Hydrogen decarbonization pathways

Potential supply scenarios

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Hydrogen Council

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Hydrogen momentum is accelerating further

Over the last two years, the Hydrogen Council launched the studies “Hydrogen, Scaling Up” (in 2017) and “Path to Hydrogen Competitiveness: A Cost Perspective” (in 2020). Together, they represented a cross-industry plan for a step-change in hydrogen deployment globally, showing that hydrogen can play an important role in the decarbonized energy system, and that hydrogen can be a cost-competitive decarbonized solution in a large number of applications before 2030.

Since then, hydrogen has built unprecedented momentum. Large-scale projects have been announced, companies have undertaken strategic moves across the value chain, and there are increasing M&A and investment activities in the sector. In parallel, governments are committing to hydrogen as a part of their climate change strategies, with some deploying significant funds and regulatory support through newly launched hydrogen strategies and funding programs in the context of Covid-19 economic recovery packages.

Life-cycle emissions are coming into focus

Given that hydrogen is one of the keys to the energy transition, it is not only important to make it economically viable, but also to 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, Japan as well as parts of the United States are increasingly introducing support mechanisms for low-carbon hydrogen routes. Countries with abundant renewable and/or fossil and carbon capture and sequestration (CCS) resources are looking to optimize the value of these attributes in destination markets. In all cases, the decarbonization potential of hydrogen is critical.

Hydrogen supply needs to be decarbonized

Currently, the vast majority of hydrogen is produced through fossil pathways. To take the role in the energy transition that the Hydrogen Council envisaged in its “Scaling Up” report, the existing use of hydrogen – and all its many potentials new roles – need to be met with decarbonized sources. It is therefore key to develop a perspective with conditions under which a “decarbonized” or “clean” hydrogen supply is possible, and which pathways can play a role in the decarbonized hydrogen ecosystem of the future.

Aims and methodology of this assessment

This short note develops a perspective on hypothetical scenarios for decarbonized hydrogen supply. Its aim is to determine whether the vision of a dramatic growth in the role of hydrogen in the energy system – as formulated in the “Hydrogen, Scaling Up” study – is possible, and what would be necessary to make it a reality.

The note draws heavily on two reports previously published by the Hydrogen Council – “Hydrogen, Scaling Up” for a vision of future hydrogen demand, and “Path to Hydrogen Competitiveness” for a perspective on the costs of various hydrogen production pathways. It also refers to the concurrently published LCA study “Hydrogen Decarbonization Pathways – A Lifecycle Assessment” for a perspective on the carbon footprint of the pathways in question.

The hypothetical scenarios presented in the following note try to answer the question of whether a decarbonized hydrogen supply is possible and what it would entail – they do not constitute a prediction nor recommendation on the optimal future hydrogen supply. The scenarios are based on a simplified model on resource availability, hydrogen production costs, and life-cycle emissions of green and blue hydrogen production routes in six global regions.[1] Two of the scenarios are hypothetical boundary cases, in which the entire hydrogen demand is met with either renewable ("green") or low-carbon ("blue") hydrogen only.[2] Their goal is to answer whether the world has sufficient resources to produce clean hydrogen, and what the consequences of a 100% green or blue pathway would be. The third scenario is a combined case, in which hydrogen is decarbonized with both green and blue pathways. The model uses a simple algorithm that chooses between green and blue hydrogen as a (weak) function of their relative costs – we purposefully assume limited price sensitivity to reflect the importance of societal and political constraints (such as the political will to favor one source of hydrogen over the other) as well as the variations in regional costs (the ratio between green and blue hydrogen differs between various European locations, for instance).[3]

A detailed, cost-optimized, localized supply model would take a much more granular regional perspective, include a wider range of hydrogen production pathways, consider regulatory restrictions on technologies such as CCS, and include scenarios on international hydrogen trade – such research is not covered by this paper but is highly encouraged to inform the debate.

1 Europe, Middle East and Africa, North America, China, Japan and Korea, rest of world.

2 In this report „green" or renewable hydrogen is shorthand for hydrogen production through water electrolysis from renewable electricity; „blue" hydrogen is shorthand for hydrogen production through a reforming process with carbon capture and storage. For green hydrogen production, we assume a mix of electrolysis from solar PV and offshore wind; for blue hydrogen production, we assume a mix of region-specific fossil sources (coal and natural gas) and a mix of ATR and SMR reforming technologies with 90-98% carbon capture rates. The focus on these two main pathways does not exclude other production pathways that can form part of a hydrogen economy, such as the biogas reforming, methane pyrolysis, and other options.

3 Our algorithm chooses between green and blue hydrogen in inverse proportion to their costs. For instance, if the cost of green hydrogen production in a given year and region exceeds the cost of blue hydrogen production by a factor of two to one, two-thirds of new hydrogen installations in the region will be blue and one-third of the installations green.

Hydrogen supply scenarios

A decarbonized hydrogen supply is feasible and underpins our vision for hydrogen scale-up

Today, the vast majority of hydrogen is used in (petro-)chemical processes and produced through fossil pathways, such as steam methane reforming (SMR) or autothermal reforming (ATR) and gasification.

The Council's "Scaling Up" report presented a rather different vision of the role for hydrogen in the global energy system: one in which global hydrogen demand increases tenfold until 2050, as the molecule takes a central role in the energy transition and the decarbonization of the residential, transportation, and industrial sectors. To play such a role in the decarbonized energy system, the hydrogen supply of course needs to be decarbonized (produced from renewable and low-carbon sources). This note aims to show that such a decarbonized hydrogen supply is feasible, and presents a potential scenario of how the industry could get there.

Various hydrogen production pathways can achieve very low emissions

Which hydrogen production pathways are relevant in a decarbonized energy system?

As "A Life-cycle Assessment" shows, several hydrogen production pathways – including renewable ("green") or low-carbon ("blue") pathways – can achieve very low CO_2 emissions and consume only limited amounts of resources such as water. This study focuses on two of these pathways: water electrolysis using renewable power (referred to here as "green hydrogen"), and reforming of natural gas or coal-derived gas with carbon capture and sequestration (SMR/ATR+CCS; referred to as "blue hydrogen"). Carbon capture rates well above 90% are possible for blue hydrogen production, allowing both routes to produce hydrogen with less than 1.5 kg of CO_{2eq} emitted per kg of hydrogen produced under favorable conditions (I.e., in regions with low upstream emissions and use of best technologies and processes)[4] – large reductions compared to today's grey hydrogen production, which emits around 10 kg of CO_{2eq} per kg of hydrogen produced.[5]

Decarbonized hydrogen supply has a clear path towards competitiveness

The second factor that determines feasibility of decarbonization is the cost competitiveness of different hydrogen production pathways.

The "Path to Hydrogen Competitiveness" report showed that green and blue hydrogen production pathways have a clear path to competitiveness with grey hydrogen production. The competitiveness of green hydrogen is driven by steep cost reductions for electrolyzer capex (around -75% between 2020 and 2030) as well as the ongoing reductions in renewables costs across regions. Since power consumption contributes 60% to 70% of green hydrogen production costs, regions with abundant low-cost renewables can break even sooner than less abundant regions. The latest cost projections

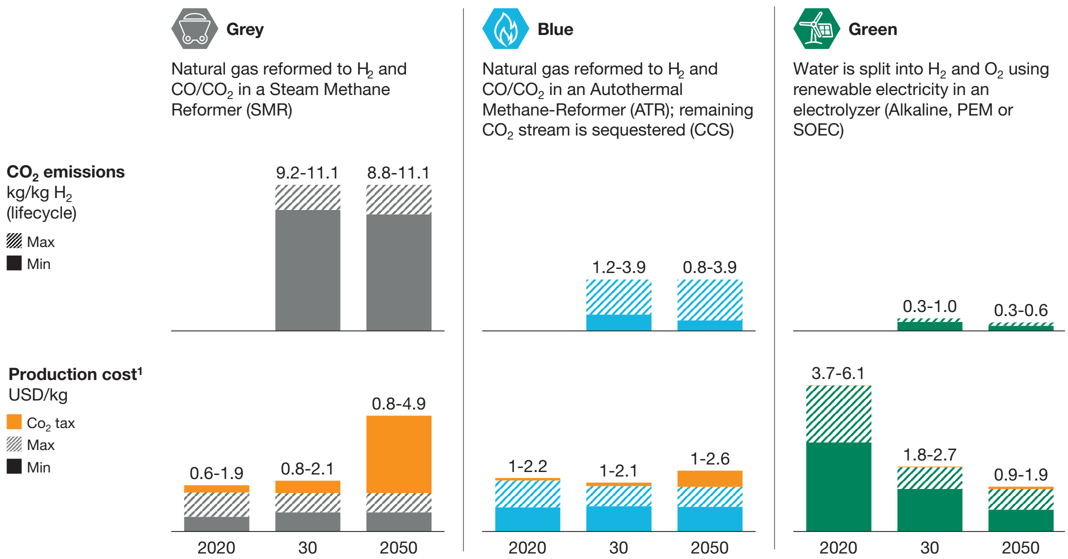
4 "Hydrogen Decarbonization Pathways – A Life-cycle Assessment" assumes 90% carbon capture rates for SMR and 98% carbon capture rates for ATR. It should be noted that a 90%/98% carbon capture rate does not reduce emissions by 90%/98%, as additional energy is needed to power the capture and sequestration process, and as some GHG emissions occur upstream. For instance, the 2030 CO_2 emissions of Norwegian blue hydrogen transported to Europe over a distance of 1,700 km amount to 1.5kg CO_{2eq}/kg H_2 using SMR with 90% CCS and 1.2 kg CO_{2eq}/kg H_2 using ATR with 98% CCS. CO_2 emissions of Russian blue hydrogen transported over a distance of 5,000 km amount to 3.9 kg CO_{2eq}/kg H_2. See "Hydrogen Decarbonization Pathways – A Life-cycle Assessment" for details.

5 Biomethane reforming and electrolysis with nuclear power can also achieve minimal emissions, but the supply of sustainably sourced biomass is expected to be limited while nuclear electrolysis is expected to be outcompeted by renewables in many regions. The following therefore focuses on "green" (wind, solar, and to a limited extent, hydropower) and "blue" pathways (natural gas and coal with CCS) only.

indicate that green hydrogen can break even with grey hydrogen production before 2030 in regions with optimal renewables, and before 2035 in regions with "average" renewables availability.[6]

The competitiveness of blue hydrogen, in contrast, depends primarily on the scale-up of CCS facilities and the value that is attributed to the CO_2 that is sequestered. Given the low potential costs of large-scale CCS, blue hydrogen can outcompete grey hydrogen as soon as moderate carbon prices or taxes of USD 50/ton are applied – a level in line with the near-term milestones of major economies with net-zero commitments, e.g., in the EU by 2030.[7] Exhibit 1 summarizes the main assumptions for selected hydrogen production pathways.

Exhibit 1: Core assumptions for selected hydrogen production pathways



[1] Costs for hydrogen produced in new installations; Assuming CO2 tax of USD 28/ton in 2020, USD 48/ton in 2030, USD 300/ton in 2050, excluding vectorization/transport
Source: LBST; Hydrogen Council – Path to Cost Competitiveness; McKinsey

The world has sufficient resources to meet hydrogen demand through either green or blue sources

In theory, green and blue hydrogen would both be able to fuel the hydrogen economy by themselves. In the "Scaling Up" report, the Hydrogen Council formulated a vision in which hydrogen provides some 78 EJ or 21,800 TWh of hydrogen in 2050 – a tenfold increase over current hydrogen consumption. While these quantities require enormous amounts of energy, they would neither exceed global renewable energy resources nor the estimated geological carbon sequestration potential. However, a "green-only" or "blue-only" world would create a different set of challenges:

A **"green-only" world** would require an exponential growth of electrolyzer capacity of more than 30% per year starting today – a huge undertaking, but one previously achieved by the build-out of

[6] Hydrogen Council: Hydrogen Insights (2021)

[7] See, e.g., ArgusMedia, September 17, 2020: "EU ETS price €32-65/t under 2030 scenarios."

solar PV (35% p.a., 2010 to 2019) and offshore wind (30% p.a., 2010 to 2018). More importantly, a green hydrogen world would require significant amounts of additional renewables capacity – at a time when the decarbonization of the grid already requires further efforts for renewable power expansion. It would also likely require public support to fund the initial capex gap for renewables assets and electrolyzer equipment in the period until green hydrogen starts to break even with grey – before 2030 in "optimal" regions (with very low-cost renewables), but as late as the late 2030s or 2040s in regions without abundant renewable energy.

A **"blue-only" world** would also require a massive scale-up of SMR/ATR and CCS storage facilities, but would likely relieve some pressure on upstream and production supply chains, given the higher maturity of the natural gas sector and the reforming equipment industry relative to the renewables and electrolyzer value chain. However, it would not achieve the benefit of domestic hydrogen production in countries without suitable fossil resources and CCS reserves. A blue hydrogen world would allow for lower costs in the short to medium term and may (under best-case assumptions) also achieve life-cycle GHG emissions almost as low as those of hydrogen from solar, wind, and water. It remains, however, more expensive in the long term, as it would not allow the world to benefit from the enormous longer-term cost-down potential in green hydrogen production.

An optimal supply would therefore likely select different mixes of green and blue across regions and over time. It would include both domestic production as well as international transport of hydrogen from lowest-cost locations in order to fully leverage the complementarities in fossil and renewable resources around the world.

Thought experiment: A "green-only world"

A "green-only" world would require about 10,000 GW of dedicated renewables capacity in 2050[8] – a formidable amount, but much less than is required to decarbonize the electricity grid. Achieving this would require the world to build out renewables at a pace of 10.5% per year over the next three decades (compared to roughly 9% per year without hydrogen) – again, a daunting growth rate, but well below the build-out rates seen by solar PV and offshore wind over the last decade (35% and 30%, respectively)[9]. By 2050, the renewables required to produce all the world's hydrogen would include solar PV farms of the size of Italy or New Zealand and offshore wind parks along an area equivalent to half the mainland exclusive economic zone (EEZ) of Chile or China[10]. Electrolyzer capacity would have to grow from about 0.1 GW to more than 600 GW by 2030, and continue to grow at a CAGR of more than 10% to an installed base of approximately 5,500 GW by 2050.

The energy required for hydrogen production in a "green-only" scenario, about 28,800 TWh in 2050, is still less than 10% of the estimated global renewable potential[11]. Since renewable resources, population density, energy demand, and consumption lifestyles vary throughout the world, some regions – especially Japan and Korea, but likely also parts of the EU and China – would have to import at least some green hydrogen from more resource-abundant regions.

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[8] Our estimation is based on a combination of solar PV and off-shore wind with regional capacity factors, and uses data from (McKinsey Energy Insights, Global Energy Perspectives 2020, Accelerated Case).

[9] Note that current renewables capacity is to a large extent hydropower, while additional renewables demand will be met primarily with solar PV and offshore wind. The growth rates required for these renewables sources are therefore higher than the 9% to 10.5% suggests.

[10] Solar: Assuming a solar farm efficiency of 29 MW/km^2 (currently achieved, e.g., at San Luis Obispo, US) and a share of solar between 45% (Europe) and 95% (Middle East) of regional energy demand for green H_2. Wind: Assuming 5 MW/km^2 energy density for offshore wind (Source: ECN 2018) and a wind share between 5% (Middle East) and 55% (Europe) of regional energy demand for green H_2.

[11] The conservative estimates for the global renewables potential are 245,000 TWh (low estimate with strict constraints) to 1,000,000 TWh (high estimate with weaker constraints) (Deng et al., 2015, Quantifying a Realistic Worldwide Wind and Solar Electricity Supply)

Overall, the cumulative costs of a “green hydrogen world” would amount to approximately USD 3 trillion at present value[12] – approximately 75% of which for renewables, 25% for electrolyzers. This amounts to USD 100 billion p.a., at present value, about 5-10% of the USD 1.5 trillion invested in the entire energy system in 2020[13]. Initially, green hydrogen production would be significantly more expensive compared to blue hydrogen production. From the late 2020s onwards, the levelized cost of green hydrogen production is expected to start to break even in regions with abundant renewables and further decrease below that of blue hydrogen in many parts of the world. In less advantaged areas, the break-even point would only materialize after 2030 or even 2040 (see our latest “Hydrogen Insights” report for the latest data).

Thought experiment: A “blue-only world”

A “blue-only” world is not constrained by natural gas or coal availability – since fossil fuel consumption is expected to stagnate and eventually decline in a net-zero world, the incremental demand from hydrogen does not create a major need for additional exploration. Carbon sequestration facilities in contrast would have to be proven and scaled up at an unprecedented rate – to approximately 50 Gt by 2050 (from less than 0.1 Gt today). The total amount of carbon sequestered by 2050 would nevertheless fill only approximately 2% of the estimated global sequestration capacity, meaning that we could continue to indefinitely store more than 500 years of 2050’s annual CO_2 emissions (amounting to about 5 Gt; not considering other industrial emissions that would have to be stored).[14]

60% of estimated global natural gas reserves are concentrated in just five countries: Russia, Iran, Qatar, Norway, the United States, and the Kingdom of Saudi Arabia. A blue-only world would therefore rely heavily on trade of hydrogen from these regions into major demand centers. Independent certification and monitoring would be needed to ensure that best available technology and operational practices are applied as assumed in this study.

Overall, the cumulative costs of a “blue hydrogen world” would amount to approximately USD 0.5 to 1 trillion in cumulative capex until 2050 at present value[15]. The vast majority of this would flow upstream (e.g., into natural gas exploration, coal gasification and carbon capture and sequestration facilities); a minority into conversion equipment such as reformers. Per year, the total capex amounts to approximately USD 15-30 billion at present value – significantly less than a “green-only” world, albeit at a higher opex in the medium to long term. While blue hydrogen costs less than half to produce as much as green hydrogen production in 2020, the costs in 2050 would exceed those of producing green hydrogen in many regions and in the global average (assuming that all greenhouse gas emissions in the hydrogen production process are taxed at rates that are consistent with a 1.5°C climate change target). A “blue hydrogen world” would emit 20 to 25 Gt of CO_2 over the period of 2020 to 2050 compared to approximately 10 Gt in a “green-only” world – 8 Gt of which (in both cases) stem from the phase-out of grey hydrogen[16]. As a

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12 Based on region-specific capex (Source: McKinsey Energy Insights, Global Energy Perspectives 2020, Accelerated Scenario); discounted to 2020 at 7% cost of capital.

13 IEA (2020): World Energy Investments. Of the USD 1.5 trillion in total investments, roughly USD 300 billion were invested into renewables.

14 The conservative estimate of the geological CCS potential is based on Global CCS Institute (2016): Global Storage Portfolio (lower bound estimate). The sequestration need is based on a conservative mix of natural gas and coal inputs as well as SMR and ATR technologies with carbon capture rates between 90% and 98%. Assuming a complete shift to ATR with 98% carbon capture for blue hydrogen production would require fewer CCS capacities.

15 Discounted to 2020 at a 7% cost of capital.

16 The CO_2 emissions generated from blue hydrogen production are based on a conservative mix of natural gas and coal inputs as well as SMR and ATR technologies with carbon capture rates between 90% and 98%. Assuming a complete shift to natural gas ATR with 98% carbon capture for blue hydrogen production would reduce CO_2 emissions by approximately 5Gt.

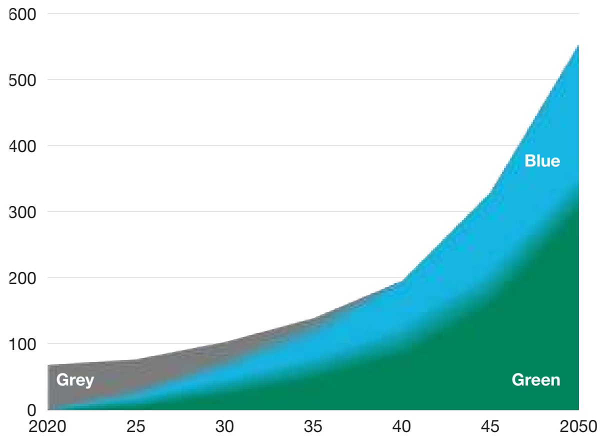
reference, the remaining carbon budget to limit global warming to well below 2°C, as agreed in the Paris Agreement, is estimated between 235 and 985 Gt[17]. Of course, the use of both green and blue hydrogen would contribute to reducing emissions from other energy sources and carriers – between 60% and 90% across the applications described in the concurrently published Life-Cycle Assessment report.

A combined hydrogen decarbonization scenario can achieve lower average hydrogen costs than either boundary scenario

While both green and blue worlds are possible, the regional complementarity of renewables and gas resources suggests that the global production portfolio will contain a mix of both hydrogen production pathways. Exhibit 2 illustrates a range of combined scenarios that could achieve a completely decarbonized hydrogen supply from 2040, implying an ambitious phase-out or conversion of existing global hydrogen production capacities.

Exhibit 2: Combined scenario for decarbonized hydrogen

Hydrogen production scenario, global
Mtpa



Key scenario assumptions

- Existing grey hydrogen capacity is phased out over 20 years
- The total hydrogen production volumes meet the ambition defined in the Hydrogen Council "Scaling Up" report
- Announced projects and government targets are implemented as announced
- Remaining hydrogen demand is met using a mix of blue and green, based on an inverse proportion to cost[1]
- All optimizations are conducted per region using regional hydrogen demand and regional hydrogen production based on the Hydrogen Council "Path to Competitiveness" report
- New green / blue projects have a 25-year lifetime and continue to produce at constant costs throughout their operations

[1] I.e., if the cost of green hydrogen production in a given year and region exceeds blue hydrogen 2:1, 2/3 of new hydrogen installations will be blue and 1/3 green
Source: Hydrogen Council, McKinsey, LBST

Like the boundary scenarios, this range of scenarios is based on the hydrogen demand envisioned in the "Scaling Up" report and assumes a (very ambitious) linear phase-out of grey hydrogen production over the next two decades. It first takes into account existing targets and announcements on green and blue hydrogen. Beyond these targets and announcements, new capacities are added in proportion to region-specific production cost differentials between green and blue hydrogen. This model results in a balanced supply pathway range, with an important role

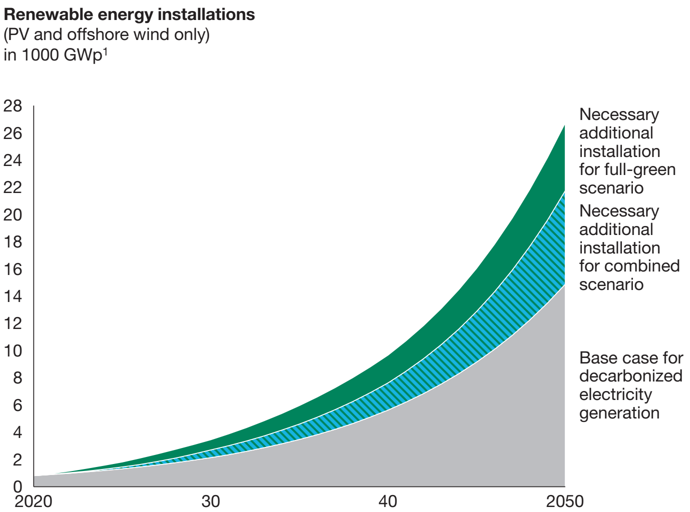
[17] IPCC (2018): Special Report on Global Warming of 1.5°C. From the start of 2020, the remaining carbon budget is estimated at 985 Gt CO_2 to limit warming to 2.0°C with a 66% probability, 395 Gt CO_2 to limit warming to 1.5°C with a 50% probability, and 235 Gt CO_2 to limit warming to 1.5°C with a 66% probability.

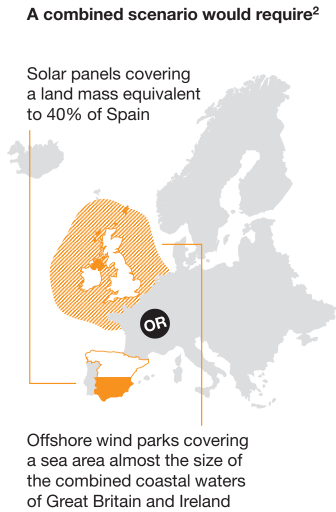
in blue hydrogen in decarbonizing the 2030 supply base and an increasing role for green hydrogen from 2040 to 2050 (and beyond).

While a green-only and blue-only hydrogen world would result in an average hydrogen cost of about USD 2.2 per kg over the next 30 years (including taxes on all upstream emissions generated in the process), the combined scenario results in less than USD 2.0 per kg – lower than either of the pure scenarios. In reality, hydrogen costs are likely to be even lower in a combined scenario, as regionally and locally optimal hydrogen sources can be used. Given the enormous hydrogen demand in our scenario, a 10% cost difference would imply savings of about USD 1 trillion – almost a third of Germany's GDP today.

The combined scenario also makes it easier to develop the hydrogen economy. It is still ambitious: decarbonizing 21,800 TWh of hydrogen through a mixture of green and blue sources would require up to 40% more renewable energy in 2050 than without any green hydrogen – an amount that can be provided through solar panels covering an area 40% the size of Spain, or offshore wind turbines covering the waters surrounding the United Kingdom and Ireland (see Exhibit 3)[18]. However, this is significantly below the renewables required for the green-only boundary case. Similarly, the need for CCS build-out is roughly halved relative to the green-only scenario.

Exhibit 3: Renewable energy requirements for decarbonized hydrogen scenarios





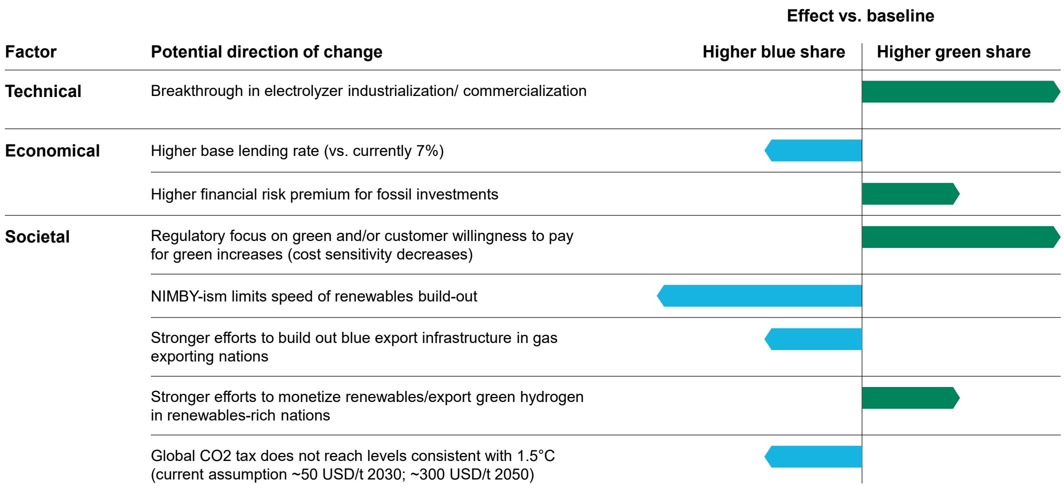
1 Base case: IRENA Global Renewables Outlook 2020, accelerated case; variable renewable energy supplying 61% of the electricity generation in 2050; assuming best-in-region load factors for renewables installation to supply green hydrogen
2 Excluding baseline hydrogen demand
Source: Hydrogen Council, McKinsey, LBST

18 Not including the renewables required for the baseline energy demand.

The realistic future supply mix will depend on a range of factors – technical, economic, and societal

The combined scenario presented here is based on a simple model and takes into account the estimated green and blue hydrogen costs in large global regions. In reality, the supply mix will depend on a range of factors, including local hydrogen production costs, existing infrastructure (such as power transmission networks or natural gas pipelines), and emerging hydrogen trade routes.
A range of factors can impact the role of each source, even within a decarbonization scenario – some sensitivities are shown in Exhibit 4.

Exhibit 4: Potential sensitivities on the decarbonized hydrogen scenario



While green and blue hydrogen both have significant potential, it is likely that the “optimal” or realistic decarbonized path will contain a combination of different renewable and low-carbon hydrogen production pathways that are suited to local conditions, political and societal preferences, and the developments in the green and blue hydrogen supply chains.