Bullish, Bearish or Somewhere in Between?

Reviewing Supply and Demand Scenarios for Blue and Green Hydrogen

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Introduction

Key Points:

- Demand scenarios from the Hydrogen Council, IEA and Goldman Sachs point to a potential clean hydrogen (both blue and green) of around 500-600 MT by 2050.
- Most of this is expected to come from green hydrogen, necessitating a massive expansion of electrolyzer and renewables capacity.
- All three organizations expect that mobility will be the largest-consuming sector. This includes road transport (especially heavy-duty trucking), marine and aviation.
- Overall, IEA projects hydrogen and hydrogen-based fuels meet 10% of global final energy demand in 2050, while the Hydrogen Council projects 22%.
- Electrolyzer capacity projections in the three analyses range from 1-4 terawatts (TW) required by 2050 and 4.5-6.5 TW in renewables expansion.
- Underpinning these analyses is the assumption that there will be stronger, tougher prices on carbon that are over USD 100/ton. As noted in last month's report, such a price only exists in three countries right now.

Over the last five years, there has been a renewed and increasing interest in hydrogen as a pathway to decarbonization across sectors, including transport. Past reports on hydrogen for members have reviewed production pathways (see report Oct. 20, 2020) and countries' plans for hydrogen in transport (see report Jan. 13, 2021). Much has happened even in the last 18 months in the hydrogen space, as last month's report on policy showed (see report Apr. 19, 2022). Countries are getting much more serious and concrete about developing their hydrogen markets.

This report is the second in a series on hydrogen planned through the June-July timeframe. It focuses on the market potential for hydrogen, particularly blue and green hydrogen, as well on underlying cost and economics. Other reports and posts will cover hydrogen for aviation and shipping, the potential for hydrogen internal combustion engine vehicles (ICEVs) and global projects and select companies in the space. Hydrogen will surface in another planned report on renewable fuels of non-biological origin (RFNBOs). An on-demand webinar is planned for the June timeframe to review the body of research to date in a more summarized way.

Currently, and as members know, hydrogen is primarily used as a feedstock in a number of key industrial processes. According to the International Energy Agency (IEA), global hydrogen demand was around 90 million metric tons (MT) in 2020. This includes more than 70 MT used as pure hydrogen, primarily in oil refining and ammonia production, and less than 20 MT mixed with carbon containing gases primarily for methanol production and steel manufacturing. This excludes around 20 MT that is present in residual gases from industrial processes used for heat and electricity. Oil refining is the largest consumer of hydrogen currently, accounting for 41% of global hydrogen demand in 2020. Natural gas is the main fuel for hydrogen production at this time, with steam methane reformation being the dominant method in the ammonia and methanol industries, as well as in refineries.

This report reviews supply, demand, costs and economics of hydrogen, especially for the 2030 and 2050 timeframes. We look through the lens of three different organizations to do so: the industry-backed Hydrogen Council, the IEA as an international organization representing governments and Goldman Sachs, one of the premier global banking institutions. In summary, each of the three organizations project a substantial scale up of both blue and green hydrogen by 2030 and continuing into 2050. The most progressive, perhaps understandably, comes from the industry through the Hydrogen Council.

Demand scenarios from all three organizations point to a potential clean hydrogen (both blue and green) of around 500-600 MT by 2050. Much of this is ultimately expected to come from green hydrogen. That means there will need to be a major scale up of electrolyzer and renewables capacity. Electrolyzer capacity projections range from 1-4 terawatts (TW) required by 2050 and 4.5-6.5 TW in renewables expansion. Addressable markets include transportation (for road vehicles, marine and aviation) and power generation, among others.

Hydrogen Council: Policy Needed to Scale Up

A November 2021 analysis from the Hydrogen Council notes that "hydrogen is central to reaching net zero emissions because it can abate 80 gigatons of CO2 by 2050."[1] The Council, with McKinsey, estimated the deployment of 75 MT clean hydrogen is needed by 2030 which would replace 25 MT of grey hydrogen in ammonia, methanol, and refining; 50 billion liters of diesel in ground mobility; and 60 MT of coal used for steel production. The Council estimates that early growth in clean hydrogen deployment will likely center on Europe, Japan, and Korea, which will account for about 30% of new clean demand. China and North America – significantly larger hydrogen markets today – will follow closely with about 20% of demand for clean hydrogen each.

To meet this demand, a mix of both green and blue hydrogen supply would require 200 to 250 Gigawatts (GW) of electrolyzer capacity and 300 to 400 GW of new renewables, as well as 45 to 55 MT of low-carbon hydrogen production capacity and associated carbon infrastructure to store 350 to 450 MT of CO2 a year. This will create the need to step up the deployment of renewables, the Council notes. But it all depends on "the right regulatory framework" and that will include policies like "robust carbon pricing" and mandates.[2] In 2020, 260 GW of capacity was commissioned, and more than 520 projects were announced in 2021 which would produce (if all constructed) 18 MT of clean hydrogen supply (accounting for USD 95 billion in investment) as well as infrastructure (USD 20 billion) and end-uses (USD 45 billion). The Council projects the total sum of estimated spending will grow to more than USD 600 billion by 2030.

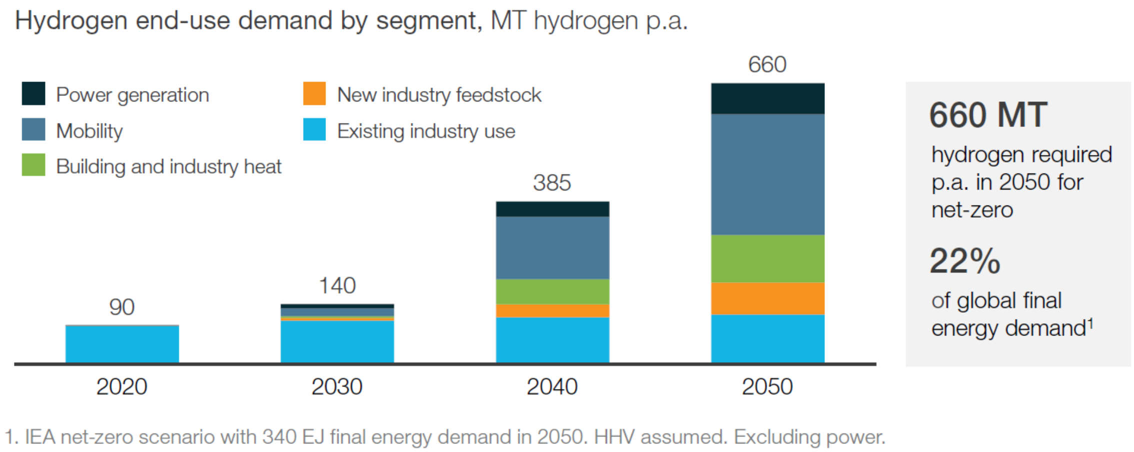
The Council notes that, "Although the pipeline of projects is strong, a significant gap to the net zero scenario remains, and the right regulatory framework is required to turn projects from concepts into actual investments. Out of the currently announced direct investments, only USD 20 billion (13%) have passed the final investment decision (FID) so far, with another USD 64 billion (40%) in the feasibility or front-end engineering and design (FEED) stage. This means many proposals are on the table awaiting the right regulatory framework to unlock

[1] Hydrogen Council, Hydrogen for Net-Zero: A Critical Cost-Competitive Energy Vector, November 2021 at https://hydrogencouncil.com/wp-content/uploads/2021/11/Hydrogen-for-Net-Zero_Full-Report.pdf (hereinafter "Hydrogen Council").
[2] The Council at 5.

demand and investments."[3] Will that "right regulatory framework" ever come though? Or will what comes be enough to really spur investment in and production of cleaner hydrogen? We can say that perhaps that is beginning to happen through the national strategies some countries are setting. Those are strategies are mostly not hard targets with defined implementation dates at this time. Moreover, it will be key to watch how whether the voluntary targets under those strategies are met and whether they evolve into more defined regulatory regimes.

Figure 1 shows hydrogen end-use demand by segment. In a net-zero world, the Hydrogen Council projects demand for clean hydrogen could reach approximately 660 MT in 2050, making up 22% of the final energy demand globally and avoiding annual emissions of 7 gigatons (GT) of CO2. China, the world's largest consumer of primary energy, should become the largest single market for clean hydrogen in 2050, with about 200 MT of demand. Europe and North America will follow, accounting for 95 MT of clean hydrogen each. By 2050, the Council notes clean hydrogen could abate a cumulative total of 80 GT of CO2 – about twice the current amount of annual anthropogenic emissions. The 80 GT cumulative CO2 abatement potential through 2050 constitutes about 11% of the emissions reductions required to stay within the carbon budget of 420 GT needed to limit global warming to 1.5-1.8 degrees Celsius.

Figure 1: Hydrogen End-Use Demand by Segment (MT)



Source: Hydrogen Council, November 2021

Mobility is expected to be the largest single hydrogen end-use segment with 285 MT of hydrogen demand in 2050. The sector includes hydrogen applications within ground mobility, maritime, and aviation. Heavy-duty trucks are expected to be the largest consumer of hydrogen long-term due to their high mileage and power characteristics, requiring 110 MT of hydrogen in 2050. Maritime and aviation are expected to account for 110 MT of hydrogen demand. One interesting use that is not noted in the other two analyses is the potential to decarbonize aromatics. The Council notes:

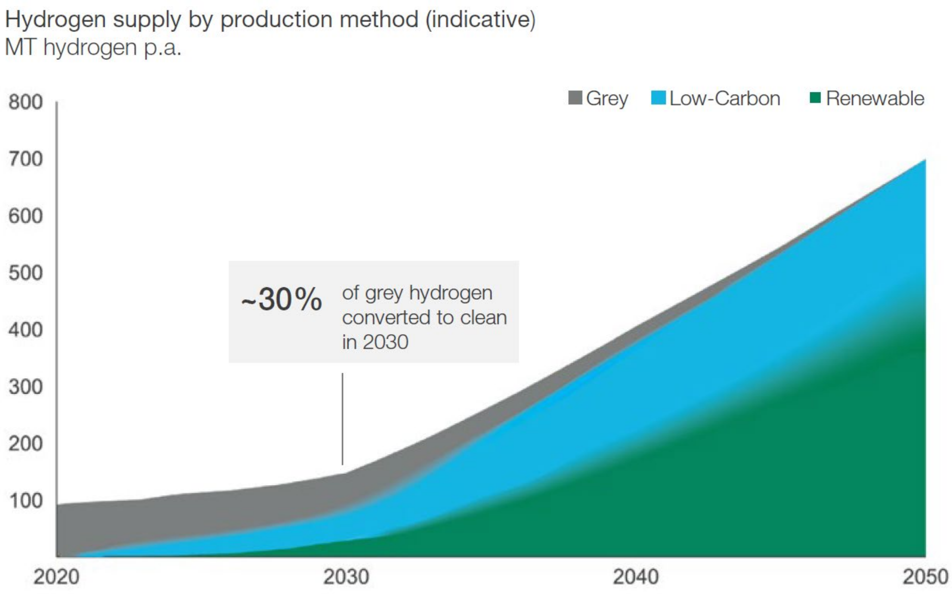
[3] The Council at 7.

"In 2050, hydrogen demand for methanol-to-aromatics could account for about 40 MT, although this is highly uncertain. If used for plastics production (e.g., nylon), BTX can act as a carbon sink by storing captured CO2 for long-duration storage. If biogenic or air-captured CO2 is used and the plastic is not incinerated, low-carbon BTX can contribute to negative carbon dioxide emissions."[4]

What will be the mix between blue and green hydrogen? Blue hydrogen is expected to account for about 20 to 40% of supply in 2050, the equivalent of 140 to 280 MT of hydrogen supply, according to the Council's projections. This amounts to about two to three times today's grey capacity and would require infrastructure to store about 1 to 2.5 GT of CO2 a year. Green hydrogen will account for 60% to 80% of supply or 400 to 550 MT of hydrogen.

The Council estimates that such a volume of renewable hydrogen will require 3 to 4 TW of electrolysis capacity and about 4.5 to 6.5 TW of renewable capacity dedicated to hydrogen production. In comparison, this is about two times the total renewable generation capacity of 2.8 TW installed through 2020. The Council notes that about 27 TW of renewable power would be required in a net-zero economy in 2050 – the estimated electrolyzer buildout would require about 20% of this capacity. Figure 2 summarizes hydrogen supply through 2050 and note that even through the late 2040s, there is still some small amount gray hydrogen that is produced.

Figure 2: Hydrogen Supply through 2050



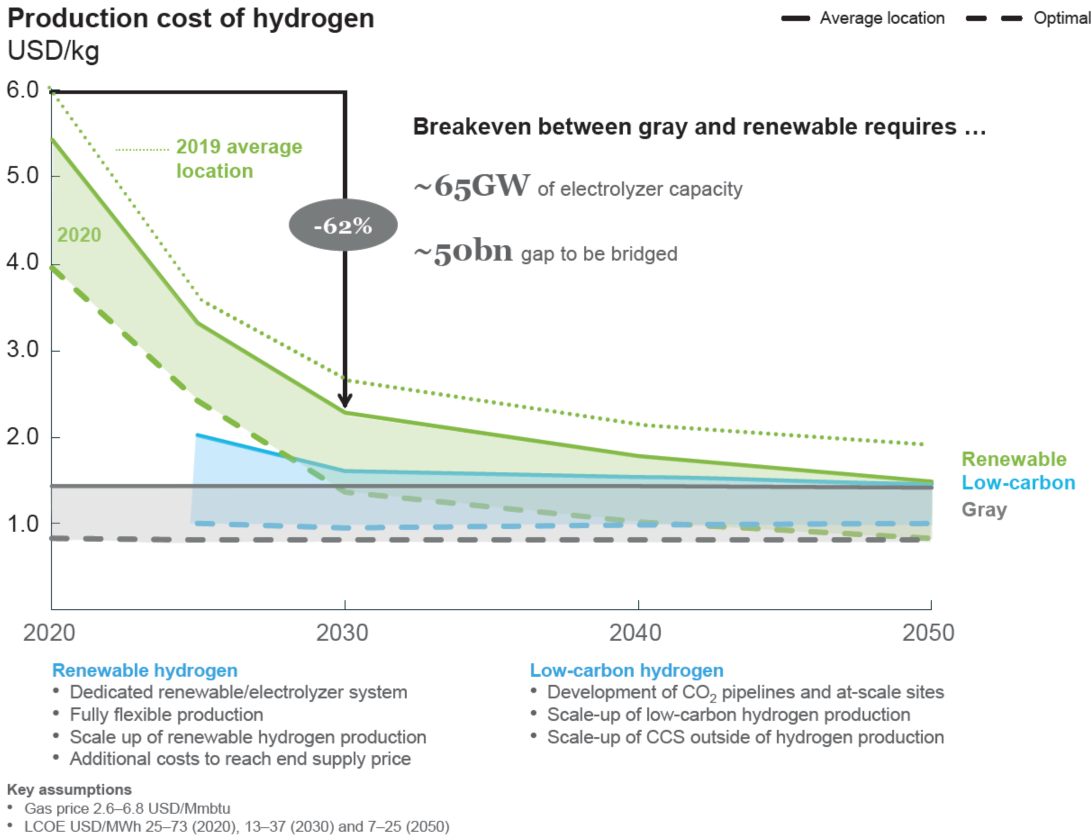
Source: Hydrogen Council, November 2021

In terms of cost projections, the Council notes green hydrogen could break even with gray hydrogen by 2030 because of electrolyzer cost capex declines, a drop in the levelized cost of energy and increasing utilization

[4] Hydrogen Council at 17.

levels.[5] The Council notes that this performance is driven largely by the centralization of production, a better mix of renewables (e.g., onshore wind and solar PV) and integrated design optimization. Figure 3 summarizes production costs by pathway.

Figure 3: Estimated Production Cost of Hydrogen for Low Carbon (Blue) and Renewable (Green) Hydrogen



Source: Hydrogen Council, February 2021

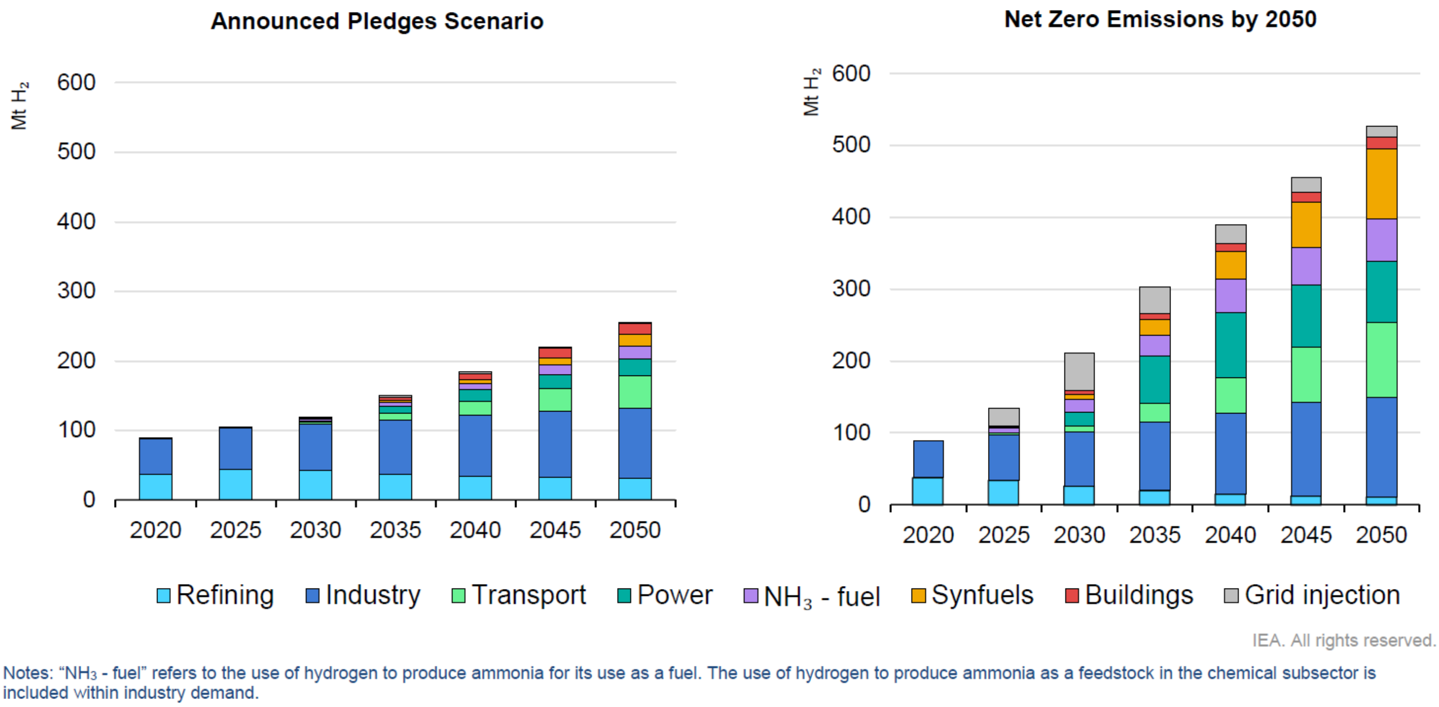
IEA: Low Carbon Hydrogen Needed for Net Zero

IEA has developed a Net Zero Scenario (NZS) to lay out in detail what is needed from the energy sector to reach net zero CO2 emissions by 2050 in line with the Paris Agreement targets. Based on these findings, IEA then compared actual implemented actions with clean energy transition needs using the NZS and an Announced Pledges Scenario (APS). The APS considers all national net zero emissions pledges that governments have announced to date and assumes they are realized in full and on time. This scenario shows how far full implementation of national net zero emissions pledges would take the world toward reaching climate goals,

[5] Hydrogen Council, Hydrogen Insights: A Perspective on Hydrogen Investment, Market Development and Cost Competitiveness, February 2021 at https://hydrogencouncil.com/en/hydrogen-insights-2021/ (hereinafter "Hydrogen Council: Insights").

and it highlights the potential contributions of different technologies. The projections for hydrogen are shown in Figure 4. Over time, beginning in 2035, hydrogen in the NZS would grow precipitously in industry, transport, power generation and for synfuels.[6]

Figure 4: Hydrogen Demand by Sector in the Announced Pledges and Net Zero Emissions Scenarios, 2020-2050



In the NZS, IEA found that hydrogen demand multiplies almost sixfold to reach 530 MT by 2050, with half of this demand in industry and transport. Industry demand nearly triples from around 50 MT in 2020 to around 140 MT in 2050. Transport demand soars from less than 20 kilotons (KT) to more than 100 MT in 2050. According to IEA, power sector penetration also increases significantly as hydrogen's use in gas-fired power plants and stationary fuel cells helps to balance increasing generation from variable renewables; integrate larger shares of solar PV and wind; and provide seasonal energy storage. Hydrogen use in buildings also increases.

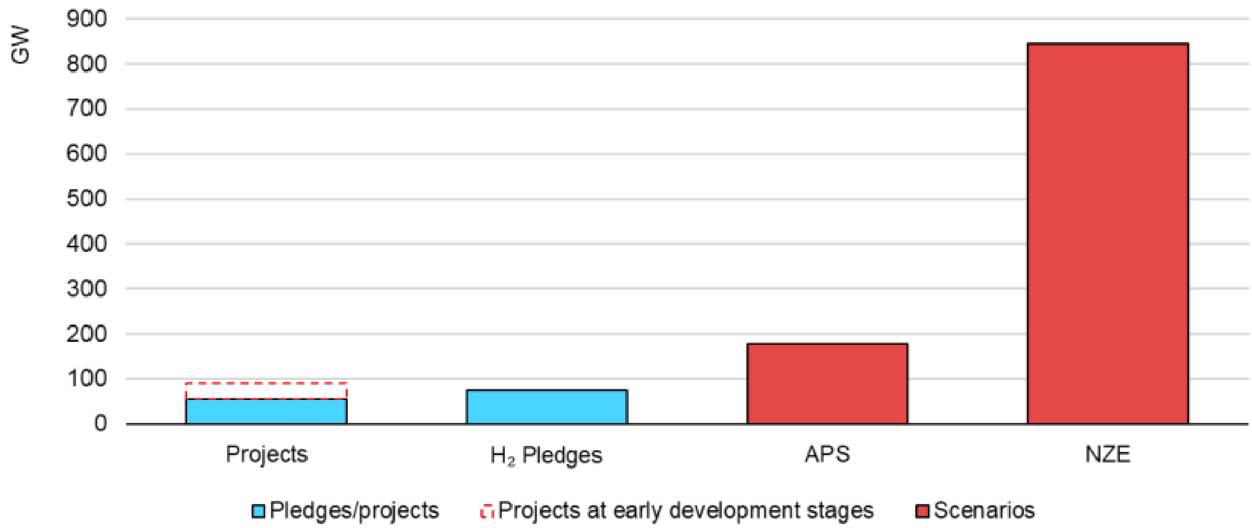
By 2050, IEA notes that around one-third of hydrogen demand in the NZS is used to produce hydrogen-based fuels such as ammonia, synthetic kerosene and synthetic methane. Ammonia use expands beyond existing applications (primarily nitrogen fertilizers) to be adopted for use as a fuel, particularly in shipping and for co-firing in some former coal plants. IEA also assumes that synthetic fuels will meet one-third of global aviation fuel demand while synthetic methane meets around 10% of demand for grid gas use in buildings, industry and transport by 2050. IEA also assumes that refining is the only application for which hydrogen demand decreases in the NZS: From close to 40 MT in 2020 to 10 MT in 2050 because the need to refine oil drops as clean fuels

[6] International Energy Agency, Global Hydrogen Review at https://www.iea.org/reports/global-hydrogen-review-2021.

and technologies replace it. Overall, IEA projects hydrogen and hydrogen-based fuels meet 10% of global final energy demand in 2050.

What about supply? Most supply is expected from green and blue hydrogen, of course. By 2030, global installed electrolyzer capacity for green hydrogen could climb to 54 GW, given capacity under construction and planned. If all projects at the very early planning stages are counted, capacity could even reach 91 GW by 2030, under IEA's projections. So far, only 4 GW (7%) are linked to projects under construction or with a final investment decision, leaving 50 GW still at various earlier stages of development. In the APS, global installed electrolyzer capacity increases to 180 GW by 2030, twice as much as national targets and three times the projects under construction and planned, and still 70% higher when including in the projects case also projects at earlier development stages. In the NZS, capacity requirements in 2030 are 850 GW, nine times the project pipeline when including projects at early development stages.

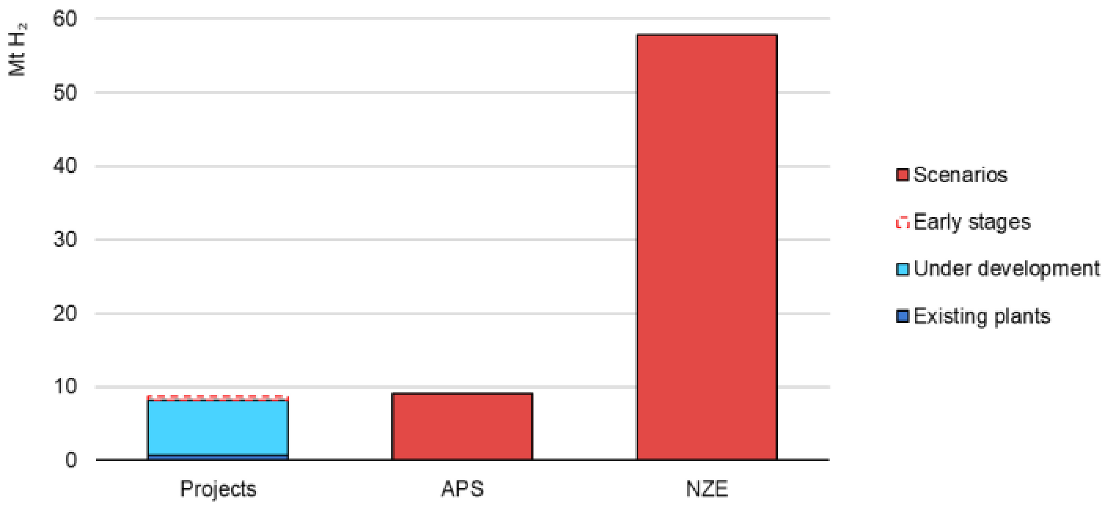
Figure 5: Electrolysis Capacity in APS and NZS (NZE) in 2030 Compared to Current Projects and Government Deployment Pledges



Source: IEA, 2021

For blue hydrogen, 40 projects for producing hydrogen with carbon capture utilization and storage (CCUS) are under development, with a total of four currently under construction in China and the U.S. (see report Nov. 2, 2021). Of these, 35 rely on natural gas with CCUS, four are linked to coal and one to oil. Geographically, Europe has 19 projects (largely in the Netherlands and the United Kingdom), while North America hosts seven and China has two. Based on planned projects and existing plants, global blue hydrogen could reach 9 MT by 2030, which aligns to IEA's APS. In IEA's NZS, demand jumps to 58 MT which is seven times the current project pipeline. This implies that by 2030, 230 hydrogen plants with capacity of 1 GW will need to be newly built or retrofitted with CCUS, according to IEA. Figure 6 summarizes IEA's projections.

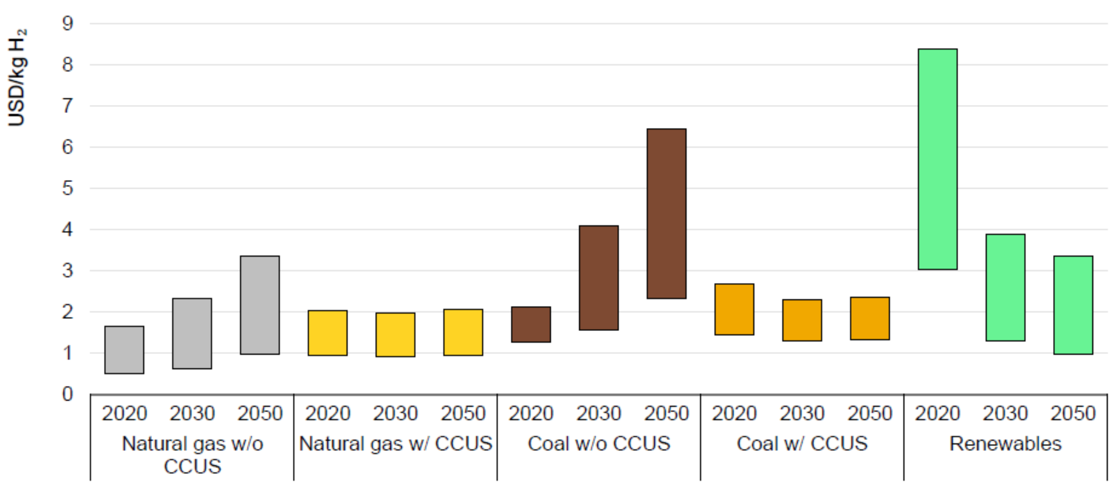
Figure 6: Fossil Fuel with CCUS in APS and NZS (NZE) in 2030 Compared to Current Projects and Government Deployment Pledges



Source: IEA, 2021

What about costs? Depending on regional gas prices, the levelized cost of hydrogen produced from natural gas is in the range of USD 0.50-1.70/kg. Renewable hydrogen is much more expensive, at USD 3.00-8.00/kg. As renewable electricity and electrolyzer costs fall, so will green hydrogen, IEA notes. Prices could come down further with a carbon price of over USD 100. Figure 7 compares the levelized cost of hydrogen production by technology in 2020, versus the NZS in 2030 and 2050. Notice that the 2030 green hydrogen (renewables) number for 2030 is above the break-even projected by the Hydrogen Council (that was USD 2.5/kg).

Figure 7: Levelized Cost of Hydrogen Production by Technology in 2020, and in the Net Zero Emissions Scenario, 2030 and 2050

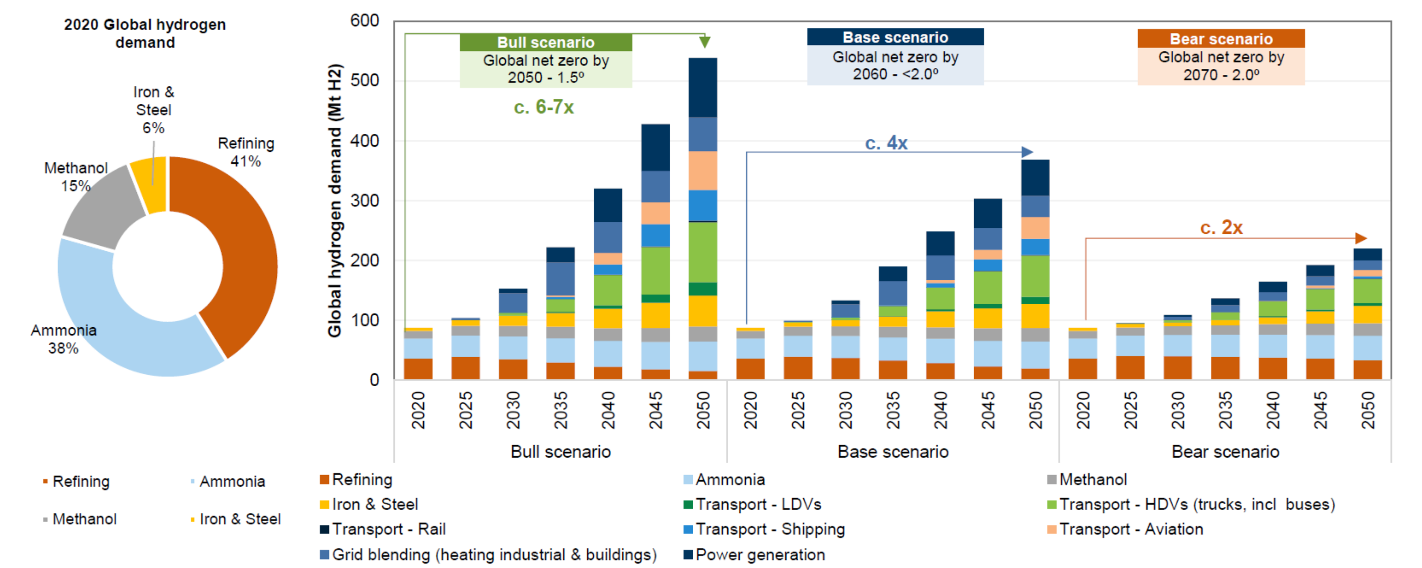


Goldman Sachs: Bullish on Blue and Green Hydrogen

Using its own net-zero model, Goldman Sachs recently devised three hydrogen scenarios based on 1.5 degree Celsius global warming, one with well below 2°C, and one on 2°C (bull, base and bear scenarios) (see also post Mar. 14, 2022). The findings, summarized in Figure 8, suggest that under all three scenarios global hydrogen demand increases at least two-fold on the path to net-zero, from two-fold in the bear scenario to seven-fold in the bull scenario.

Figure 8: Goldman Sachs Hydrogen Demand Scenarios

Global hydrogen demand for the three scenarios, split by industry (Mt H2)

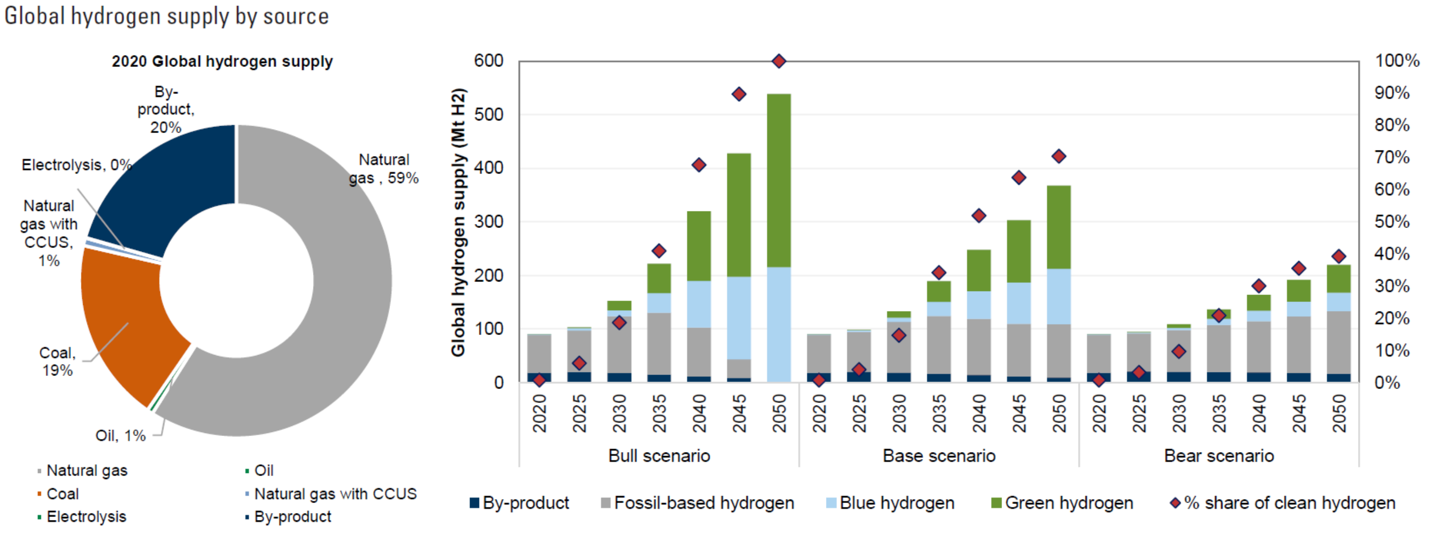


Source: Goldman Sachs Global Investment Research

In Goldman Sachs' scenarios, blue and green hydrogen take off (naturally) under its bull scenario, grow more modestly under the base scenario and grow much more slowly in its bear scenario. The bank notes: "Our global GS hydrogen scenarios all show stellar growth of the clean hydrogen economy. We assume that both blue and green hydrogen play a critical role in each of these paths and assume a long-term split between the two technologies of 40% and 60%, respectively."[7] This is shown in Figure 9.

[7] Carbonomics at 44.

Figure 9: Global Hydrogen Supply by Source and Goldman Sachs Scenarios by Hydrogen Type



Source: IEA (2020), Goldman Sachs Global Investment Research

The figure below breaks this demand out further by key addressable markets and compares to other key competing decarbonization technologies such as bioenergy (biofuels), electrification and carbon capture. With respect to the bull scenario, the findings are similar to IEA's NZS: major growth in road transport, power generation, shipping and aviation. Refining usage declines, but not as dramatically as in IEA's scenario.

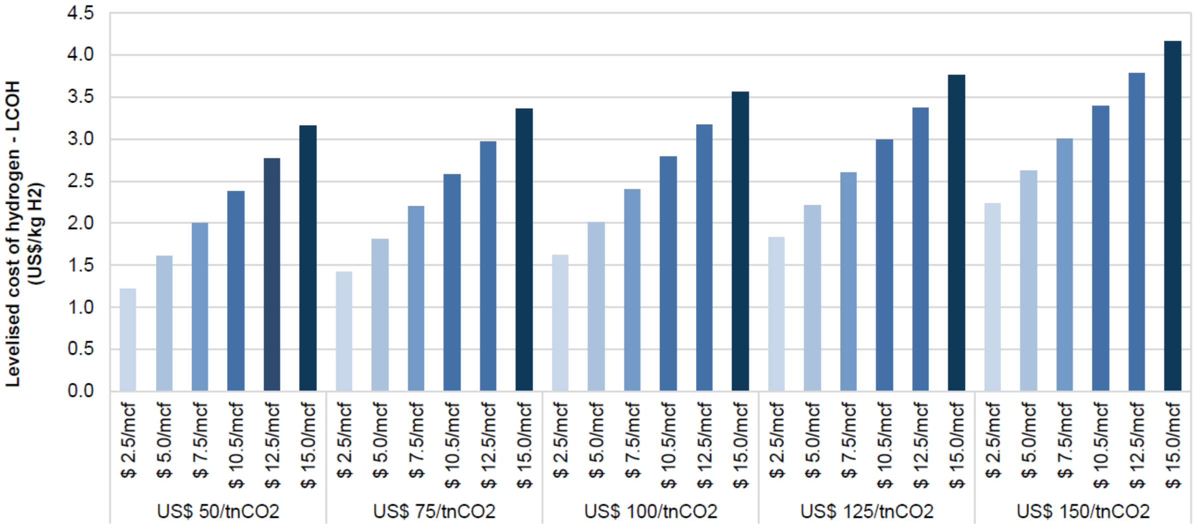
Figure 10: Addressable Markets

		Key competing de-carbonization technologies			Potential role for hydrogen	GS global hydrogen demand models – Hydrogen potential demand in 2050		
End-use market	**% of global CO2 emissions (direct, 2019)**	**Bioenergy**	**Electrification (renewable power & storage)**	**Carbon Capture**	**Hydrogen stage of development**	**GS Bull case**	**GS Base case**	**GS Bear case**
Refining	1.3 GtCO2, c. 3%	●	◐	◐	●	15 MtH2	19 MtH2	33 MtH2
Primary chemicals	0.9 GtCO2, c. 3%	◐	◐	◕	◕	74 MtH2	68 MtH2	62 MtH2
Iron & Steel	2.6 GtCO2, c. 7%	○	◐	◐	◐	52 MtH2	40 MtH2	29 MtH2
Road transport Light-duty vehicles *(LDVs)*	3.9 GtCO2, c. 10%	●	●	○	◕	22 MtH2	12 MtH2	5 MtH2
Road transport Heavy-duty vehicles *(HDVs, incl. trucks and buses)*	2.3 GtCO2, c. 6%	●	◕	○	◕	100 MtH2	68 MtH2	40 MtH2
Rail	0.2 GtCO2, <1%	◕	●	○	◕	3 MtH2	2 MtH2	1 MtH2
Shipping	0.9 GtCO2, c.2%	◕	◔	○	◔	52 MtH2	27 MtH2	4 MtH2
Aviation	1.0 GtCO2, c.3%	◕	◔	○	◔	64 MtH2	36 MtH2	10 MtH2
Power generation	13.8 GtCO2, c.36%	●	●	◕	◐	100 MtH2	60 MtH2	20 MtH2
Buildings *(incl. space and water heating)*	3.5 GtCO2, c.9%	●	●	○	◐	56 MtH2	35 MtH2	16 MtH2

Source: Goldman Sachs Global Investment Research

What about the economics? For blue hydrogen, Goldman notes that the two key variables determining the levelized cost of blue hydrogen are the price of natural gas and CCUS (including capex and opex). The bank notes that both of these parameters vary significantly between regions globally, including the ability and cost to store the captured CO2 (with onshore storage being more cost competitive than offshore storage, with regions with vast amounts of storage potential in depleted oil and gas fields screening better than others in that aspect). In Figure 11, Goldman presents the sensitivity of the levelized cost of hydrogen to the natural gas price and CCUS cost.

Figure 11: Sensitivity Analysis for the Cost of Production of Blue Hydrogen Under Different Natural Gas Prices and Carbon Capture Cost Assumptions



Source: Goldman Sachs, March 2022

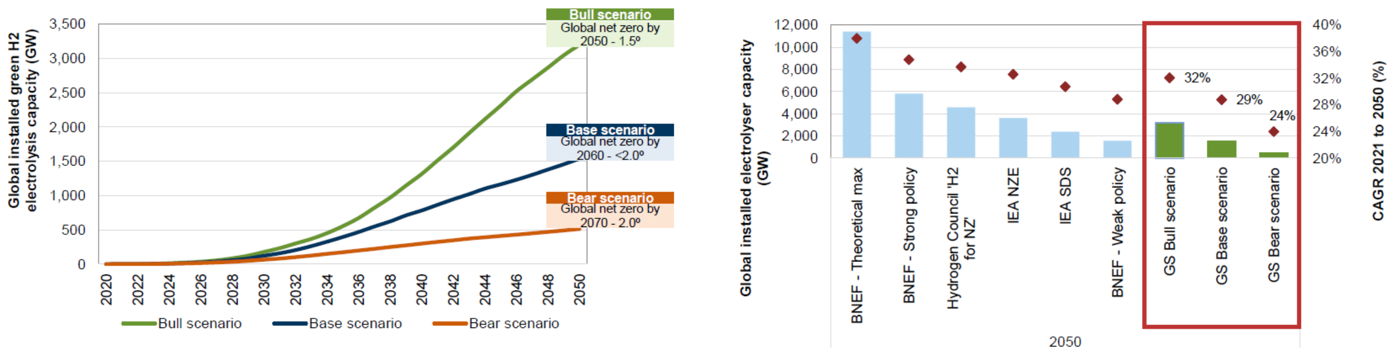
What about green hydrogen? Goldman notes, "Overall, we estimate that between 65 and 180 GW of electrolyzer capacity will need to be installed by 2030 and 500-3,200 GW by 2050 under the three scenarios. This represents a stellar 200-570-fold increase to 2030, given the very low starting base of around 0.3-1.0 GW(2021), and a 20%-30% CAGR to 2050 depending on the scenario considered."[8] With the industry likely to experience substantial growth, the bank projects that the cost of these electrolyzer units (in US$/kW) has the potential to decrease by 50%-65% by 2030 for alkaline and PEM electrolysis systems, respectively. Longer term, the cost of alkaline and PEM electrolyzers is likely to converge to around US$300-400/kW (2030E), with PEM enjoying a higher learning rate compared to alkaline given its higher starting point and earlier stage of development. This analysis is shown in Figure 12. Goldman Sach's bull scenario aligns with IEA's NZS, and both are slightly lower than the Hydrogen Council's projections.

[8] Carbonomics at 44.

Figure 12: Electrolyzer Capacity

Global installed electrolyzer capacity based on our GS global hydrogen demand models (GW)

Global installed electrolyzer capacity under various scenarios and vs GS global hydrogen models (GW)



Source: Goldman Sachs Global Investment Research

Source: BNEF, Hydrogen Council, IEA, Goldman Sachs Global Investment Research

Conclusion

All three analyses' hinge on two major developments happening. One concerns technological development and readiness which will bring down cost curves. That has already been happening and will continue to happen for both blue and green hydrogen, as CCUS becomes more mainstream and scaled and as more electrolyzers are put into production over this decade and into the next. It is an oversimplification, but I have been told by a number of contacts and colleagues involved in the green hydrogen industry that more electrolyzers equals lower costs or faster cost declines.

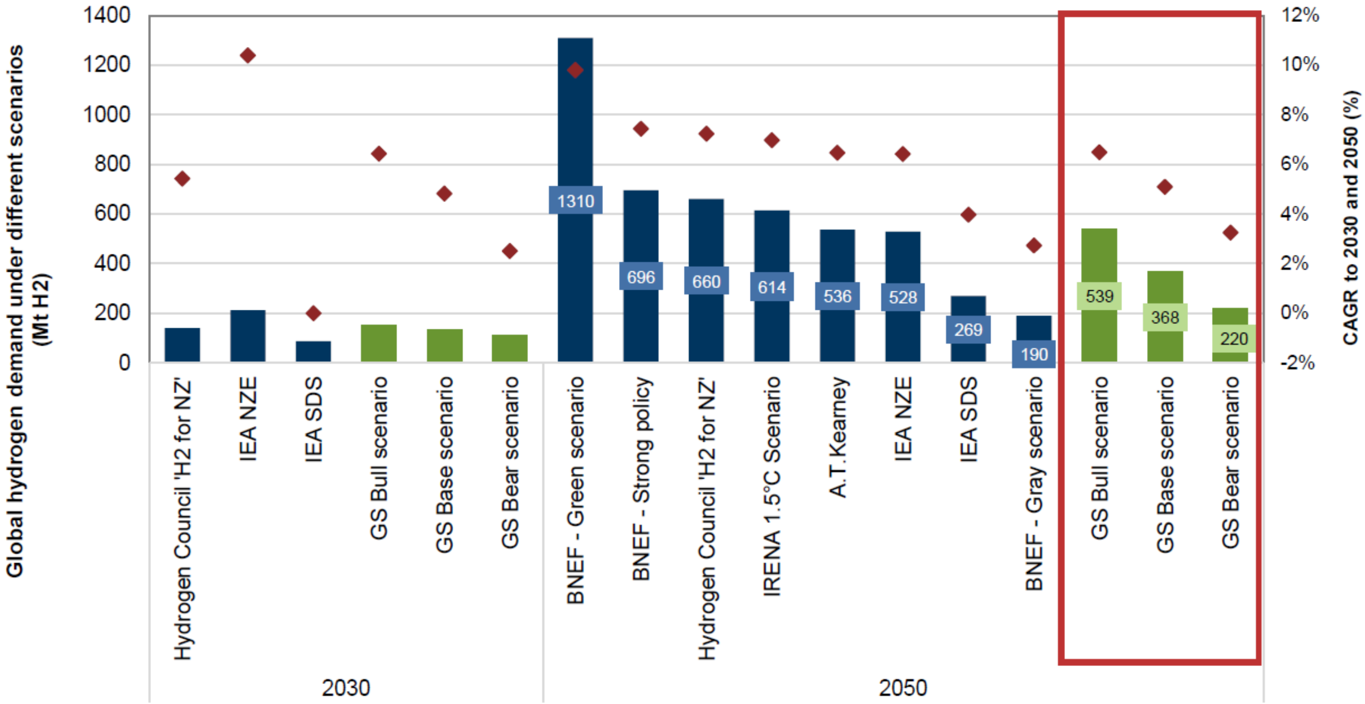
The second major development relates to the cost of carbon. All three analyses depend on a higher price on carbon above USD 100/ton. Goldman Sachs notes:

> *"Given the broad range of end uses and potential markets for hydrogen, the scenarios reflect a broad range of estimates, with the key difference primarily stemming from different hydrogen penetration rates assumed across these markets. We believe the two key factors that ultimately influence the penetration of hydrogen in these industries are (a)the level of policy support and (b) the cost associated with hydrogen adoption compared to alternative technologies in each of these industries…In our GS global hydrogen demand models, the pace and ultimate penetration of clean hydrogen technologies in each industry is correlated to the carbon abatement cost and technological readiness of these technologies on our Carbonomics cost curve."*

As noted in the last month's report, with very few exceptions (e.g., Sweden, the UK and Liechtenstein), the carbon prices a handful of countries have set do not come close to what is needed (over USD 100/ton) to really generate cost curve reduction that reflects the more progressive projections presented in the three analyses. I doubt, given our current environment with inflation, fuel shortages and global instability (including the war in Ukraine) this will change, at least in the next few years. Major emitters such as the U.S., China and India are missing entirely.

We may see more of the base or bear scenarios (in the case of the Goldman projections). Demand scenarios are compared in Figure 13.

Figure 13: Comparison of Hydrogen Demand Scenarios



Source: BNEF, IEA, Hydrogen Council, AT Kearney, Goldman Sachs Global Investment Research