity for underground gas storages. If you have a consumer in the centre of a country or a region, then it's a whole new story, because you have to transport hydrogen by a pipeline. And then the only way to balance the market is to have a storage facility available near the consumer. **So it is highly difficult to estimate a value for the potential hydrogen storage demand, as it is very context-dependent. But the first indication to consider here should be current storage demand for natural gas.** This will give a first rough number for each specific country.

(Kiss, 2021, Hydrogen Workshop)

Gas pipelines

Retrofitting and repurposing existing gas pipeline network is often considered as the most cost-efficient way to develop the hydrogen market for long-distance transport of large hydrogen quantities. For instance, HyDeal provides the following comparative estimations of costs related to hydrogen pipeline transportation: €0.5 million per km for repurposing versus €2.3 - 2.4 million per km for new pipes of 48,256 inches.

The cost reductions can be achieved by reusing instead of rebuilding. Hydrogen-repurposed pipelines can provide direct connection between core production sites (e.g. renewable or low-carbon energy from Southern Europe, Africa, Central Asia, or the Middle East) and points of consumption (e.g. any region with low capacities for renewable input).

Hydrogen pipeline development is expected to go through two major phases: hydrogen blending and pure hydrogen injection.

Pipes in solar and renewable hydrogen scenario

HyDeal modelling predicts that the way to achieve low-carbon hydrogen economy (implying its cost-efficient value chain) is to use solar energy as the major source. The experts anticipate that today it is the only technically possible way to secure 1.2 euro/kg production costs for hydrogen.

The HyDeal representative provides one core reason for such important solar role in hydrogen economy: "You need to go where resources are very cheap. And very cheap electricity comes from solar". This also implies that solar sourcing is only feasible in countries with high capacities for such input. In the European Union, for instance, HyDeal qualifies only Spain and Portugal. When it comes to a broader geography, "North Africa comes in, Tunisia and Morocco, among others, and further is Turkey".

(Lepercq, 2020)

Hydrogen Blending

Hydrogen can be blended with natural gas and transmitted via existing gas infrastructure. Studies indicate that natural gas burning boilers and pipelines can safely operate with up to 5-15% of hydrogen content. Furthermore, according to the US DoE Hydrogen Strategy, pipelines can handle from 15% to 30% hydrogen blends without modifications.

Blending hydrogen into the natural gas pipeline network can also be an option for delivering pure hydrogen to end-markets. This is possible by applying hydrogen separation and purification technologies downstream and extracting hydrogen from the blend near the point of end use.

An economic perspective on hydrogen blending implies developing Guarantees of origin – tradable certificates for zero/low-carbon hydrogen – or similar market mechanisms promoting non-governmental financial stimulus to actors engaged in this venture. Such business model already exists for biogas and renewable energy.

Hydrogen blending in Germany

Thüga Aktiengesellschaft, a German utility company, is implementing several practical projects on hydrogen injection. Hydrogen mixing is the priority stream – it allows using existing infrastructure and appliances. Currently it investigates injection of 20 % H₂ in the DSO* grid as part of a complex project with refinery, TSO-grid, cement factory, underground storage, green kerosene for airport. Thüga also plans to launch pure hydrogen projects anticipating that, **in time, they will move ahead from a blend to pure hydrogen** -as soon as the hydrogen backbone is developed in Germany.

Pure hydrogen transmission

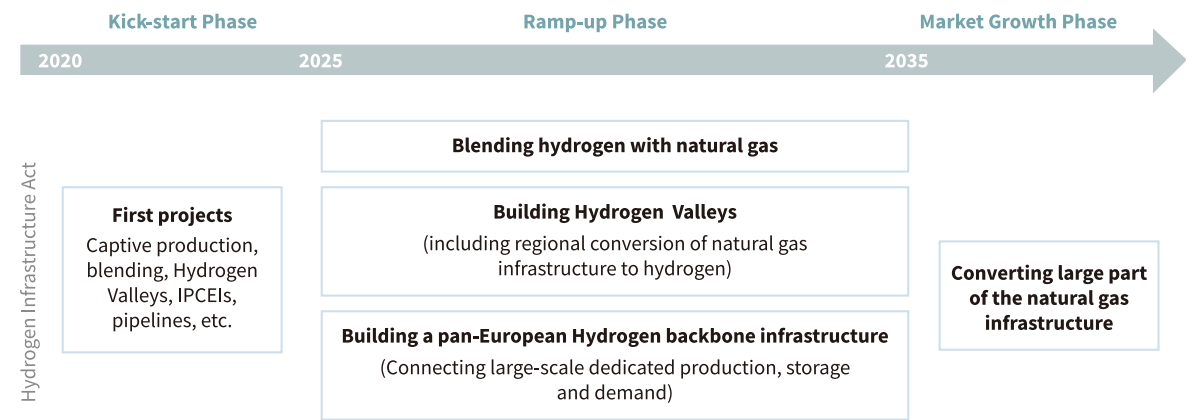
Despite the barriers to entry, pure hydrogen transmission is expected to lead the future hydrogen economy. Yet the key precondition for this is to have capacity to build such

new infrastructure quickly and extensively. The necessary preconditions here are uniform regulatory framework and investment flows. Recent policy signals imply that long-term trends are going in this direction across different countries within and outside European borders.

Policy actions

- Combine local, regional and national capacities of micro-rids, DSO(distribution system operators) and TSOs and build hydrogen valleys with regional and local hydrogen infrastructure and connect them to the national and European hydrogen backbones.
- Support the development of guidelines for the UNECE-wide harmonisation of regulations, uniform standards, definitions and technical rules that govern natural gas and hydrogen blending in all proportions.
- Discuss within the UNECE context the implications of relevant EU gas directives (such as the updated 2009 Gas Directive) that foresee the use of natural gas networks to transport and store hydrogen.
- Legislation should recognise that gas TSOs can own and operate H2 networks.

Figure 17 Gas infrastructure transition transition roadmap



Source: Hydrogen Europe 2021

The development of hydrogen infrastructure will evolve over time from more local and cluster-driven projects to regional and cross-border initiatives. Hydrogen Europe foresees a three-phased approach to the development of both the hydrogen market and hydrogen infrastructure. The first being the “kick start” phase, which will require, for a limited period of time, exceptions and derogations from the existing EU rules, such as relaxation and/or reform of EU state aid rules. Considering the challenges, the hydrogen sector is confronted with in the context of the EU Green Deal, the European economy recovery post-COVID19 and the Hydrogen Strategy, the dedicated guidelines on the state aid for hydrogen technologies should be promoted. In the “ramp up” phase, we will begin to see the forming of a European hydrogen backbone before we enter a “market growth” in which a hydrogen economy will be realised. With regards to hydrogen infrastructure regulation, a gradual approach **is recommended, in line with infrastructure and market developments is needed. Europe is currently at the forefront of hydrogen regulation and has an opportunity to develop a blueprint which can be mirrored by other parts of the world, thus promoting the development of a global hydrogen industry and the trading of hydrogen as a global commodity.**

4. APPLICATIONS OF HYDROGEN ACROSS SECTORS

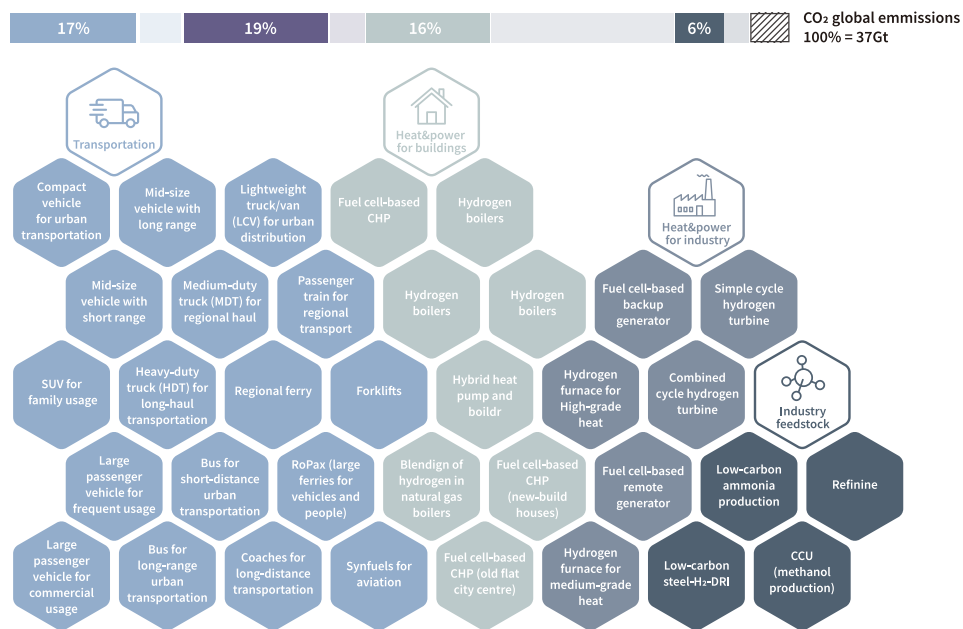
Hydrogen can help achieve a clean, secure and affordable energy future and decarbonize a range of sectors. Hydrogen as energy carrier can be used as fuel in transport sector or for power generation. It can also be used for heating in residential and commercial sector or in high-temperature heat processes in production of steel, aluminium, paper or food. Today, hydro-

gen applications are most common as a feedstock in chemical industry for production of fertilizers, plastics and fuel refining.

Hydrogen can support applications which account for 60% of total GHG (see Figure 18).

- **Transportation:** Hydrogen applications in transport are possible with use of internal combustion engines (ICE) or turbines, and with use of fuel cells. While ICE technology is more mature, fuel cell technology has received faster market pull thanks to higher efficiency of energy conversion.
- **Power generation:** Hydrogen application in power sector is limited today, but there is potential for increasing role in the future. Hydrogen powered gas turbines could be a source of flexibility in electricity system. Also, Solid Oxide Fuel Cells can offer the highest conversion efficiency. In addition, hydrogen can become a long-term storage option to balance seasonal variations in electricity demand.
- **Industry:** In industry hydrogen (mainly in the form of methane) applications include demand for industrial heat or feedstock. At present, hydrogen is used in large-scale industrial processes like oil refineries, petrochemicals, ammonia production, methanol production, and steel production. In oil refineries, hydrogen is used to remove sulphur crude oil and produce lighter oil products from heavy oil. (But electrification of transport means that this market will shrink) Hydrogen with a source of carbon will replace natural gas and to a smaller degree oil as the basis for production of synthetic gases under the concept of power-to-X conversion that includes power-to-ammonia, power-to-chemicals, and power-to-methane.
- **Buildings:** hydrogen can play an important role in decarbonisation of buildings. It can be applied in buildings for power and heating appliances. The potential of hydrogen in this sector is a debatable topic. Technologies such as heat pumps are still more efficient and economical solution. While the electrification of buildings sector on the back of renewable energy sources is a growing trend, the question is whether a 100% electrified system is feasible given the intermittence of most renewable energy sources in combination with large scale electric heating and electric mobility. Hydrogen can here play a role as a solution with storage and flexibility properties.

Figure 18 Hydrogen applications across sectors



Source: Path to hydrogen Competitiveness - Hydrogen Council

In addition, hydrogen can also be used in

Mobility: Container ships, tankers, tractors, motorbikes, tractors, off-road applications, fuel cell airplanes.

Other: Auxiliary power units, large scale CHP for industry, mining equipment, metals processing (non-DRI steel), etc..

4.1 Application of hydrogen in power sector

State of Play

Hydrogen, in compressed form, has the potential to become a storage option in electricity demand and help solve the energy seasonal storage challenge. Hydrogen and hydrogen-based fuels can be used in gas turbines for power generation. Hydrogen technologies are at the heart of sector coupling (power to gas technology that brings together the gas and electricity systems and provides storage solutions) and sector integration. Both hydrogen and electricity grid infrastructures together with large scale seasonal hydrogen storage and small-scale day-night electricity storage, in mutual co-existence, will be essential to realise a sustainable, reliable, zero-emission, and cost-effective energy system.

Potential of this application

Hydrogen can help decarbonize energy by integration of larger shares of renewable energy into the market. In power-based applications, hydrogen can stabilize the electricity system by providing ancillary services through highly flexible operations.

Power-to-X (P2X) is the process to produce hydrogen and derived products (climate-neutral fuels). The challenge for the integration of P2X technologies is also co-localization of the production and consumption sites. A successful P2X/hydrogen economy combines low-cost electricity production sites with hydrogen demand hubs as well as suitable carbon sources in the case of synfuel and syngas production. In addition, and the case of high-temperature hydrogen applications, heat-system-integration represents a further criterion for site selection.

As a technology that enables the interconnection of different energy supply and consumption sectors (sector coupling technology), it is important for a successful market integration of P2X technology to be able to generate revenues in different markets.

Policy actions

- Eliminate ambiguities in regulation frameworks to promote benefits of sectoral integration and hydrogen's role as a producer and consumer of electricity.
- Scale-up pilot P2X plants to reach commercial unit sizes.
- Develop suitably scaled hydrogen gas turbines operating on blends of hydrogen to 100% in open cycle & combined cycle gas turbines for electrical power generation.
- Share knowledge by learning-by-using and technology integration through well-designed sub-systems
- Create innovative policy to strengthen the domestic market for hydrogen and P2X products
- Produce clear rules to promote environmental and economic benefits of P2X fuels
- Research system integration and local aspects of consumption structures, availability of resources and infrastructure to increase optimal use of hydrogen in the power sector.

4.2 Application of hydrogen in transport sector

State of Play

In transport, hydrogen Fuel Cell Electric Vehicles (FCEVs) offer a low carbon alternative to fossil fuels and are the only vehicles alongside battery electric vehicles (BEV) that offer no exhaust emissions. BEVs may be more competitive in light duty and lower utilization applications while FCEVs will have an advantage in heavier duty and higher utilization applications. Any road transport can use hydrogen either by a fuel cell or by hydrogen-based fuels.

Early adoption of hydrogen in transport sector is possible in captive uses, such as urban buses, commercial taxi fleets, or in railway network for specific routes, where electrification is difficult.

There is an existing market for hydrogen-powered forklifts, buses as well as trucks and logistic vehicles. There are

estimated to be around 2,000 such buses, 1,500 trucks, and 30,000 forklifts that are in use today. Passenger hydrogen fuel cell electric vehicles are expected to rapidly increase from the current number of 15,000 following the widespread availability and cost-effectiveness of fuel cell technology. At the end of 2020, Europe, the Middle East and Africa region accounted for only 36% the 580 hydrogen stations worldwide.

Potential of this application

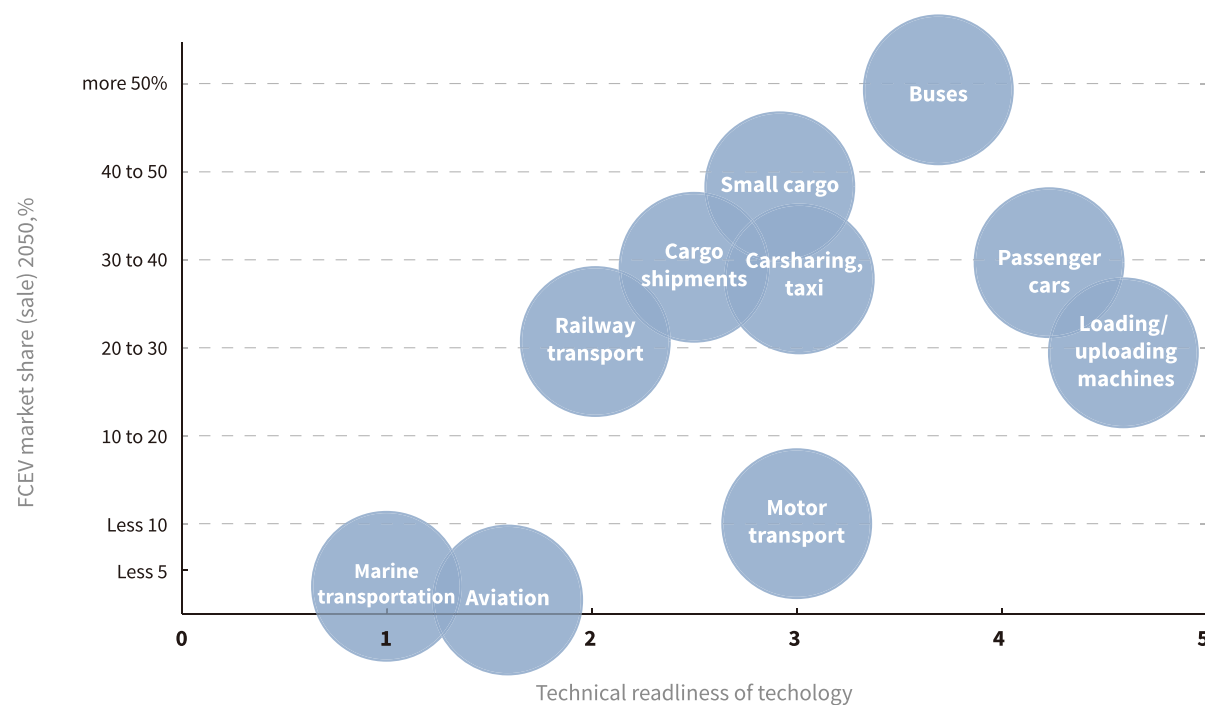
Current estimations of hydrogen costs 'at the pump' are between €7-9/kg. By 2030, hydrogen costs are expected to be less than €6/kg and competitive with fossil fuels.

Filling stations infrastructure is the key barrier for market expansion of FCEVs. This is similar to electric transport and both have pros and cons. While it is easier to place an electric charging station in public places to hydrogen charging, charging of an electric vehicle can take up to 2 hours while a hydrogen vehicle can be fully recharged in a couple of minutes.

Hydrogen refuelling stations can be supplied by regional or local electrolyzers or low carbon H₂ (via pipeline). Deployment of electrolyzers will need to be developed on clear analysis of fleet demand and different requirements for light and heavy-duty vehicles.

By 2030, current estimations indicate that the US will have over 7,000 hydrogen refuelling stations and 5.3 million FCEVs, with Europe close behind with 3.7 million FCEVs. Assuming that the hydrogen is zero carbon sourced, this could save more than 29MtCO₂ transport emissions per year.

Figure 19 Projected market share of hydrogen transport depending on the technical readiness of its segments



Source: An analysis by A. Glagoleva (Skoltech) based on the Hydrogen Council and Shell's data

Policy actions

- Focus the supply of H₂ to transport to heavy-duty transport applications and fleets of vehicles (e.g. buses, trucks, and near-coastal maritime operations).
- Invest into refuelling station infrastructure to allow commercialization of hydrogen application in transport sector.
- Perform an LCA to compare energy storage as electricity in batteries or as chemical energy in carbon neutral ammonia or methanol
- Invest in R&D to reduce the cost of green hydrogen based synthetic fuels to enable low carbon aviation & shipping sectors

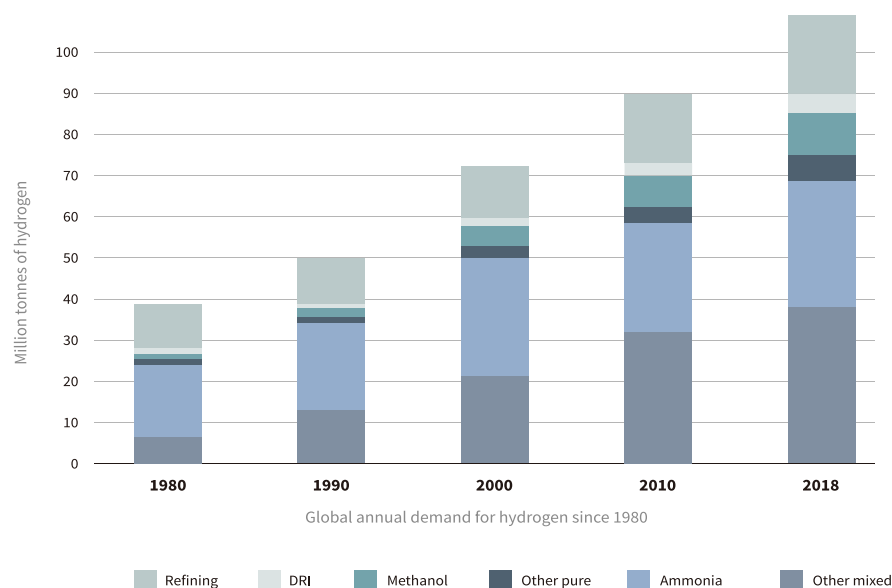
4.3 Application of hydrogen in industrial sector

State of Play

Industry is one of the main user of using hydrogen. Current applications of hydrogen include oil refining, as well as production of ammonia, methanol and other hydrogenation reactions such as vegetable oils and animal fats. Most current processes almost exclusively use hydrogen produced from natural gas through SMR without CCS.

Nonetheless, there are promising signs of further uses of hydrogen in industry. For example, industry in Sweden has recently announced multi-billion dollar plans to produce carbon-free iron ore through hydrogen. This major development could lead other “hard to decarbonize” sectors to follow suit and displace fossil fuels for industrial high-temperature heat required in industrial plants.

Figure 20 Global annual demand for hydrogen since 1980



Potential of this application

Many industry leaders have taken the first step towards researching the potential of using hydrogen. However, it is seen as less attractive in the short term as it is in competition with cheaper high carbon emitting fuels. In the long term, hydrogen could displace fossil-fuels as the primary fuel for industrial high temperature heat.

It is estimated that the iron and steel industry alone contribute to nearly 10% of global greenhouse gas emissions. If industry can shift to low, zero carbon energy sources such as hydrogen, this could be a game changer in reaching carbon neutrality targets.

The prospects for synthetic hydrogen-based fuels and feedstocks are positive. Hydrogen can form ammonia. Also, when combined with CO₂/CO it can produce synthetic fuels, such as synthetic methanol, diesel and jet fuel.

- **Ammonia:** ammonia has double energy density of liquified hydrogen and its properties imply that it can be used as a medium to store hydrogen. The Bosch-Haber Process combines nitrogen from the air with hydrogen into ammonia. Ammonia can then be liquified and more easily transported. After this ammonia can either be sold as an independent product or separated into hydrogen and nitrogen
- **Synthetic methane:** most common production route of a synthetic hydrogen-based fuel. It involves methanation process that is based on direct reaction between hydrogen and CO₂ to produce methane and water as by product.
- **Synthetic methanol:** methanol has 80% higher energy density to hydrogen. The process depends on CO₂ feedstock captured with CCS technology. CO₂ reacts with hydrogen. And using methanol synthesis converted into methanol.
- **Synthetic fuels:** similar to the methanol synthesis. Using the Fischer Tropsch synthesis captured CO₂ and H₂ are converted into synthetic fuels, such as synthetic gasoline, diesel, kerosene for hard to decarbonise areas such as aviation.

Policy actions

- Transform industry business models from chemical producer to fuel supplier.
- Support and incentivize hydrogen application to decarbonize production of steel and iron.
- Integrate and deploy hydrogen through a cross-sector approach.

4.4 Application of hydrogen in residential & commercial sector

State of Play

Hydrogen-powered buildings have often been the reserve of eccentric trailblazers, but the idea is now gaining traction from industry and governments alike. In the United Kingdom, plans are afoot to build homes with appliances fuelled entirely by hydrogen and even a 'hydrogen town' by the end of the decade. In Scotland, 300 homes are to be retrofitted with hydrogen powered appliances, including heating, by 2022.

Potential of this application

Existing pilot schemes have required strong government and industry support. Around \$350,000 matched by the local energy industry as well as support from national energy regulators was required to build two hydrogen powered homes. These projects are part of wider national hydrogen strategies, such as [Hy4Heat](#) and [H100 Fife](#). In years to come, the cost is expected to decrease rapidly when built at scale. Despite extensive upfront costs, final energy prices for hydrogen are expected to be competitive with natural gas and electricity in major markets.

Using sustainable hydrogen instead of fossil fuels could be a green alternative towards the wider goal of carbon neutrality. Hybrid integrated systems including fuel cells could help support heating, cooling and electricity demand, thereby supporting decarbonization targets. Hydrogen could work alongside a range of other energy sources and improve grid flexibility, especially in energy systems with a high degree of variable renewable energy.

Policy actions

- Encourage financing of pilot projects across the UNECE region to explore potential in various population settings, particularly in urban areas.
- Include residential hydrogen actions in national hydrogen strategies.
- Share knowledge and good practice from existing pilot projects to other international partners.
- Build inter-connectivity into energy systems through industry and government partnerships

ANNEX I COMPARATIVE ANALYSIS

focus on technology, commercial and social readiness

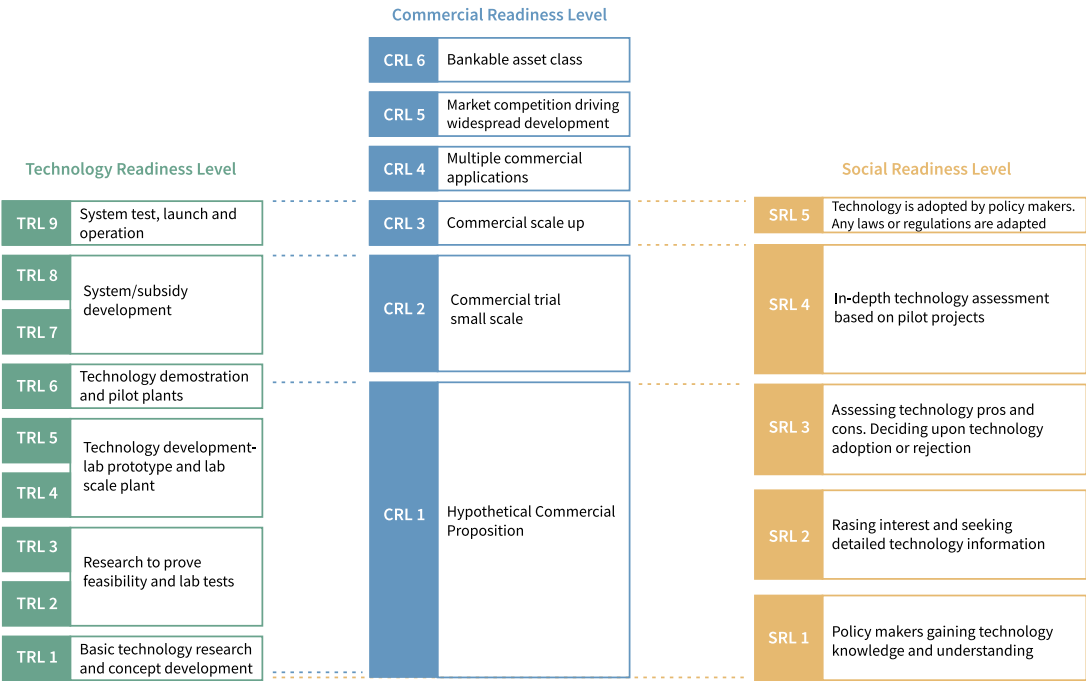
Technology readiness levels (TRLs) are a method for estimating the maturity of technology.

Commercial readiness levels (CRLs) are a method that assesses various indicators which influence the commercial and market conditions beyond just the technology maturity.

Social readiness levels (SRLs) are a method that assesses to what extent new ideas and innovations resonate with individuals and groups and whether they will be integrated into society and reach decisions concerning their adoption in the form of a regulatory and financial regime.

Figure 21 Technology, Commercial and Social Readiness Level

Carbon neutrality will need major changes to the way economies work. Any rapid introduction of change requires coordination of technology development, commercialization and the social acceptance. 'Readiness Levels' are a commonly used indicator of describing what needs to be addressed during the introduction of a change. Figure 6.2.1 shows how these can be used to coordinate public and private actors. If the steps are not synchronised there will be delays, additional costs and, potentially, a failure to enact the change.



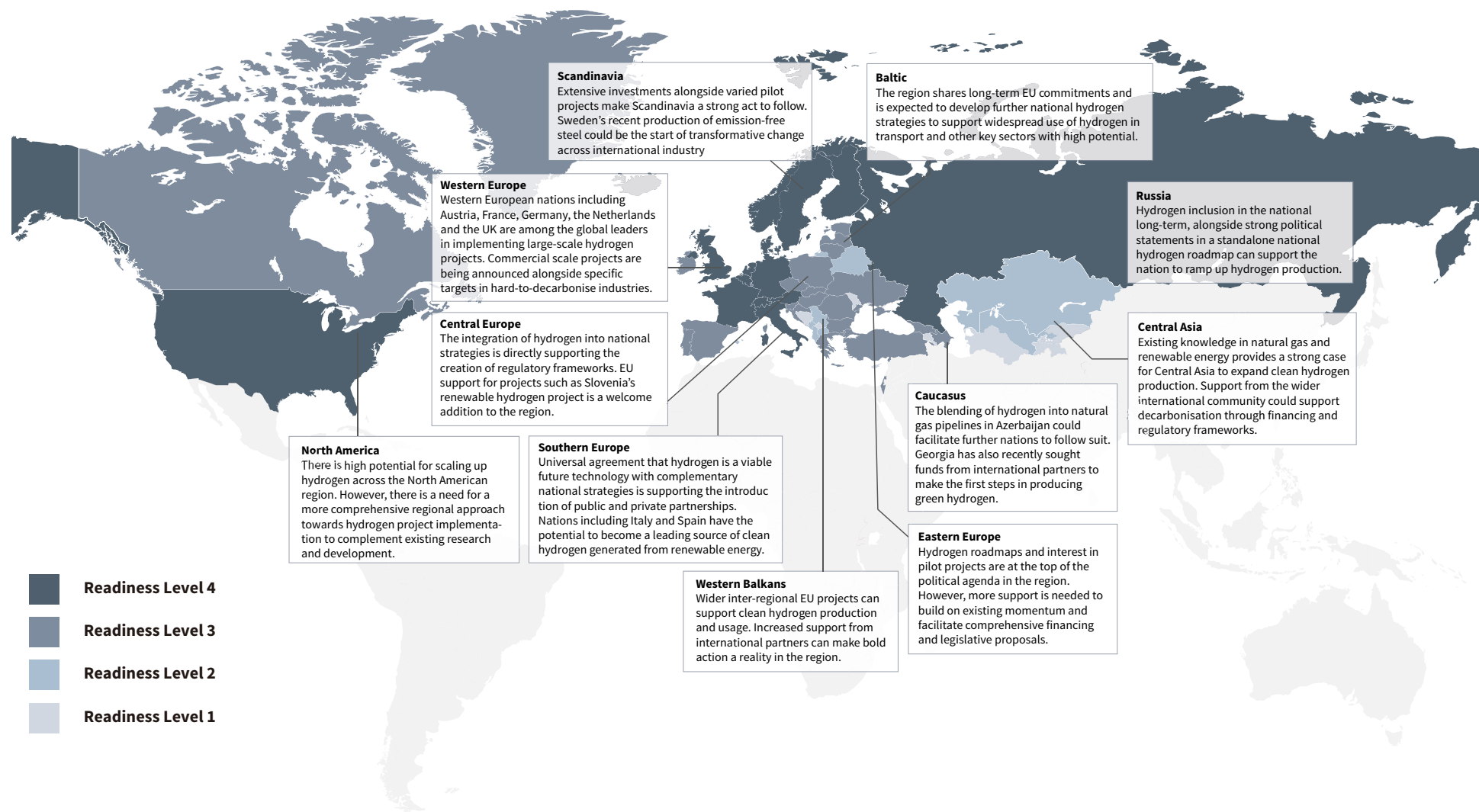
Sources: Developed based on Based on Bruce Adderley (et. al) 2016, Greg Kelsall 2020 and Denis Hicks 2020

ANNEX II COMPARATIVE ANALYSIS

The European Hydrogen underground hydrogen storage analysis 2030 - 2050

COUNTRY	HYDROGEN DEMAND 2030	HYDROGEN DEMAND 2050	HYDROGEN STORAGE NEED 2030	HYDROGEN STORAGE NEED 2050	POTENTIAL HYDROGEN STORAGE CAPACITY – SALT CAVERNS	POTENTIAL HYDROGEN STORAGE CAPACITY – ALL TYPES
Austria	8.0	43.8	1.9	10.4	0.0	22.9
Belgium	18.7	94.3	4.4	22.3	0.0	2.2
Czech Republic	4.0	25.4	1.0	6.0	0.0	10.4
Denmark	3.1	22.3	0.7	5.3	1.3	3.3
Estonia	0.1	1.8	0.0	0.4	0.0	0.0
Finland	5.7	26.7	1.4	6.3	0.0	0.0
France	34.7	182.1	8.2	43.1	2.5	31.9
Germany	66.9	470.0	15.9	111.4	39.5	61.4
Greece	9.4	43.9	2.2	10.4	0.0	0.0
Hungary	3.3	25.1	0.8	6.0	0.0	16.8
Ireland	1.9	30.7	0.4	7.3	0.0	0.0
Italy	34.9	237.1	8.3	56.2	0.0	47.1
Luxembourg	0.3	2.9	0.1	0.7	0.0	0.0
Netherlands	26.6	133.4	6.3	31.6	0.9	34.6
Poland	15.3	153.8	3.6	36.5	2.2	9.3
Slovakia	2.7	24.0	0.6	5.7	0.0	12.0
Slovenia	0.5	6.6	0.1	1.6	0.0	0.0
Spain	30.6	165.4	7.3	39.2	0.0	8.2
Sweden	8.5	34.7	2.0	8.2	0.0	0.02
UK	29.1	244.2	6.9	57.9	3.7	4.8
Total	304.5	1,968.1	72.2	466.4	50.0	246.7

ANNEX III ASSESSMENT OF READINESS LEVEL ACROSS UNECE REGION



Nations across the UNECE region are at various levels of actions taken towards the integration of hydrogen into energy systems. Using hydrogen as an innovative tool towards sustainable energy will require cross-border sub-regional cooperation. Therefore, this comparative analysis seeks to highlight the current level of progress at a sub-regional level using national and multinational strategies and projects as a focal point.

The European Union published a wide-ranging Hydrogen Strategy in mid-2020. The headline aim is to deliver 10 million tonnes of renewable hydrogen by 2030 and 1 million tonnes by 2024. Many EU member states are following the EU's lead and including hydrogen into long-term sustainable energy strategies. This strategy is also in line with the European Green Deal's wider target of carbon neutrality by 2050.

North America

United States has huge potential for growth in the hydrogen industry. A coalition of partners have created the Road Map to a US Hydrogen Economy. Individual states have individual policies in relation to hydrogen. The state of California leads the way in hydrogen-fuelling infrastructure, as well as plans to build the world's biggest green hydrogen plant. A more comprehensive national approach could bring nationwide support towards hydrogen implementation and usage.

Readiness Level: **4**

Canada published its national hydrogen strategy in January 2021. Despite being an industry leader in research and development, Canada can utilise its skills in research and development to build commercial-scale green hydrogen production plants to complement existing production.

Readiness Level: **3**

Western Europe

Austria has high hopes of being the number one country in Europe for Hydrogen production, as it currently reportedly hosts the world's largest green hydrogen pilot project. The country sets a specific focus on renewable hydrogen for hard-to-abate sectors like industrial applications and heavy duty transport.

Readiness Level: **4**

Belgium has worked together with the Netherlands on previous hydrogen projects and announced plans to build a commercial scale hydrogen plant on its coastline in 2020.

Readiness Level: **4**

France was ahead of many European nations when it published its own national strategy in 2018. It included supplemental government funding towards hydrogen production in the multi-annual energy plan in 2020 supporting the plentiful new and existing pilot projects across the country.

Readiness Level: **4**

Germany published its own National Hydrogen Strategy before it took over the Presidency of the Council of the European Union in June 2020. It touches upon the potential for key industries such as steel-making, chemical and transportation can benefit from hydrogen.

Readiness Level: **4**

Ireland has agreed with the wider EU hydrogen strategy and is starting to create a national strategy with stakeholders. It currently has two pilot projects in hydrogen-led public transport.

Readiness Level: **3**

Luxembourg was one of few EU member states to call on the EU to develop further legislation and financing towards green hydrogen as its own national strategies seek to accelerate the transition towards carbon neutrality.

Readiness Level: **3**

The Netherlands national hydrogen strategy seeks to become world leaders in the production and use of green hydrogen. It has already retrofitted natural gas pipelines, completed a solar/hydrogen plant, and part of the country has been deemed a 'hydrogen valley' with a hydrogen-led economy and supply chain.

Readiness Level: **4**

Switzerland is home to much industry-led innovation from high-speed hydrogen fuel stations and hydrogen powered truck fleets. It has also announced plans for a commercial scale hydro-generated hydrogen plant.

Readiness Level: **4**

United Kingdom has gained interest in hydrogen as capital markets in London invest in decarbonisation. A national strategy on hydrogen is expected imminently and is likely to invest in various projects beyond its sole initiative on developing next generation electrolyzers.

Readiness Level: **4**

Scandinavia

Denmark has already extensive investments and pilot projects on the production and use of sustainable hydrogen. There are plans between Denmark and Norway to build world's largest hydrogen ferry. Developing specific national targets could encourage hydrogen deployment.

Readiness Level: **4**

Finland has seen great interest in utilising hydrogen. Business Finland have published a Hydrogen Roadmap in 2020, has come a long way since the government-funded hydrogen plan in 2013. Pilot projects are already on course in transport, fossil-free steel in line with wider EU targets.

Readiness Level: **4**

Norway unveiled its national hydrogen strategy in mid-2020. Aims including increasing the number of pilot projects particularly in the maritime sector, heavy duty transport and industrial processes. Financial, political and legal frameworks are being developed with international partners.

Readiness Level: **4**

Sweden is not alone in Scandinavia in having ambitious climate targets. Sweden is one of the first in the world to be working on emission-free steel production using hydrogen. The government will soon commission authorities to develop a comprehensive national strategy in line with Sweden's and the European Union's climate and energy targets.

Readiness Level: **4**

Iceland is a leader when it comes to including hydrogen in its national strategies towards decarbonisation. Low-carbon transportation is high on the agenda with pilot projects already long established. Nonetheless, progress needs to be accelerated across the board in reaching desired targets

Readiness Level: **4**

Baltic

Estonia started the process of developing a national hydrogen strategy in late 2020 which is expected to call for extensive use of hydrogen. Pilot projects are expected to be implemented in line with the future Estonia roadmap in line with wider agreed EU targets.

Readiness Level: **3**

Latvia has not included hydrogen in its current energy strategy but already has functioning hydrogen-powered transport. Long-term EU commitments are shared by Latvia. Creating specific objectives while incentivising a hydrogen-led economy can boost decarbonisation.

Readiness Level: **3**

Lithuania has recently established a hydrogen platform in cooperation with various ministries and industry leaders to develop innovative hydrogen technologies. It has already included hydrogen in various strategies including investment into research and development.

Readiness Level: **3**

Southern Europe

Cyprus does not currently include hydrogen in its current long-term energy plans or is involved in any EU projects. There is potential for hydrogen to be used from the vast potential of solar energy on the island and could be included in long-term strategies.

Readiness Level: **1**

Greece has huge potential to use hydrogen in areas such as shipping. Hydrogen is seen as a long-term solution according to current government policy. Pilot projects including hydrogen micro-grids and interest in the wider-EU initiatives.

Readiness Level: **3**

Italy launched its hydrogen strategy in 2020 to build on existing pilot projects with billions of euros of investment from public and private partnerships. Italian targets of producing 5 gigawatts of green hydrogen complement shared wider EU targets.

Readiness Level: **4**

Malta is pursuing hydrogen as a viable future technology across various fields including proposals for the world's first international offshore hydrogen pipeline.

Readiness Level: **2**

Portugal published its national hydrogen strategy in mid-2020. Various pilot projects including solar-hydrogen production, transport, industry and heating are planned. EU investment alongside willingness to create a competitive environment are positive signs towards decarbonisation.

Readiness Level: **3**

Spain released its national hydrogen strategy in 2020 with targets in line with the wider-EU hydrogen strategy. Pilot projects of various scales are being put into practice in hydrogen production through electrolyzers and transportation. The recently published strategy could strengthen the existing impetus in hydrogen technologies.

Readiness Level: **3**

Central Europe

Czech Republic has some pilot projects in the pipeline with ambitious goals particularly in transport and fuel. Regulations towards a hydrogen economy are slowly being implemented in line with wider EU strategy.

Readiness Level: **3**

Hungary includes hydrogen in existing national policy. It has also played a vital role in supporting inter-regional EU sustainable hydrogen projects on the river Danube. Removing regulatory barriers could make hydrogen a driving force in the energy sector.

Readiness Level: **3**

Poland's hydrogen strategy is expected to be approved in the first quarter of 2021. Objectives includes creating regulatory frameworks to reach hydrogen targets in the coal industry and public transportation and chemical production.

Readiness Level: **3**

Slovakia's bulging automotive industry could lead the way in hydrogen utilisation in the country and beyond. There is interest amongst those in industry and government to develop infrastructure in transport, and to enable hydrogen injection into the main gas grid. A national strategy is expected in 2021.

Readiness Level: **3**

Slovenia has recently green-lit a various hydrogen projects including one for converting renewable electricity to green hydrogen and synthetic methane with support from the European Innovation Fund. The government has also signalled the potential for financial support for hydrogen energy storage projects.

Readiness Level: **3**

Western Balkans

Albania

Vast renewable energy potential as a basis for renewable hydrogen production. Italian energy company Saipem and Alboran Hydrogen planning to develop a plant for the production of green hydrogen through the electrolysis process in Albania.

Readiness Level: **2**

Bosnia and Herzegovina

The energy system is based on high coal dependency although with gas network developments. Hydrogen is still not part of agenda, although EU accession programmes promote it.

Readiness Level: **1**

Croatia is involved in wider inter-regional EU projects promoting sustainable hydrogen production and usage. According to existing energy plans, Croatia plans to integrate hydrogen into the energy system and create an enabling environment for a hydrogen economy.

Readiness Level: **3**

Montenegro has limited detail on a comprehensive hydrogen strategy. Using international organisations to gain support, knowledge and good practice can enable change.

Readiness Level: **2**

Serbia

Hydrogen strategy in preparation. The draft outline of Serbia's hydrogen strategy envisages the installation of 10 MW of electrolysis facilities using renewable energy by 2025, and 100 MW by 2030.

Readiness Level: **2**

North Macedonia

Awareness of potential of hydrogen to decarbonise the domestic energy system is still limited. EU accession programmes promote hydrogen potential feasibility studies.

Readiness Level: **1**

Central Asia

Kazakhstan has existing hydrogen plants within refineries, and its universities have conducted research into hydrogen transportation. Regulatory frameworks could inspire a comprehensive sustainable hydrogen strategy to utilise its existing knowledge.

Readiness Level: **2**

Kyrgyzstan has expressed interest in building hydrogen projects that are green and sustainable. Support from international partners through financing and regulatory frameworks can help boost the potential hydrogen economy.

Readiness Level: **1**

Tajikistan has undertaken research in producing hydrogen by electrolysis and thermolysis gas from hydrocarbons and coals using energy idle discharges of water. Support from the wider international community can expand developments in sustainable hydrogen production.

Readiness Level: **1**

Turkmenistan has the only natural gas-to-gasoline complex in the world. It can utilise its existing expertise in gas to begin rapid decarbonisation through sustainable hydrogen production.

Readiness Level: **1**

Uzbekistan has collaborated with international partners to support its low-carbon strategy. Harmonisation of targets and frameworks within government and with international stakeholders are a good basis to commence rapid decarbonisation.

Readiness Level: **2**

Eastern Europe

Belarus has nearly completed construction of a new hydrogen plant as part of an oil refinery. More support is needed to promote green hydrogen and sustainable energy.

Readiness Level: **2**

Bulgaria's hydrogen roadmap is currently being prepared. It is expected to compliment the national climate and energy plan as well as the EU hydrogen strategy in creating a hydrogen-led economy in the medium and long-term. Projects are expected to focus on the transport and electricity sectors.

Readiness Level: **3**

Moldova can develop regulatory frameworks and work with international partners to create a hydrogen strategy to utilise its existing gas pipe infrastructure.

Readiness Level: **1**

Romania is keen to commence several pilot projects in electricity and industrial sectors, according to government plans. Facilitating legislative changes while working with EU partners could accelerate change.

Readiness Level: **3**

Ukraine established the Ukrainian Hydrogen Council alongside a low-carbon hydrogen-focused government department. These preliminary policy steps could instigate hydrogen extraction, production and utilisation. Draft Roadmap for production and use of hydrogen was developed with support of UNECE and the Hydrogen Strategy of Ukraine is currently under development.

Readiness Level: **3**

Caucasus

Armenia has potential to use hydrogen to make up for its limited energy resources. Little information exists on Armenia's Hydrogen Strategy, and funding for previous research has come from external sources.

Readiness Level: **1**

Azerbaijan has made the first steps in blending hydrogen in its natural gas pipeline to Europe. Industry has also signed international agreements to develop clean hydrogen production.

Readiness Level: **3**

Georgia is making the first steps towards green hydrogen production with financing from the European Bank for Reconstruction and Development.
Readiness Level: **3**

UNECE and Beyond

Russian Federation's Deputy Prime Minister aims for world leader status in hydrogen production and exports. Hydrogen was already included in the national long-term energy strategy, but more detail has been included in the first national hydrogen roadmap. Russia's National Association of Hydrogen Energy has supported in creating national targets including the establishment of a regulatory framework and setting national and international standards. Ramping up its hydrogen production will be crucial in reaching Russia's and supporting wider region's decarbonisation targets.
Readiness Level: **4**

Turkey aims to use hydrogen as part of its energy security in the short and long-term. A national hydrogen strategy is expected to be published in early 2021 after a consultation of stakeholders. Pilot projects are in use include hydrogen filling plants and UN supported energy production plants. Feasibility studies into commercial production and transportation are underway and tests are being done in injecting hydrogen into the national gas supply. More needs to be done to transition to green hydrogen.
Readiness Level: **3**

Israel has used its technological expertise in research and development towards green hydrogen. In 2020, Israeli researchers developed a way to produce hydrogen using only solar energy. Government, industry and business can accelerate the Implementation of hydrogen into the electricity system.
Readiness Level: **3**

ABBREVIATIONS

BEV	Battery electric vehicles
CRL	Commercial readiness level
DSO	Distribution system operator
CCUS	Carbon capture, use and storage
CHP	Combined heat and power
EOR	Enhanced oil recovery
FCEV	Fuel cell electric vehicles
GHG	Greenhouse gas
IAEA	International Atomic Energy Agency
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
LNG	Liquefied natural gas
LPG	Liquefied petroleum gas
P2X	Power-to-X
SRL	Social readiness level
TRL	Technology readiness level

TSO	Transmission system operator
UNECE	United Nations Economic Commission for Europe

REFERENCES

Amjad Al-Qahtani et al., 2021, Uncovering the true cost of hydrogen production routes using life cycle monetisation, Applied Energy, Volume 281, 2021

Blank, T. K., Molly, P., 2020, Hydrogen's Decarbonization Impact for Industry Near-term challenges and long-term potential, Insight brief, https://rmi.org/wp-content/uploads/2020/01/hydrogen_insight_brief.pdf

BloombergNEF, 2020a, Hydrogen: The Economics of Production from Fossil Fuels with CCS, March 2020

BloombergNEF, 2020b, Liebreich: Separating Hype from Hydrogen – Part One: The Supply Side, <https://about.bnef.com/blog/liebreich-separating-hype-from-hydrogen-part-one-the-supply-side/>

BloombergNEF, 2020c, Hydrogen economy outlook, <https://data.bloomberglp.com/professional/sites/24/BNEF-Hydrogen-Economy-Outlook-Key-Messages-30-Mar-2020.pdf>

Demirbas Ayhan 2016, Comparison of thermochemical conversion processes of biomass to hydrogen-rich gas mixtures, Energy Sources, Part A Recover, Util. Environ. Eff. 38 (2016) 2971–2976, <https://doi.org/10.1080/15567036.2015.1122686>

Energy Information Administration (EIA), 2021, Hydrogen explained - Production of hydrogen <https://www.eia.gov/energyexplained/hydrogen/production-of-hydrogen.php>

Energy Transitions Commission, 2021, Making the Hydrogen Economy Possible: Accelerating Clean Hydrogen in an Electrified Economy, <https://www.energy-transitions.org/publications/making-clean-hydrogen-possible/>

Enriquez, Abel, 2021, UNECE Workshop-Attaining Carbon Neutrality: The Role of Hydrogen. Presentations, https://unece.org/sites/default/files/2021-03/UNECE_workshop_Attaining_Carbon_Neutrality_Role_of_Hydrogen_24.03.2021_0.pdf

European Commission, 2020a, A Hydrogen Strategy for a Climate-neutral Europe, https://ec.europa.eu/energy/sites/ener/files/hydrogen_strategy.pdf

European Commission, 2020b, EU Strategy for Energy System Integration, https://ec.europa.eu/energy/topics/energy-system-integration/eu-strategy-energy-system-integration_en

European Hydrogen Backbone, 2021, Analysing future demand, supply, and transport of hydrogen, <https://www.grtgaz.com/sites/default/files/2021-06/European-Hydrogen-Backbone-report-June2021.pdf>

Gas Infrastructure Europe, 2021, Picturing the value of underground gas storage to the European hydrogen system, https://www.gie.eu/wp-content/uploads/filr/3517/Picturing%20the%20value%20of%20gas%20storage%20to%20the%20European%20hydrogen%20system_FINAL_140621.pdf

GoldmanSachs, 2020, Carbonomics, The Rise of Clean Hydrogen

Goyal H.B., D. Seal, R.C. Saxena, 2008, Bio-fuels from thermochemical conversion of renewable resources: a review, *Renew. Sustain. Energy Rev.* 12 (2008) 504–517, <https://doi.org/10.1016/j.rser.2006.07.014>

Grin, E., 2021, UNECE Workshop-Attaining Carbon Neutrality: The Role of Hydrogen. Presentations, https://unece.org/sites/default/files/2021-03/UNECE_workshop_Attaining_Carbon_Neutrality_Role_of_Hydrogen_24.03.2021_0.pdf

Huber G.W., S. Iborra, A. Corma, 2006, Synthesis of transportation fuels from biomass: chemistry, catalysts, and engineering, *Chem. Rev.* 106 (2006) 4044–4098, <https://doi.org/10.1021/cr068360d>

Hydrogen Council, 2021, Hydrogen decarbonization pathways A life-cycle assessment, https://hydrogencouncil.com/wp-content/uploads/2021/01/Hydrogen-Council-Report_Decarbonization-Pathways_Part-1-Lifecycle-Assessment.pdf.

Hydrogen Europe, 2019, Trans-European hydrogen transmission and distribution pipeline network

International Atomic Energy Agency (IAEA), 2013, Hydrogen Production Using Nuclear Energy, https://www-pub.iaea.org/MTCD/Publications/PDF/Pub1577_web.pdf

International Energy Agency (IEA), 2020, Global average levelised cost of hydrogen production by energy source and technology, 2019 and 2050, <https://www.iea.org/data-and-statistics/charts/global-average-levelised-cost-of-hydrogen-production-by-energy-source-and-technology-2019-and-2050>

International Renewable Energy Agency (IRENA), 2020, Green Hydrogen Cost Reduction, <https://www.irena.org/publications/2020/Dec/Green-hydrogen-cost-reduction>

Kayfeci, M., Keçebaş, A., Bayat, M., 2019, Solar Hydrogen Production Processes, Systems and Technologies. Chapter 3 - Hydrogen production. Retrieved from <https://www.sciencedirect.com/science/article/pii/B9780128148532000035>

UNECE Workshop-Attaining Carbon Neutrality: The Role of Hydrogen. Presentations, https://unece.org/sites/default/files/2021-03/UNECE_workshop_Attaining_Carbon_Neutrality_Role_of_Hydrogen_24.03.2021_0.pdf

Kothari R., D. Buddhi, R.L. Sawhney, 2008, Comparison of environmental and economic aspects of various hydrogen production methods, *Renew. Sustain. Energy Rev.* 12 (2008) 553–563, <https://doi.org/10.1016/j.rser.2006.07.012>

Lepage,T., M. Kammoun, Q. Schmetz, A. Richel, 2021, Biomass-to-hydrogen: A review of main routes production, processes evaluation and techno-economical assessment, *Biomass and Bioenergy* 144 (2021) 105920

Martinez-Merino, V. M.J. Gil, A. Cornejo, 2013, Biomass sources for hydrogen production, in: *Renew. Hydrog. Technol. Prod., Purif., Storage, Appl. Saf.*, Elsevier B.

Niel, 2016, Biological Processes for Hydrogen Production, *Anaerobes in Biotechnology*, 2016, Volume 156V., 2013, pp. 87–110, <https://doi.org/10.1016/B978-0-444-56352-1.00005-2>

Oxford Institute for Energy Studies (OIES), 2020, EU Hydrogen Vision: regulatory opportunities and challenges, <https://www.oxfordenergy.org/wpcms/wp-content/uploads/2020/09/Insight-73-EU-Hydrogen-Vision-regulatory-opportunities-and-challenges.pdf>

Skolkovo, 2019, The Hydrogen Economy – a Path towards Low Carbon Development, June 2019, https://energy.skolkovo.ru/downloads/documents/SEneC/Research/SKOLKOVO_EneC_Hydrogen-economy_Eng.pdf

Trabelsi, A.B.H., A. Ghrib, K. Zaafour, A. Friaa, A. Ouerghi, S. Naoui, H. Belayouni, Hydrogen-rich syngas production from gasification and pyrolysis of solar dried sewage sludge: experimental and modeling investigations, *BioMed Res. Int.* (2017) 1–14, <https://doi.org/10.1155/2017/7831470>

UNECE, 2016, Proposal for a global technical regulation on hydrogen and fuel cell vehicles, ECE/TRANS/WP.29/2013/41, <https://unece.org/DAM/trans/doc/2013/wp29/ECE-TRANS-WP29-2013-041e.pdf>

UNECE, 2020, Pathways to Sustainable Energy - Accelerating Energy Transition in the UNECE Region, https://unece.org/fileadmin/DAM/energy/se/pdfs/CSE/Publications/Final_Report_PathwaysToSE.pdf

UNFCCC, 2015, The Paris Agreement, https://unfccc.int/sites/default/files/english_paris_agreement.pdf

US Department of Energy, 2021, Hydrogen Production: Natural Gas Reforming, <https://www.energy.gov/eere/fuelcells/hydrogen-production-natural-gas-reforming>

Yang, Q., Chen, Y., Yang H., Chen, H., 2016, Greenhouse gas emissions of a biomass-based pyrolysis plant in China. *Renewable and Sustainable Energy Reviews.* 53. Pp. 1580-1590. DOI <http://dx.doi.org/10.1016/j.rser.2015.09.049>



Information Service
United Nations Economic Commission for Europe

Palais des Nations
CH - 1211 Geneva 10, Switzerland
Telephone: +41(0)22 917 12 34
Fax: +41(0)22 917 05 05
E-mail: unece_info@un.org
Website: <http://www.unece.org>