Hydrogen decarbonization pathways

A life-cycle assessment

January 2021

Hydrogen Council

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Introduction and methodology

Life-cycle emissions are coming into focus with scaling-up of hydrogen

Hydrogen is one of the keys to the energy transition, a facilitator to sector integration, and the basis for decarbonizing hard-to-abate applications. To deliver on the sustainability promise, it is therefore not only important to make it economically viable, but also maximize its decarbonization potential and minimize its impact on resources, such as water. The European hydrogen strategy and the targets of many EU member states are geared to place most of their support on renewable hydrogen production, while countries such as China, Korea, and Japan are supporting other low-carbon hydrogen routes as well. Countries with abundant renewable and/or fossil and CCS resources are looking to optimize the value of these attributes in destination markets, such as Australia, the MENA region, and Southern Latin America. In all cases, the decarbonization potential of hydrogen is critical, including understanding potential contributions from the manufacturing of plants for primary energy supply, hydrogen production, transport, distribution, and use. An evaluation of the carbon-saving potential of hydrogen over the life cycle is therefore an important piece of the Hydrogen Council's perspective.

Methodology of the LCA study

— This report is an assessment that uses an LCA approach for greenhouse gas (GHG) emissions regarding "well-to-supply" and "well-to-use", including end-of-life/recycling; it is, however, not a detailed LCA study.

— The assumptions for the LCA analysis have been reviewed by the 23 member companies of the Hydrogen Council LCA project team, as well as by an independent group of experts, including Michael Wang, Manager Systems Assessments at ANL, Stephanie Searle, Fuels Program Director at ICCT, and Dolf Gielen, Director Innovation and Technology at IRENA.

— The analysis includes GHG emissions related to energy supply and use, as well as capex emissions, i.e., "grey emissions" related to the manufacturing of energy conversion assets.

— Fugitive gas emissions, such as methane slip across gas production and supply or hydrogen losses from flushing procedures, have been considered in the assessments assuming best available technology and operational practices for a given regional energy source or route.

— Production and manufacturing conditions can vary significantly from producer to producer and region to region, resulting in a wide range of capex-related impacts. Global assumptions have been applied for a generalized LCA assessment, such as for the grid mix[1] and recycling shares[2].

— To capture the picture for different hydrogen value chains, the primary energy used for hydrogen supply as well as for eight "well-to-use" illustrative pathways in this report have been regionalized.

— For coherence, technology data for the different elements in hydrogen value chains have been taken from previous Hydrogen Council studies. Where needed, this has been updated and enriched with data based on current literature, including own calculations.

1 Global grid mix assumed with 68% and 90% low-carbon contribution from renewable and nuclear sources in 2030 and 2050 derived from [IRENA 2020], resulting in carbon-intensities of 229 g CO_{2eq}/kWh_e and 61 g CO_{2eq}/kWh_e, respectively.

2 Recycling shares of 80%, going up to over 90%, assumed for selected metals in 2030 and 2050, respectively, based on [UNEP-IRP 2011] and expert input from the Hydrogen Council member pool.

- For life-cycle modeling and calculations, the LBST software E3database was used in accordance with standard practices regularly applied to life-cycle assessments for clients such as the Joint Research Centre of the European Commission, EUCAR, Concawe, and other industry as well as environmental interest groups.

- Data quality and the availability of data to calculate capex-related GHG emissions is generally poor – therefore, to the extent possible, this study attempts to shed light on their potential magnitude of impact.

- GHG emissions are the focus of this report. Unless stated otherwise, "carbon" and "carbon dioxide" includes all relevant GHGs, according to the latest 5th IPCC Assessment Report (AR5) and energy values refer to the lower heating value (LHV, H_i).

- Water footprint calculations take gross water demand into account[3].

- To give the full picture, different primary energies and conversion technologies for hydrogen supply are presented, including renewable power, fossil (with and without carbon sequestration), as well as nuclear-based primary energies.

Various hydrogen production pathways can achieve very low life-cycle emissions

There are various ways of producing hydrogen. The most common way of producing hydrogen today is by reforming natural gas into hydrogen and CO_2[4], which is often referred to as "grey hydrogen" if the CO_2 is emitted into the atmosphere, or "blue hydrogen" if the CO_2 is captured and permanently sequestrated. If sustainable biomass is gasified and the resulting biogas is reformed or pyrolyzed, the hydrogen is considered "green," and carbon-negative if the CO_2 is sequestrated.

Water electrolysis uses electricity to split water into hydrogen and oxygen. If renewable sources are used, the hydrogen produced is often referred to as "green". Other pathways include the gasification of coal into hydrogen and carbon monoxide (which can be captured and sequestrated) or the pyrolysis of natural gas into hydrogen and solid carbon.

The emission intensity varies between these pathways, but also within pathways: for instance, due to different energy mixes and efficiency of production operations, hydrogen derived from natural gas produced in Norway has different emissions than natural gas produced in Russia and transported to centers of consumption.

Exhibit 1 summarizes the results. Overall, we find that:

Electrolysis using 2030 global average grid electricity (11.1 kg CO_{2eq}/kg H_2)[5] and SMR without CCS with Russian natural gas transported over 5,000 km (11.0 kg CO_{2eq}/kg H_2) show the highest GHG

[3] For gross water demand, green and blue water are taken into account in this study, i.e., water from precipitation and abstraction, respectively. Grey water demand has not been differentiated in this study for reasons of data availability. Grey water refers to water contaminated continuously (effluent water) and/or incidents (e.g., oil spills) and is understood to be of less relevance in the pathways analyzed in this study.

[4] Mainly using steam methane reforming (SMR). Autothermal reforming (ATR), another technology available for producing hydrogen from natural gas, is today mainly used for the production of synthesis gas, a mixture of H_2 and CO, e.g., for methanol synthesis.

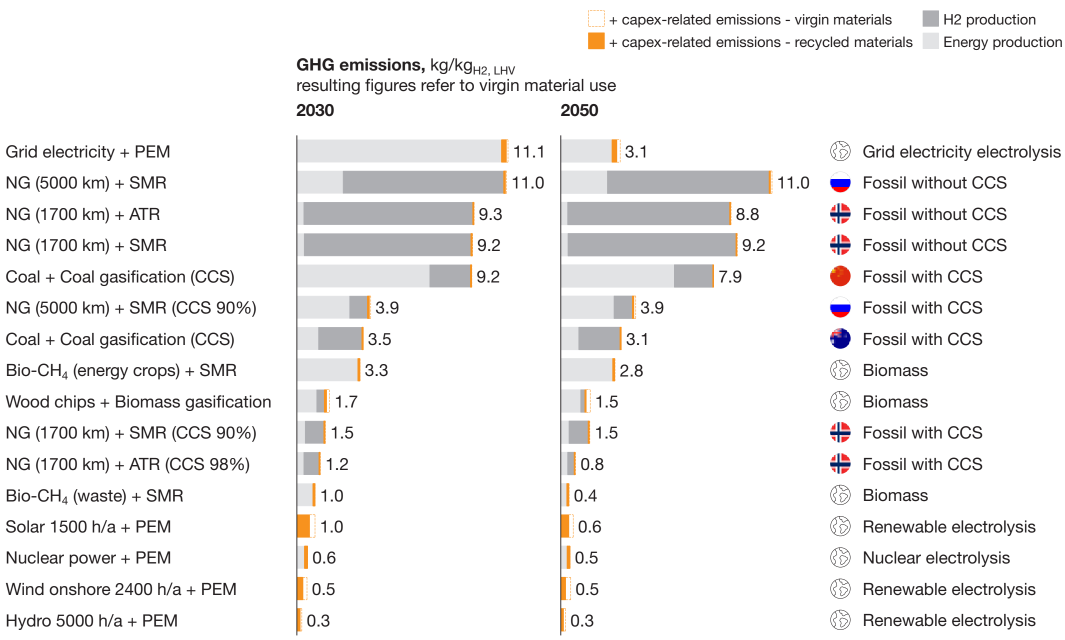
[5] GHG emissions are expressed in kgCO_{2eq}/kg H_2 here and include CO_2 equivalents of other emissions with climate impacts. Multiply by 30 to convert kg CO_{2eq}/kg H_2 to g CO_{2eq}/kWh H_2.

emissions for 2030 of pathways analyzed here. In the case of water electrolysis, this is mostly due to the 16% coal power share in the global grid mix assumed. SMR fed with Norwegian natural gas and 1,700 km transport has slightly lower GHG emissions (9.2 kg CO_{2eq}/kg H_2). For comparison, the fossil comparator in the European Renewable Energy Directive is 94 g CO_{2eq}/MJ of final fuel, i.e., 11.28 kg CO_{2eq}/kg H_{2eq}, in the case of transportation fuel, 183 g CO_{2eq}/MJ of electricity in the case of electricity generation, and 80 g/MJ of heat in the case of heat generation. Furthermore, the guarantees of origin system *CertifHy* has defined a fossil fuel comparator for hydrogen of 10.92 kg CO_{2eq}/kg H_2.

Among the CCS pathways for blue hydrogen supply, coal gasification with CCS using Chinese coal shows high GHG emissions of 11.8 kg CO_{2eq}/kg H_2 due to methane and CO_2 emissions from uncontrolled coal-seam fires. Sweet natural gas sources in combination with high carbon capture rates and transport distances in the low thousand kilometers can reduce GHG emissions substantially: for example, in the case of SMR with a carbon capture rate of 90%[6] and natural gas from Norway transported over a distance of 1,700 km to the German or Dutch North Sea coast, GHG emissions amount to 1.5 kg CO_{2eq}/kg H_2, and to 2.7 kg CO_{2eq}/kg H_2 in the case of an SMR with a CO_2 capture rate of 75%[7].

It should be noted that a 90% carbon capture rate does not reduce emissions by 90%, as additional energy is needed to power the capture and sequestration process, and GHG emissions occur over the natural gas supply chain. Both these emission sources are reflected in our analysis.

Exhibit 1: Carbon-equivalent emissions by hydrogen production pathways, 2030 and 2050 (resulting figures refer to virgin material use); energy production refers to GHG emissions from the supply of the main input into the H_2 plant (natural gas, coal, electricity), while H_2 production refers to direct GHG emission of H_2 plant, including from plant auxiliary electricity use



Source: Hydrogen Council, LBST

[6] Reference: Amec Foster Wheeler; IEAGHG: Techno-Economics of Deploying CCS in a SMR Based Hydrogen Production using NG as Feedstock/Fuel; IEAGHG Technical Report, February 2017.

[7] Reference: Hydrogen Council: Path to Hydrogen Competitiveness: A Cost Perspective, 2020.

Electrolysis can achieve very low emissions if powered with renewable energy or nuclear power. Solar power achieves 1.0 kg CO_{2eq}/kg H_2 and wind 0.5 kg CO_{2eq}/kg H_2 in 2030, the difference resulting from the higher embedded capex emissions for solar panels[8] (due to global grid mix[9] assumed for the panel manufacture). Electrolysis with run-of-river hydropower can achieve even lower emissions of 0.3 kg CO_{2eq}/kg H_2. Nuclear power comes in at 0.6 kg CO_{2eq}/kg H_2, but it is also important to note in this context that it leads to 0.115 g of radioactive waste per kg of hydrogen[10].

Capex-related emissions based on global average grid mix (66% renewable power in 2030) for asset manufacturing are very low across hydrogen production pathways. For fossil, nuclear, and most renewable power sources, capex-related emissions are in the single-digit g CO_{2e}/kWh range only, and a very low double-digit number in the case of photovoltaics (PV).

Applying recycling rates of 80% and more for different metals at end of life versus using virgin materials reduces GHG emissions by 0.1 to 0.3 kg CO_{2eq}/kg H_2 (equivalent to about 1 to 3% of the fossil comparator, i.e., Norway natural gas steam methane reforming without sequestration).

The move towards a carbon-neutral electricity mix will benefit hydrogen production across the board

Towards 2050, in order to achieve a net-zero emission economy, the global power supply has to be largely decarbonized. This will also impact hydrogen emissions – as shown in Exhibit 1. Most notably, electrolysis with grid electricity becomes viable compared to 2030's global average grid mix which still remains carbon intensive.

For blue hydrogen, decarbonization of the power supply (for 2050, we assume 86% renewable share, 90% including nuclear) also allows for significant emissions reduction: hydrogen from natural gas with 98% CCS capture rate using ATR technology will achieve life-cycle emissions comparable to 100% solar powered electrolysis when the ATR is powered with fully decarbonized energy.

In a world striving for low to net carbon-negative emissions, recycling[11] plays an important role in the context of a circular economy with a sensitivity towards additional sustainability aspects, such as resource consumption (abiotic depletion), i.e., the use of resources that are nonrenewable in human-relevant timeframes.

For wind and hydropower combined with water electrolysis, the numbers for 2030 and 2050 are approximately the same if virgin materials are used because conventional blast furnace technology has been assumed for steel production. If recycling is taken into account, the GHG emissions for hydrogen from wind power decreases from about 9 g CO_{2eq}/kWh of hydrogen in 2030 to about 7 g CO_{2eq}/kWh in 2050 (or 0.31 kg/kg_{H2} in 2030 to 0.24 kg/kg_{H2}). Recycling of steel is carried out via electric arc furnaces (EAFs) where the electricity mix influences the GHG footprint. Some GHG emissions for the manufacturing of wind and hydropower plants result from the production of concrete, for which GHG intensity has not been assumed to change between 2030 and 2050.

8 Based on a GHG-intensity of 20 and 13 g/kWh for PV electricity at 1,500 h_{eq}/a for 2030 and 2050, respectively.

9 Based on scenario in [IRENA, Global Renewables Outlook 2020, April 2020] for 2030: 20% wind, 15% PV, 6% biomass, 15% hydro, 1% geothermal, 11% nuclear, 16% natural gas, 16% coal.

10 Based on spent nuclear fuel of 0.0021 to 0.0027 g/kWh of electricity.

11 For metals, we have assumed for this study an 80% and above 90% recycling share for 2030 and 2050, respectively, which today is achieved with selected industrial products.

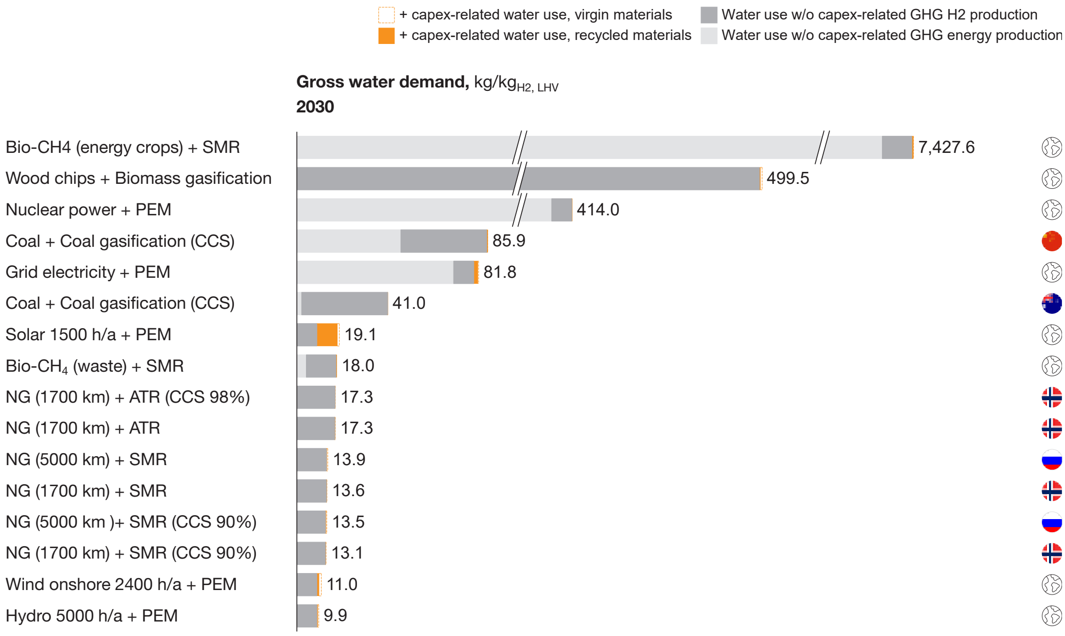
Water consumption and other environmental damage can be minimized in the production of hydrogen

Water demand for hydrogen production via electrolysis, reforming or gasification is marginal. For example, in the case of water electrolysis, about 9 kg of water per kg of hydrogen is needed[12]. The one electricity-based technology for which it is significantly higher is electrolysis via nuclear electricity, which uses about 270 kg of cooling water per kg of hydrogen due to nuclear power production. For SMR/ATR specific water demand is very low with 13-18 kg of water per kg of hydrogen. Nevertheless, gigawatt-scale projects can be a significant local water consumer. In regions prone to water supply stress, sea water desalination is required. While this adds little incremental electricity use to power-to-X projects, it requires the environmentally benign management of the effluent brine.

Process cooling for thermal power generation typically is a major source of water demand embodied in the energy conversion process (energy-water-nexus). Today, usually open cooling is used for large power plants which results in gross water demands in the order of several hundreds of kg water per kg of hydrogen. In arid regions and regions that are already under water stress, dry cooling should be considered.

Gross water demand for **bio pathways** is much more significant and can be up to 1,000 times higher than for other routes. Thus, bio feedstock is preferably used in water-rich regions with moderate climatic conditions. Biowaste may also have a certain water demand, as illustrated in Exhibit 2[13].

Exhibit 2: Gross water demand for hydrogen production pathways



Source: Hydrogen Council, LBST

[12] Net water demand from chemical reaction. Mehmeti et al. (2018) report approximately 18 kg_{H2O}/kg_{H2} and 9 kg_{H2O}/kg_{H2} for proton exchange membrane (PEM) and solid oxide electrolyzer (SOEL), respectively.

[13] In case of hydrogen from gasification of waste wood (forestry residues) rapeseed methylester (RME) is consumed by the gasifier for syngas clean-up, which comes with a water demand burden.

Another potentially relevant source of water demand is evaporation from an increased water surface of large **hydropower** dams. This is particularly an issue for countries in dry regions that largely depend on surface water as a key source of water replenishment.

Water demand for **coal mining and gas production** varies significantly, subject to the local geology and processes applied, such as underground stimulation of tight gas through hydraulic fracturing. Other environmental impacts may result from the mobilization of, e.g., heavy metals, naturally occurring radioactive materials and other effluents that can impact water quality (grey water), air, soil, and the living environment.

On a **methodology** note, gross water demand in Exhibit 2 is depicted by the stage of use in the energy process chain for a high-level comparison across main hydrogen value chains, i.e., a water inventory that is neither making a reference to the water source nor a reference to potential impacts from water use. In contrast, a full water footprint and impact assessment commonly differentiates between different water sources and may also include "grey water"[14]. As water footprint results are highly sensitive to process design and local conditions – such as the availability of rainfall – which is beyond the scope for this study, we here refer to the gross water demand only.

[14] "Grey water" refers to water that is contaminated through continuous (effluent water) and/or incidents (e.g., oil spills). For the pathways analyzed here, it can be considered of less relevance under the assumption of best available technology and best operational practice and is thus not included.

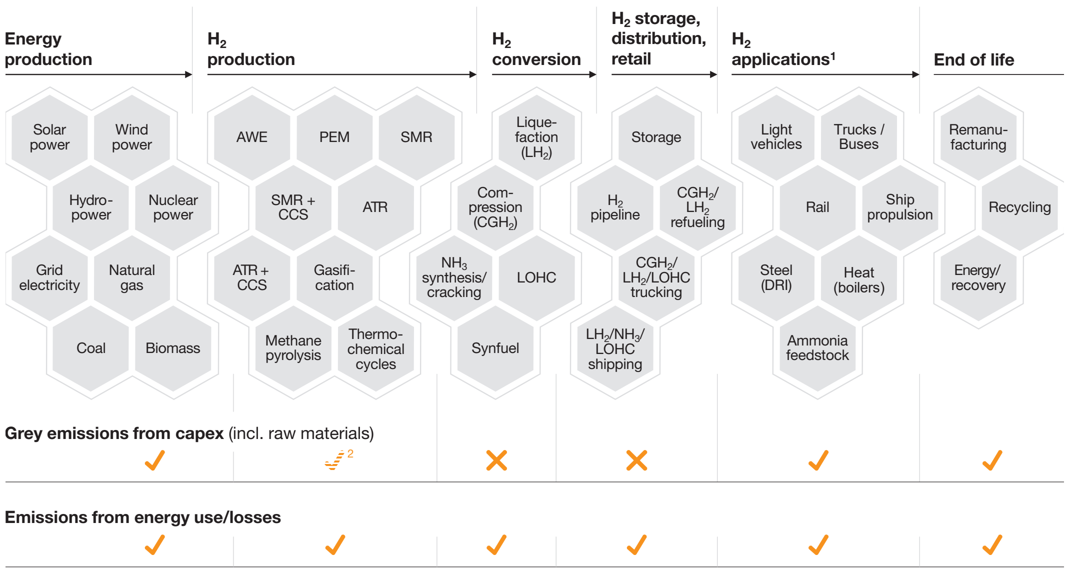
Eight illustrative pathways for hydrogen use in the global energy transition

Hydrogen is a versatile carrier for decarbonized energy

Hydrogen is a uniquely versatile energy carrier. As the previous chapter showed, it can be produced using different energy inputs and different production technologies. It can also be converted to different forms and distributed through different routes – from compressed gas hydrogen in pipelines through liquid hydrogen on ships, trains or trucks, to synthesized fuel routes (see Exhibit 3).

Of course, hydrogen can also be used across a range of different applications – including the 36 end-use applications described in the Hydrogen Council´s “Path to Hydrogen Competitiveness” study.

Exhibit 3: Hydrogen pathways from production to use



1 Including repair, maintenance, lubes, etc.
2 Included on a best-effort basis, depending on data availability

The GHG emissions (carbon intensity) of each individual brick has been calculated, parameterized in key aspects such as the capacity rate (renewable power production) or shipping distances (H_2 transport), and compiled in a simplified LCA tool. This tool also comprises the eight illustrative pathways laid out in this report as default data, including key assumptions. The simplified LCA tool allows the footprint of hundreds of different pathways to be estimated.

Eight pathways illustrate how hydrogen can support the energy transition

We selected eight illustrative pathways out of the large set of potential options to showcase how hydrogen can support the energy transition and the life-cycle emissions hydrogen generates compared to alternative solutions (see Exhibit 4). The pathways were selected to cover a wide range of geographies, production technologies, midstream transmission and distribution vectors, as well as end-use applications, but are by no means comprehensive.

The eight illustrative pathways are realistic examples for potential value chains, and several Hydrogen Council members are working on projects similar to some of the pathways described. However, the illustrative pathways do not reference any concrete projects, nor imply any preference to future developments, and actual emissions may differ between our examples, which build on deep-decarbonization technologies within the green (wind, solar) and blue (ATR with 98% capture rate) technology portfolio, and any projects that are currently being implemented (given, e.g., high regional variations in the energy mix).

Exhibit 4: Eight illustrative pathways

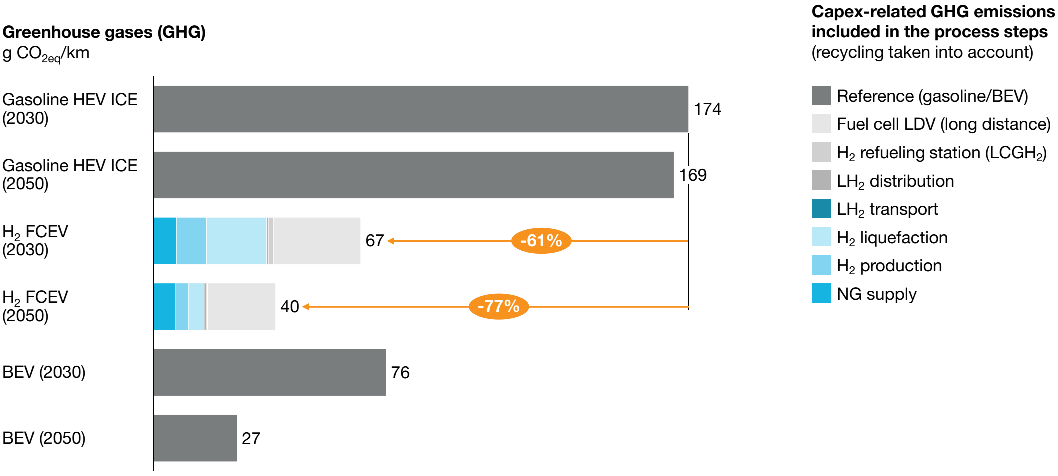
	Origin region	Destination region	Energy production	H_2 production	H_2 conversion	H_2 transport, distribution	H_2 application	Alternatives
1	Australia	East Asia	Natural gas	ATR + CCS	LH_2	LH_2 shipping (9,000 km)	Light-duty vehicles (e.g., fleets)	Gasoline ICE BEV
2	Scandinavia	Scandinavia	Natural gas	ATR + CSS	LH_2	LH_2 trucking (100 km)	Shipping (e.g., cruise ship)	Diesel ICE
3	North/West Europe	North/West Europe	Natural gas	ATR + CCS	–	H_2 pipeline network	Industrial heat (e.g. boiler/furnace)	Natural gas
4	Middle East	East Asia	Natural gas	ATR + CCS	NH_3 synthesis	NH_3 shipping (12,000 km)	Central power generation	Natural gas
5	North America	North America	Wind + solar	Central EL	NH_3 synthesis	NH_3 shipping (2,000 km)	Fertilizer	Natural gas
6	China	China	Solar	Central EL	–	H_2 pipeline (2,500 km)	Buses	Diesel ICE
7	USA	USA	Wind + solar	On-site/ Decentral EL	–	Refueling station	Trucks	Diesel ICE
8	West/Central Europe	West/Central Europe	Offshore wind	On-site/ Decentral EL	–	–	Steel plant (DRI + EAF)	Steel plant (BF + BOF)

Note: These pathways are the result of an exercise to adhere to a long list of pre-conditions. It is neither the intention to reflect actual projects nor to imply developments of any sort

The eight illustrative pathways are depicted in the following sections with some further background information. The pathways presented include assumptions for recycling of metals at equipment end of life (as far as data was available). The excess heat (low temperature) from hydrogen production via electrolysis has not been taken into account in the GHG balance, as this is subject to the availability of a low-temperature heating grid or the addition of a heat pump.

1. Long-distance passenger cars

Exhibit 5: Long-distance passenger cars in East Asia, using imported blue hydrogen



Source: LBST

Pathway description: For the use of hydrogen as in fuel cell electric vehicle (FCEV) powertrain, hydrogen is supplied from Australian natural gas with carbon capture using autothermal reformer with a capture rate of 98 %, which would then be stored in suitable disposal formations. The hydrogen is liquefied and transported via ship over a distance of 9,000 km to East Asia. The liquefied hydrogen is distributed to refueling stations via truck. At the refueling station, the liquefied hydrogen is vaporized and dispensed to the LDV.

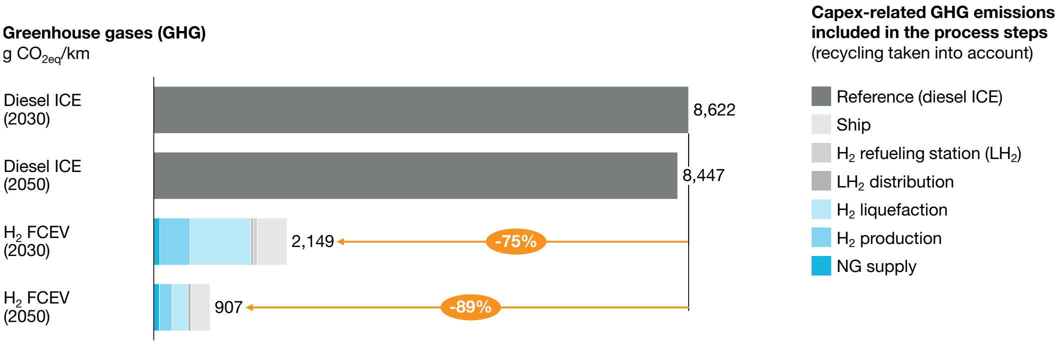
Overall GHG reduction: This solution offers a reduction in GHG emissions of approximately 60% in the short term, and a reduction of 75% in the long run, compared to a hybrid electric vehicle with an internal combustion engine (ICE). GHG emissions of a battery-electric vehicle (BEV) of similar range using the global grid mix are in the same order of magnitude as the FCEV.

Reference GHG: The hybrid reference vehicle improves marginally towards 2050 because of improving vehicle capex-related GHG. The battery-electric alternative (BEV) improves significantly with both capex-emissions and opex-related GHG emissions from reduced carbon-intensity of the global grid mix. However, it has to be noted that there are applications where fast refueling, longer driving ranges (over 300 km), or higher loads are required simultaneously, which cannot currently be achieved by BEV, especially in cases of very cold or very hot weather.

GHG reduction drivers in H_2 pathways: Progress in GHG emission reductions in the FCEV well-to-wheel pathway mainly results from improved H_2 liquefaction (higher per unit capacities, further improved processes). It also benefits from much better global grid mix for auxiliary energy supply in H_2 production.

2. Ships

Exhibit 6: Ships fueled with Norwegian blue hydrogen



Source: LBST

Pathway description: For the use of hydrogen as a transport fuel in fuel cell ship propulsion, hydrogen is supplied from Norwegian natural gas with carbon capture using an autothermal reformer with a very high capture rate and storage in former offshore gas fields. The hydrogen is then liquefied and distributed via trucks to bunker stations for ship fuel in Norway. In our example, a fuel-cell-powered Ro-Ro ferry with a capacity of 50-95 passenger is assumed.

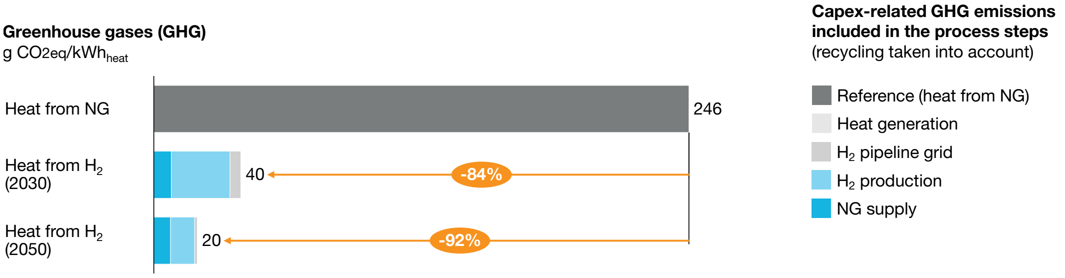
Overall GHG reduction: Compared to the diesel reference, GHG emission reductions in the order of 75% and almost 90% can be realized by 2030 and 2050, respectively.

Reference GHG: Marginal GHG emission reductions going forward can be observed in the fossil reference pathway based on progress assumptions in the grid mix carbon intensity and increased metal recycling efforts, i.e., both referring to improvements in capex-related GHG emissions only.

GHG reduction drivers in H_2 pathways: Main GHG emission contributors in 2030 are ATR operation and hydrogen liquefaction – as both consume significant amounts of auxiliary electricity from global grid mix, the GHG intensity of which substantially improves towards 2050.

3. Industrial heat

Exhibit 7: Industrial heat from blue hydrogen in Northern Europe



Source: LBST

Pathway description: UK natural gas is split into hydrogen and CO_2 via autothermal reforming (ATR) using a 98% carbon capture rate. The CO_2 is sequestered offshore. The hydrogen is transported via a pipeline network to industry clusters in the UK, e.g., to produce industrial heat in boilers/furnaces.

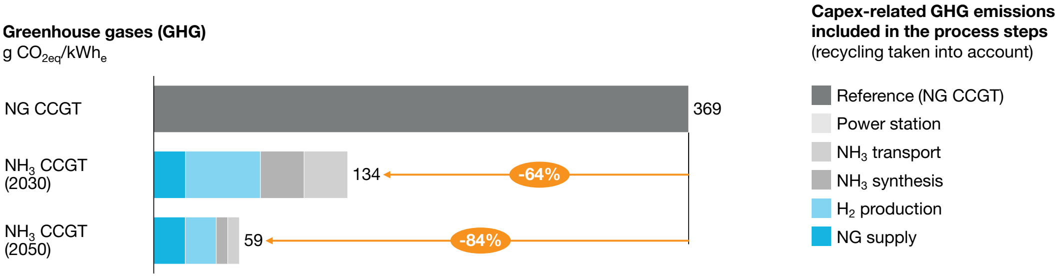
Overall GHG reduction: Compared to the fossil reference (natural gas used in boiler or furnace), GHG emission reductions of over 80% and over 90% can be realized by 2030 and 2050, respectively.

Reference GHG: From a GHG-emission balance perspective, differences between methane- and hydrogen-fed burners are marginal in terms of material intensity and conversion efficiency.

GHG reduction drivers in H_2 pathways: Carbon capture via ATR requires significant auxiliary electricity to achieve the assumed high capture rate of 98%. The main GHG emission contributor in the H_2 value chain 2030 is grid mix for hydrogen production from natural gas, which more than halves by 2050 due to substantial further improvements in the assumed global grid mix.

4. Power generation

Exhibit 8: Blue hydrogen use in East Asian power generation



Source: LBST

Pathway description: In this example, natural gas produced in Saudi Arabia is converted via autothermal reforming with a 98% carbon capture rate. The CO_2 is injected into old underground gas sources for permanent storage. Nitrogen is produced via air separation (using grid power) and synthesized with hydrogen to create ammonia (NH3). The ammonia is transported in refrigerated vessels that use dedicated ammonia for propulsion (boil-off gas to the extent available) over a distance of about 12,000 km to East Asia. In the destination region, the ammonia is used to fire central thermal power plants. In this case, a combined cycle gas turbine (CCGT) modified to run on ammonia has been assumed, including selective catalytic reduction for exhaust gas treatment.

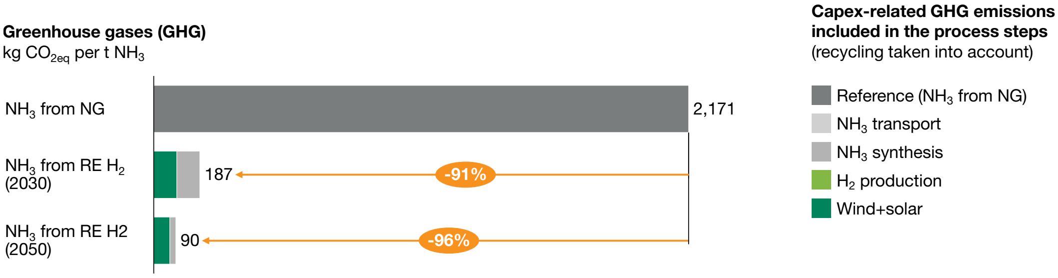
Overall GHG reduction: Compared to the fossil reference (natural gas used in CCGT power plants), GHG emission reductions in the order of over 60% and over 80% are achieved by 2030 and 2050, respectively.

Reference GHG: Differences between the methane and ammonia combustor unit are considered negligible from a GHG emission point of view, both in terms of efficiency as well as in terms of material intensity. Already today, very high efficiency is achieved with large-scale combined-cycle gas turbine (CCGT); hence, 2030 and 2050 efficiencies have been kept constant.

GHG reduction drivers in H_2 pathways: Main GHG emission contributors in 2030 that could significantly improve towards 2050 are hydrogen production, synthesis to ammonia, as well as ammonia transport. GHG emissions from global grid mix serving the auxiliary electricity needs for ATR hydrogen production significantly improve towards 2050, both with positive additional reductions in ammonia synthesis and transport, respectively.

5. Fertilizer feedstock

Exhibit 9: Ammonia fertilizer from green hydrogen



Source: LBST

Pathway description: Today, ammonia derived from natural gas is a main feedstock for the production of synthetic fertilizer. In our example here, a mix of wind and solar power with production conditions typically found in North America is used to produce hydrogen via water electrolysis and nitrogen via an air separation unit. Hydrogen and nitrogen are synthesized to create ammonia, which is then transported to fertilizer production facilities via inland navigation (2,000 km).

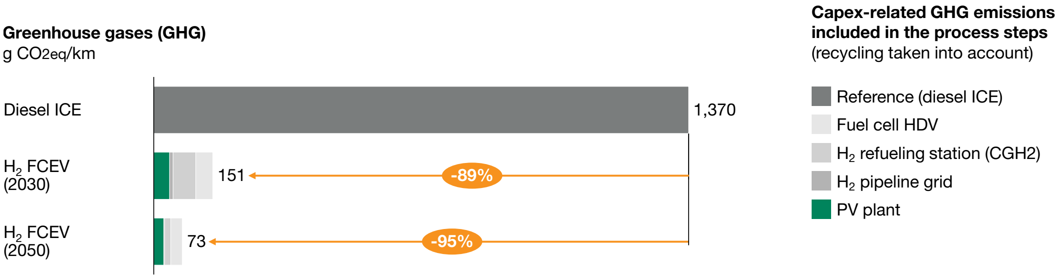
Overall GHG reduction: Compared to the fossil reference, GHG emission reductions of more than 90% and close to 100% can be achieved by 2030 and 2050, respectively, when using renewable power as the primary energy source.

Reference GHG: Ammonia production from natural gas is a long-established process. Main value chain elements are shared between the fossil reference and alternative renewable pathway. Changes in capex-related GHG emissions of the fossil reference through improving global average grid mix are considered negligible against the bandwidth of process data available from several projects.

GHG reduction drivers in H_2 pathways: Main GHG emission contributors in 2030 are capex-related GHG emissions from the manufacturing of wind and solar power plants and ammonia synthesis, both benefitting from the carbon-intensity improvements in the global grid mix.

6. Buses

Exhibit 10: Buses fueled with green hydrogen



Source: LBST

Pathway description: Remote solar power installations in China are used to produce bulk green hydrogen. The hydrogen is transported via gas pipeline over 2,500 km to consumption centers, where it is used to refuel buses that can serve longer routes also under more challenging climatic conditions (heat, cold) by using hydrogen fuel cell electric powertrain (FCEV).

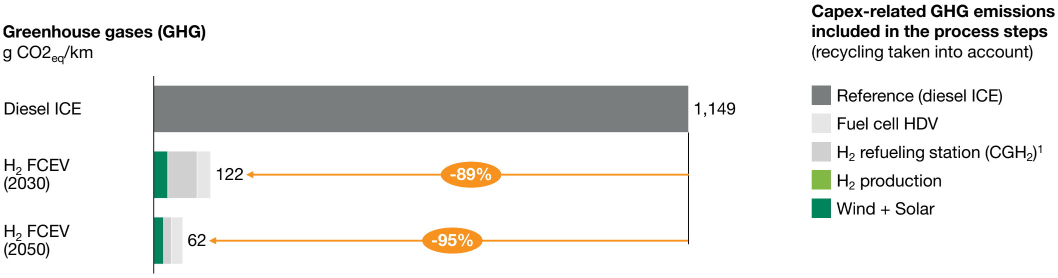
Overall GHG reduction: Compared to the diesel bus reference, GHG emission reductions of close to 90% and 95% can be achieved for 2030 and 2050, respectively.

Reference GHG: The fossil comparator is diesel consumed by an ICE.

GHG reduction drivers in H_2 pathways: Main GHG emission contributors in 2030 are long-distance pipeline transport (compression) and auxiliary energy supply for operating the H_2 refueling station. From 2030 to 2050, GHG emissions from these are reduced significantly due to an improving global grid mix.

7. Heavy-duty transport trucks

Exhibit 11: Heavy-duty trucks fueled with green hydrogen



[1] Using LH_2 as a fuel for long-haul trucks, supplied to refueling stations from central production hubs, is another relevant supply option currently pursued by stakeholders in the value chain.
Source: LBST

Pathway description: Electricity from US wind (2,500 h_{eq}/a) and solar (1,500 h_{eq}/a) hybrid power plants is fed into the grid with an assumed energy curtailment of 5%. Hydrogen is produced via water electrolysis on site at the H_2 refueling station and dispensed to heavy-duty trucks[15].

Overall GHG reduction: Compared to the diesel truck reference, GHG emission reductions of close to 90% and well above 90% can be realized by 2030 and 2050, respectively.

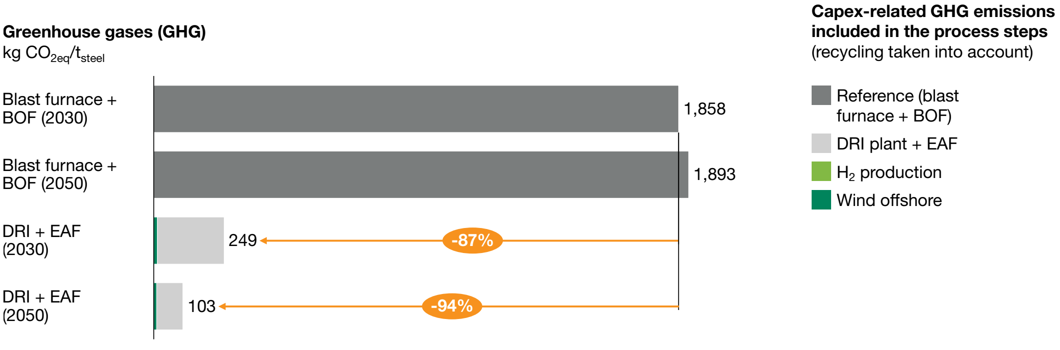
Reference GHG: The fossil comparator is diesel consumed in an ICE.

GHG reduction drivers in H_2 pathways: Main GHG emission contributors for the renewable hydrogen pathway in 2030 are capex-related GHG emissions for the manufacturing of wind and solar power plants and auxiliary electricity demand for the operation of the H_2 refueling station. These already very low emissions can be approximately halved by improving the background energy system (global grid mix).

[15] Using LH_2 as a fuel for long-haul trucks, supplied to refueling stations from central production hubs, is another relevant supply option currently pursued by stakeholders in the value chain.

8. Steel production

Exhibit 12: Green steel production in Western Europe



Source: LBST

Pathway description: Electricity produced from offshore wind parks in the North or Baltic Seas is transported by a high-voltage direct current cable onshore from where it is further distributed to industrial demand centers. Green hydrogen is produced via water electrolysis on site at a steelmaking facility. In direct reduction of iron ore (DRI) using hydrogen, so-called sponge iron is produced, which is further processed in an EAF to specified steel qualities.

Overall GHG reduction: Compared to the conventional primary iron production via blast furnace and basic oxygen furnace process, GHG emission reductions in the order of 87% and 95% can be realized by 2030 and 2050, respectively, by using green hydrogen in a DRI and EAF configuration.

Reference GHG: The GHG emissions of the conventional steelmaking route marginally increase from 2030 to 2050 as the carbon-intensity of the electricity mix decreases, leading to a lower credit for the excess electricity (about 0.3 MWhe per ton of steel) from the blast furnace gas.

GHG reduction drivers in H_2 pathways: Main GHG emission driver in the DRI and EAF configuration is the auxiliary electricity consumption of the EAF. The attributed GHG emissions more than halve from 2030 to 2050 as the global grid mix significantly improves.

Conclusions

- Results from life-cycle assessments of GHG emission for hydrogen supply shows that natural gas with CCS and renewable power for water electrolysis can achieve low and marginal well-to-use GHG emissions, including end-of-life, respectively. For fossil primary energies with CCS, a number of requirements must be met, namely sweet natural gas sources, highest capture rates (98% assumed in the eight illustrative pathways), as well as best available technologies and operational practices.

- Biogenic feedstock for hydrogen production can result in a wide range of GHG emissions. While energy crops are between natural gas-based and renewable electricity-based pathways, GHG emissions from biogenic wastes can be as low as the best renewable power-to-hydrogen pathways (or even negative in case of bio + CCS) but with waste streams somewhat limited at global scale.

- Capex-related GHG emissions for the manufacturing of assets are low across the H_2 supply options compared to the carbon intensity of incumbent fossil pathways, and have been calculated based on global average carbon intensities for energies used in manufacturing. Some manufacturers already today excel beyond average by using renewable and low-carbon energy sources for product manufacturing. GHG emissions of power-to-hydrogen pathways are dominated by capex-related emissions, albeit at very low levels compared to fossil references and alternatives. In this study, a global grid mix with decreasing carbon intensity towards 2050 has been assumed for the capex-related emissions of energy production assets and a number of hydrogen applications where data was available (here, data availability is generally weak). The impact of selected recycling on the well-to-use GHG emission balance is small compared to the fossil reference, most pronounced with solar and wind power pathways, and of wider strategic relevance for deep decarbonization in the context of a circular economy.

- With a view to sustainability aspects other than GHG emissions, specific gross water demand has been assessed for hydrogen supply pathways. Gross water demand is most pronounced with water needs for biomass cultivation and cooling of thermal power plants, hence, a focus on biogenic waste streams and dry-cooling systems is recommended for regions prone to water supply stress or already under supply risk. Gross water demand with photovoltaic (PV) and wind power for water electrolysis is very low. Power-to-X plants at gigawatt-scale nevertheless can be a significant point-demand for water especially in arid regions. Site-specific water supply and demand assessments are regular tasks in environmental impact assessments prior to plant approvals. For large plants in dry regions, seawater desalination with adequate effluent management is an option. Water desalination for Power-to-X plants requires marginal additional energy.

- Eight illustrative pathways for hydrogen value chains from primary energies to hydrogen use have been laid out and GHG emissions calculated for 2030 and 2050. Thereof, four pathways describe mobility and industry applications each. Half of the eight illustrative pathways each comprise green and blue hydrogen value chains. Across the selected hydrogen pathways and applications, very high (about 90% or higher) to high (about 60%) GHG emission reductions can be demonstrated using green (solar, wind) and blue (98% carbon capture rate) hydrogen, respectively. GHG emission reductions observed from 2030 to 2050 are largely capex related, assuming a strong improvement to the global grid mix to reach Paris Agreement targets.

- On a sensitivity note, renewables and electrolysis show the strongest GHG reduction of the different supply pathways assessed in this study, with the best-case blue pathway delivering a reduction in the same order of magnitude. Renewables + electrolysis and fossil + CCS do come with different risks:

  - While all blue options considered in this study show a noticeable but wide range of GHG reduction versus incumbent (grey) H_2 production, blue pathways are connected with higher GHG upwards sensitivities (not using sweet gas sources and best available technology as well as operational practices)

  - Though they have not been analyzed in the study, we note that there are discussions about long-term carbon storage and technology path dependencies, potentially impacting post-2050 emission reduction trajectories

  - Small differences in specific GHG emissions stack up to noticeable absolute emission volumes, requiring larger shares from remaining carbon budgets to stay well below the 2°C target.

- H_2 pathways derived from fossil resources can significantly improve carbon intensity if the auxiliary energy required for primary energy supply or carbon capture is provided from dedicated renewable sources. This could also provide the opportunity to gain organizational knowledge, practical experience, and thus enable a seamless transition beyond 2050.

- Certification of origin and sustainability metrices are key for political support, social acceptance, and consumer willingness to pay the premium for low-carbon and renewable hydrogen supply and applications.