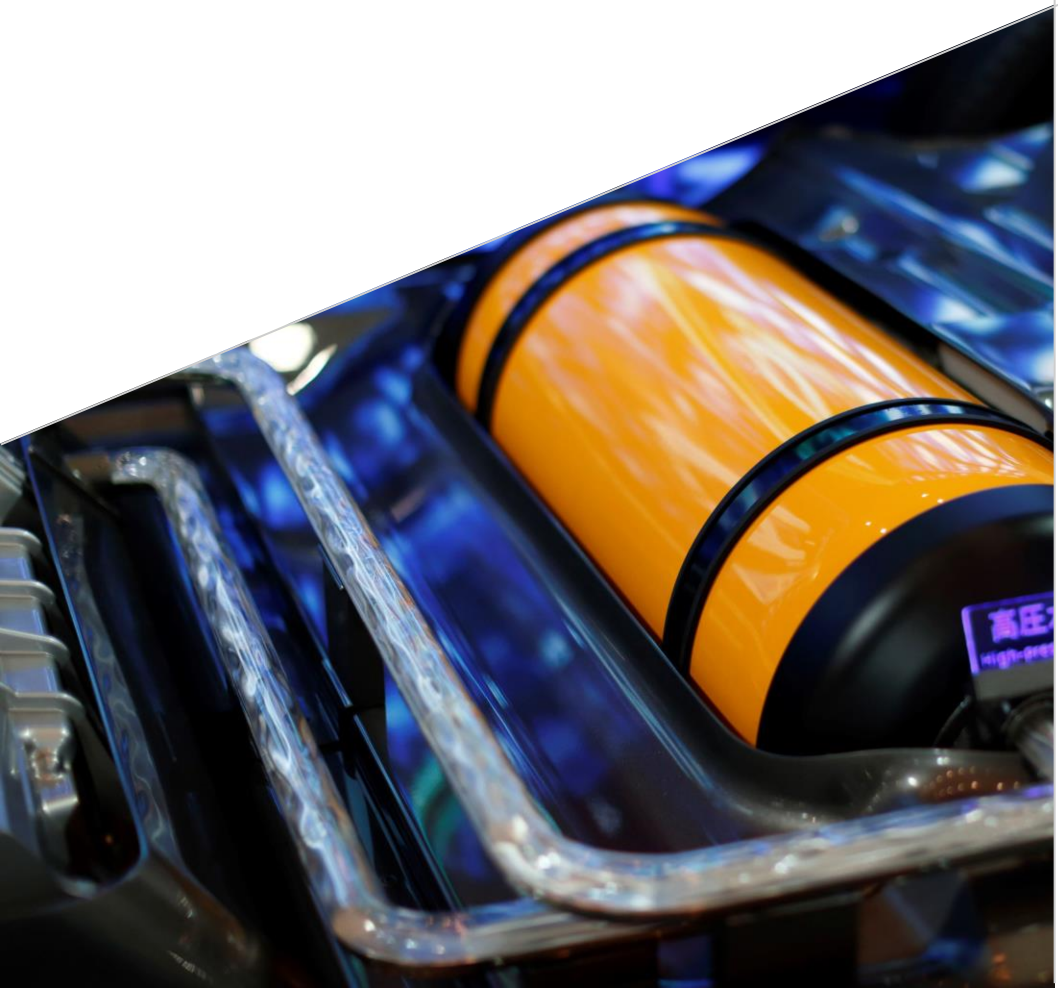
Hydrogen Economy Outlook

Key messages

March 30, 2020



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On April 23, BNEF made two changes to this report. This version corrects a rounding error in the cost range of renewable hydrogen displayed on page 2 and updates Figure 12 to exclude some countries.

Key messages

Hydrogen is a clean-burning molecule that could become a zero-carbon substitute for fossil fuels in hard-to-abate sectors of the economy. The cost of producing hydrogen from renewables is primed to fall, but demand needs to be created to drive down costs, and a wide range of delivery infrastructure needs to be built. That won't happen without new government targets and subsidies. These are the key messages of BNEF's *Hydrogen Economy Outlook*, which provides a global, independent analysis and outlook for a hydrogen economy.

A full copy of the Hydrogen Economy Outlook is available for BNEF clients **(web | terminal)**. It draws together analysis and key findings from 12 studies published in 2019 and 2020 from BNEF's Hydrogen Special Project. The full suite of BNEF research on hydrogen is also available for clients on the **hydrogen theme page (web | terminal)**.

Figure 1: Summary of the economics of a hydrogen economy

Scaling-up hydrogen

Requires **$150 billion** of cumulative subsidies to 2030

Which should drive the delivered cost of clean hydrogen down to **$15/MMBtu** in many parts of the world by 2030

Delivered costs could fall further to **$7.4/MMBtu** by 2050

Which would make clean hydrogen **competitive** with current natural gas prices in China, India, Brazil and Germany

Enables

Making green steel with a **$50/tCO2** price on coking coal

Clean dispatchable power with a **$32/tCO2** price on natural gas

Green ammonia with a **$78/tCO2** price on natural gas

Fuel cell powered trucks to compete by **2031-34** with diesel internal combustion engines

Abatement

Of up to **one-third** of global emissions from fossil fuels and industry

Reduction of up to 20% of global emissions for **under $100/tCO2** using hydrogen at $7.4MMBtu

However the signs of scale-up are **not yet there** as policy support is insufficient

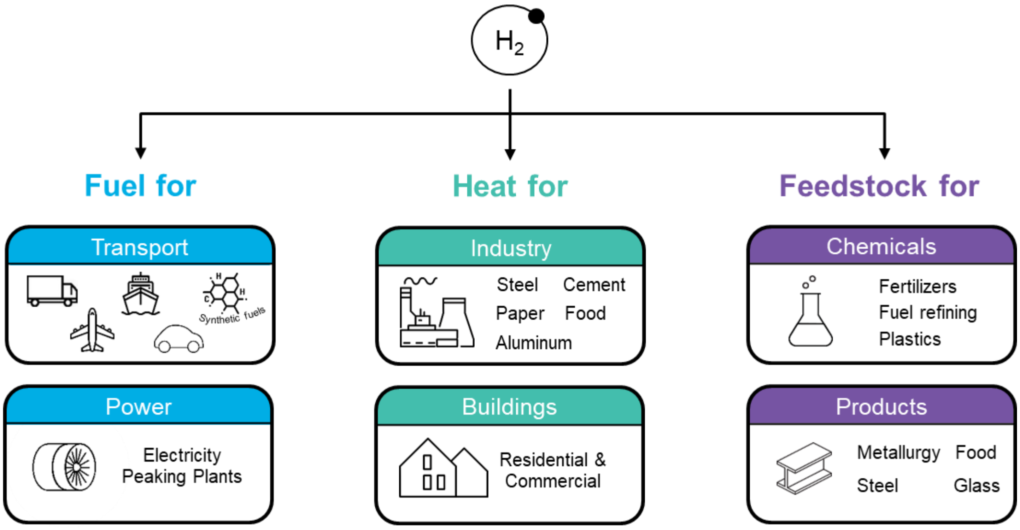
Investors should keep watch for **seven signposts** to determine whether a hydrogen economy is emerging

Source: BloombergNEF. Note: Clean hydrogen refers to both renewable and low-carbon hydrogen (from fossil-fuels with CCS). Abatement cost with hydrogen at $1/kg (7.5/MMBtu). Currency is US dollars.

Meeting climate targets is likely to require a clean molecule

Renewable electricity can help reduce emissions in road transport, low-temperature industrial processes and in heating buildings. However, fossil fuels have a significant advantage in applications that require high energy density, industrial processes that rely on carbon as a reactant, or where demand is seasonal. To fully decarbonize the world economy, it's likely a clean molecule will be needed and hydrogen is well placed to play this role (Figure 2). It is versatile, reactive, storable, transportable, clean burning, and can be produced with low or zero emissions.

Figure 2: The many uses of hydrogen

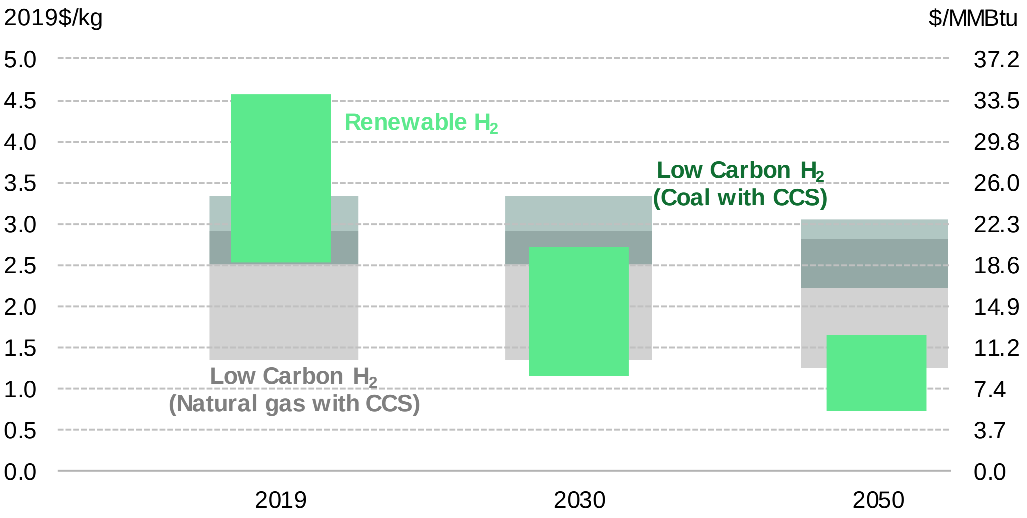


Source: BloombergNEF

Renewable hydrogen is currently expensive, but costs are coming down

In 2018, over 99% of hydrogen was made using fossil fuels, but hydrogen can also be produced cleanly using renewable electricity to split water in an electrolyzer. With the cost of wind and solar continuing to fall, the question is whether the cost for electrolyzers and renewable hydrogen can follow. While they are still expensive in Western markets, there are encouraging signs. The cost of alkaline electrolyzers made in North America and Europe fell 40% between 2014 and 2019, and Chinese made systems are already up to 80% cheaper than those made in the west. If electrolyzer manufacturing can scale up, and costs continue to fall, then our calculations suggest renewable hydrogen could be produced for $0.7 to $1.6/kg in most parts of the world before 2050. This is equivalent to gas priced at $6-12/MMBtu, making it competitive with current natural gas prices in Brazil, China, India, Germany and Scandinavia on an energy-equivalent basis, and cheaper than producing hydrogen from natural gas or coal with carbon capture and storage (Figure 3).

Figure 3: Forecast global range of levelized cost of hydrogen production from large projects



Source: BloombergNEF. Note renewable hydrogen costs based on large projects with optimistic projections for capex. Natural gas prices range from $1.1-10.3/MMBtu, coal from $30-116/t.

Transporting and storing hydrogen needs massive infrastructure investment

Hydrogen's low density makes it considerably harder to store than fossil fuels. If hydrogen were to replace natural gas in the global economy today, 3-4 times more storage infrastructure would need to be built, at a cost of $637 billion by 2050 to provide the same level of energy security. Storing hydrogen in large quantities will be one of the most significant challenges for a future hydrogen economy. Low cost, large-scale options like salt caverns are geographically limited, and the cost of using alternative liquid storage technologies is often greater than the cost of producing hydrogen in the first place (Table 1).

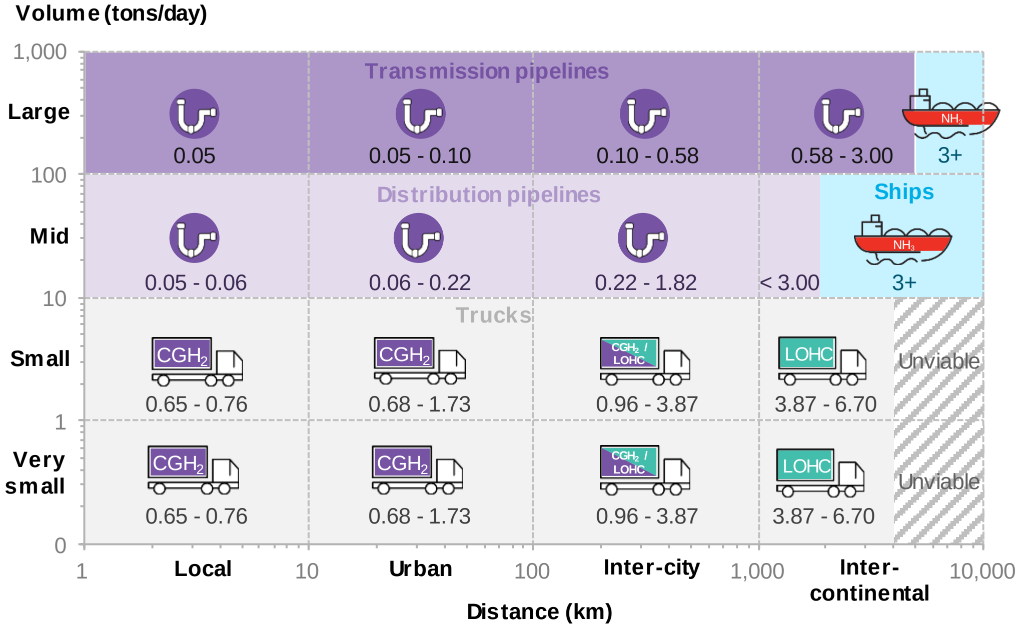
Table 1: Hydrogen storage options

	Gaseous state				Liquid state			Solid state
	Salt caverns	Depleted gas fields	Rock caverns	Pressurized containers	Liquid hydrogen	Ammonia	LOHCs	Metal hydrides
Main usage (volume and cycling)	Large volumes, months-weeks	Large volumes, seasonal	Medium volumes, months-weeks	Small volumes, daily	Small - medium volumes, days-weeks	Large volumes, months-weeks	Large volumes, months-weeks	Small volumes, days-weeks
Benchmark LCOS ($/kg)[1]	$0.23	$1.90	$0.71	$0.19	$4.57	$2.83	$4.50	Not evaluated
Possible future LCOS[1]	$0.11	$1.07	$0.23	$0.17	$0.95	$0.87	$1.86	Not evaluated
Geographical availability	Limited	Limited	Limited	Not limited	Not limited	Not limited	Not limited	Not limited

Source: BloombergNEF. Note: [1] Benchmark levelized cost of storage (LCOS) at the highest reasonable cycling rate (see detailed research for details). LOHC – liquid organic hydrogen carrier.

Low density also makes hydrogen expensive to transport via road or ship. However, hydrogen flows nearly three times faster than methane through pipes, making this a cost-effective option for large-scale transport (Figure 4). But for hydrogen to become as ubiquitous as natural gas, a huge, coordinated program of infrastructure upgrades and construction would be needed, as hydrogen is often incompatible with existing pipes and systems.

Figure 4: H_2 transport costs based on distance and volume, $/kg, 2019



Legend: Compressed H_2 Liquid H_2 Ammonia Liquid Organic Hydrogen Carriers

Source: BloombergNEF. Note: figures include the cost of movement, compression and associated storage (20% assumed for pipelines in a salt cavern). Ammonia assumed unsuitable at small scale due to its toxicity. While LOHC is cheaper than LH_2 for long distance trucking, it is less likely to be used than the more commercially developed LH_2.

A scaled-up industry could deliver hydrogen for a benchmark cost of $2/kg in 2030 and $1/kg in 2050 in many parts of the world

Hydrogen is likely to be most competitive in large-scale local supply chains. Clusters of industrial customers could be supplied by dedicated pipeline networks containing a portfolio of wind- and solar-powered electrolyzers, and a large-scale geological storage facility to smooth and buffer supply. Our analysis suggests that a delivered cost of green hydrogen of around $2/kg ($15/MMBtu) in 2030 and $1/kg ($7.4/MMBtu) in 2050 in China, India and Western Europe is achievable. Costs could be 20-25% lower in countries with the best renewable and hydrogen storage resources, such as the U.S., Brazil, Australia, Scandinavia and the Middle East. However, cost would be up to 50-70% higher in places like Japan and Korea that have weaker renewable resources and unfavorable geology for storage (Figure 5 and Figure 6).

Figure 5: Estimated delivered hydrogen costs to large-scale industrial users, 2030

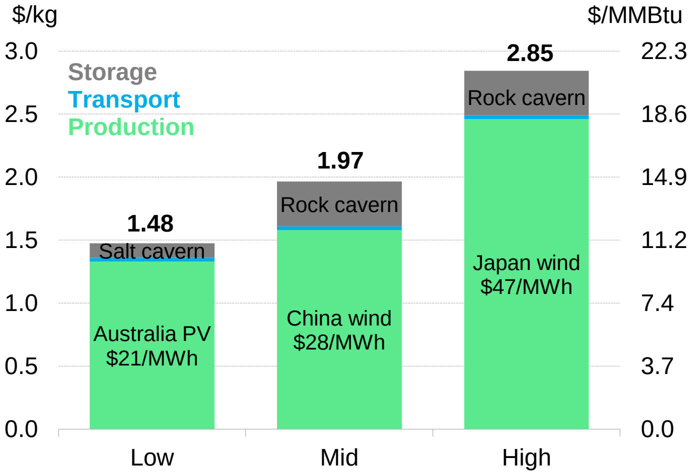
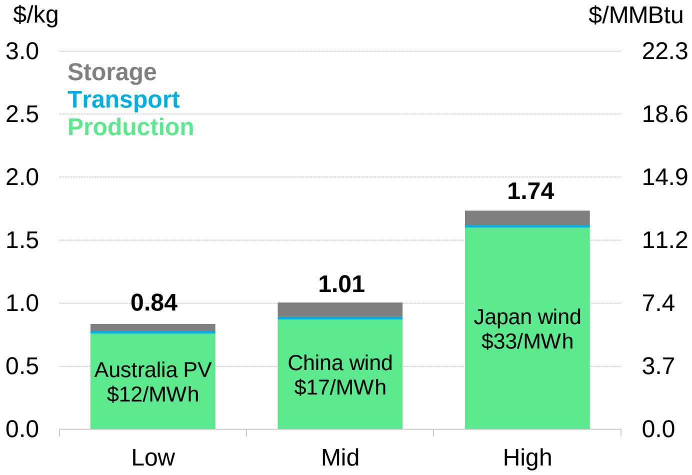


Figure 6: Estimated delivered hydrogen costs to large industrial users, 2050



Source: BloombergNEF. Note: Power costs depicted are the LCOE used for electrolysis, and are lower than the BNEF's standard LCOE projections in 2050 due to savings from integrated design of the electrolyzer and generator, and anticipated additional learning from increased renewable deployment for hydrogen production. Production costs are based on a large-scale alkaline electrolyzer with capex of $135/kW in 2030 and $98/kW in 2050. Storage costs assume 50% of total hydrogen demand passes through storage. Transport costs are for a 50km transmission pipeline movement. Compression and conversion costs are included in storage. Low estimate assumes a salt cavern, mid and high estimate a rock cavern for both 2030 and 2050.

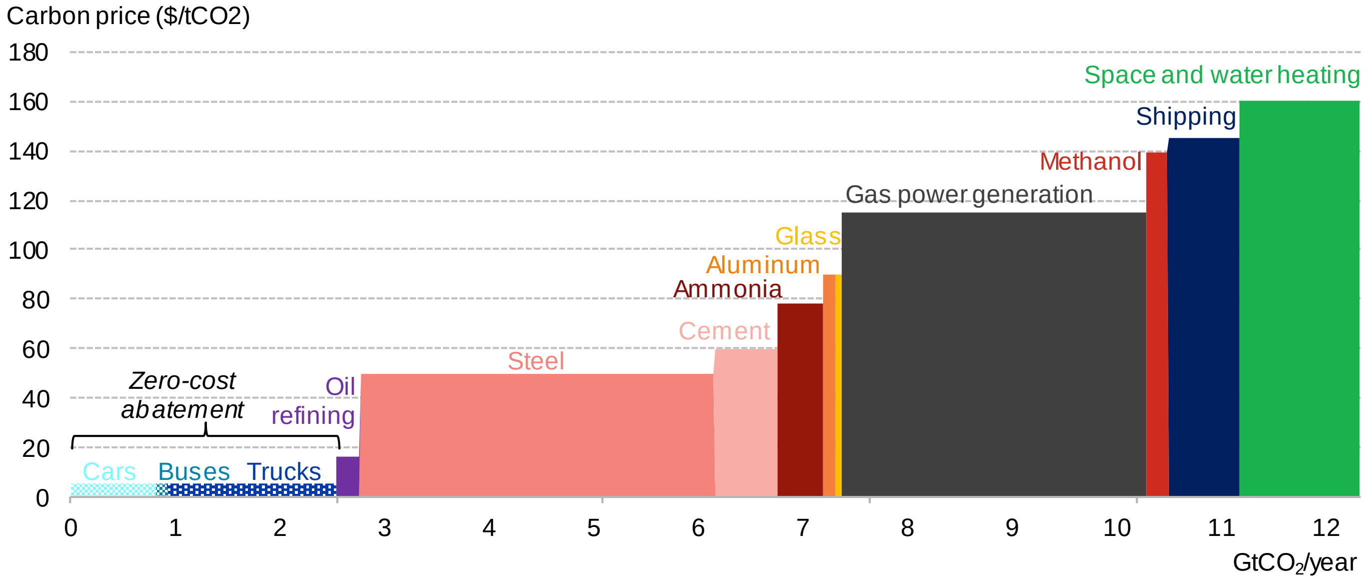
Policy is critical

Reaching a delivered hydrogen cost of $1/kg will require massive scale-up in demand as well as cost declines in transport and storage technologies. And while hydrogen is a hot topic right now, there is little government policy currently in place to help this happen. Policy measures are generally focused on expensive road transport applications, and programs are poorly funded. The more promising use cases in industry are only funded with one-off grants for demonstration projects. For the industry to scale up, demand needs to be supported with comprehensive policy coordinated across government, and the roll-out of around $150 billion of cumulative subsidies to 2030.

…and so is carbon pricing

Even at $1/kg, carbon prices or equivalent measures that place a value on emission reductions are still likely to be needed for hydrogen to compete with cheap fossil fuels in hard-to-abate sectors. This is because hydrogen must be manufactured, whereas natural gas, coal and oil need only to be extracted, so it is likely always to be a more expensive form of energy. Hydrogen's lower energy density also makes it more expensive to handle. But if the required policy is in place, up to 34% of greenhouse gas emissions from fossil fuels and industry could be abated using hydrogen – 20% for less than $100/tCO2 (Figure 7).

Figure 7: Marginal abatement cost curve from using $1/kg hydrogen for emission reductions, by sector in 2050



Source: BloombergNEF. Note: sectoral emissions based on 2018 figures, abatement costs for renewable hydrogen delivered at $1/kg to large users, $4/kg to road vehicles*. Aluminum emissions for alumina production and aluminum recycling only. Cement emissions for process heat only. Refinery emissions from hydrogen production only. Road transport and heating demand emissions are for the segment that is unlikely to be met by electrification only, assumed to be 50% of space and water heating, 25% of light-duty vehicles, 50% of medium-duty trucks, 30% of buses and 75% of heavy-duty trucks.*

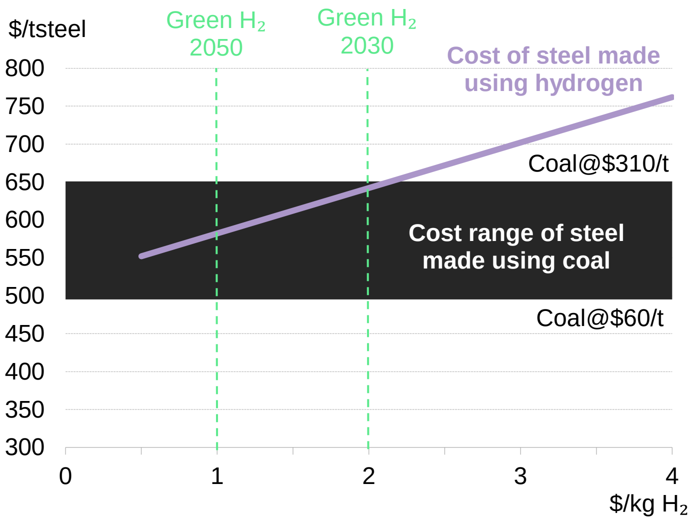
Hydrogen is a promising emissions reduction pathway for the hard-to-abate industry sectors

The strongest use cases for hydrogen are the manufacturing processes that require the physical and chemical properties of molecule fuels in order to work. Hydrogen can enable a switch away from fossil fuels in many of these applications at surprisingly low carbon prices. For example, at $1/kg, a carbon price of $50/tCO2 would be enough to switch to renewable hydrogen in steel making (Figure 8), $60/tCO2 to use renewable hydrogen for heat in cement production, $78/tCO2 for ammonia synthesis, and $90/tCO2 for aluminum and glass manufacturing.

But its role in transport should be focused on trucks and ships

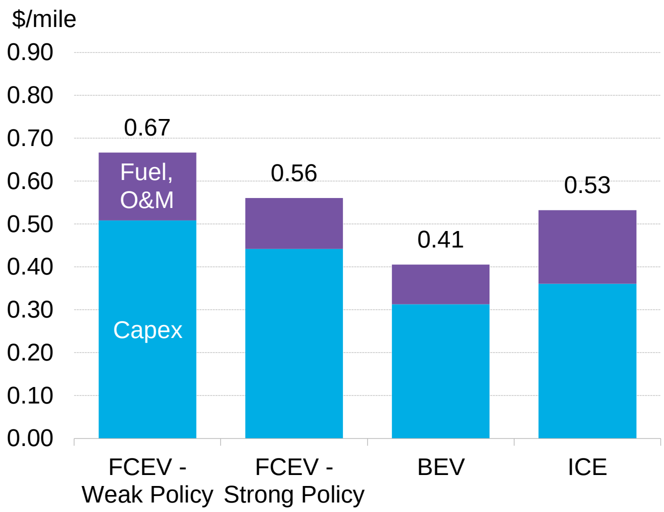
Hydrogen can play a valuable role decarbonizing long-haul, heavy-payload trucks. These could be cheaper to run using hydrogen fuel cells than diesel engines by 2031. But the bulk of the car, bus and light-truck market looks set to adopt battery electric drive trains, which are a cheaper solution than fuel cells (Figure 9). In our view, the fuel cell vehicle industry will also be the most expensive sector to scale up, requiring $105 billion in subsidies to 2030. For ships, green ammonia from hydrogen is a promising option, and could be competitive with heavy fuel oil with a carbon price of $145/tCO2 in 2050.

Figure 8: Levelized cost of steel: hydrogen versus coal



Source: BloombergNEF. Note: levelized costs do not include carbon prices.

Figure 9: Total cost of ownership of SUVs in the U.S., 2030

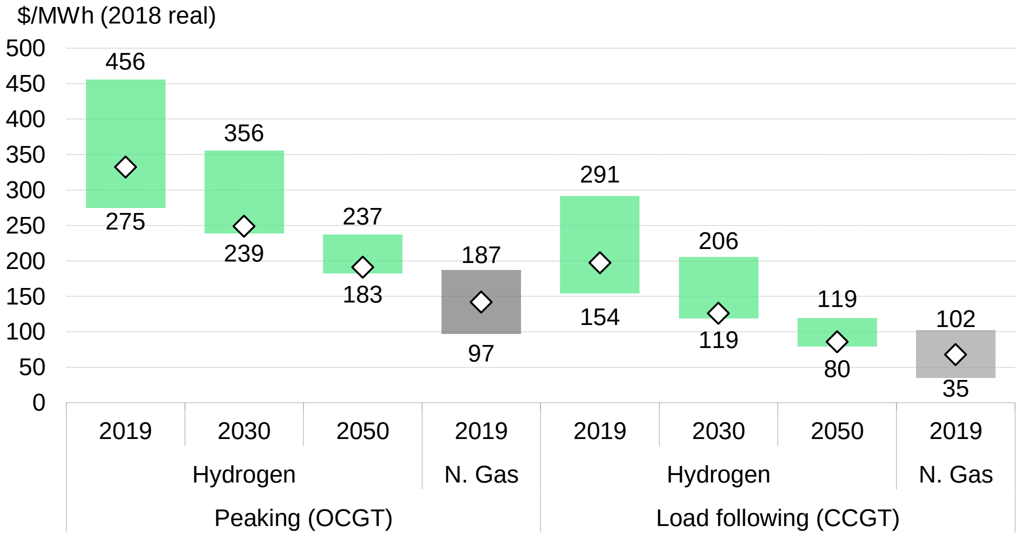


Source: BloombergNEF. Note: FCEV – fuel cell electric vehicle, BEV – battery electric vehicle, ICE – internal combustion engine.

A hydrogen supply chain could deliver carbon-free dispatchable power

With large-scale geological storage in place, hydrogen could be produced from renewable power that would otherwise be curtailed, stored and transported back to a generator at a cost of $8-14/MMBtu by 2050 in most locations. If gas turbines are hydrogen-ready, a carbon price of $32/tCO2 would be enough to drive fuel switching from natural gas to hydrogen, and generate clean, dispatchable power at a competitive price (Figure 10). Producing hydrogen from excess renewable electricity would reduce waste and help to deliver a zero-emissions electricity system.

Figure 10: Levelized cost of electricity of hydrogen-fuelled turbine power plants

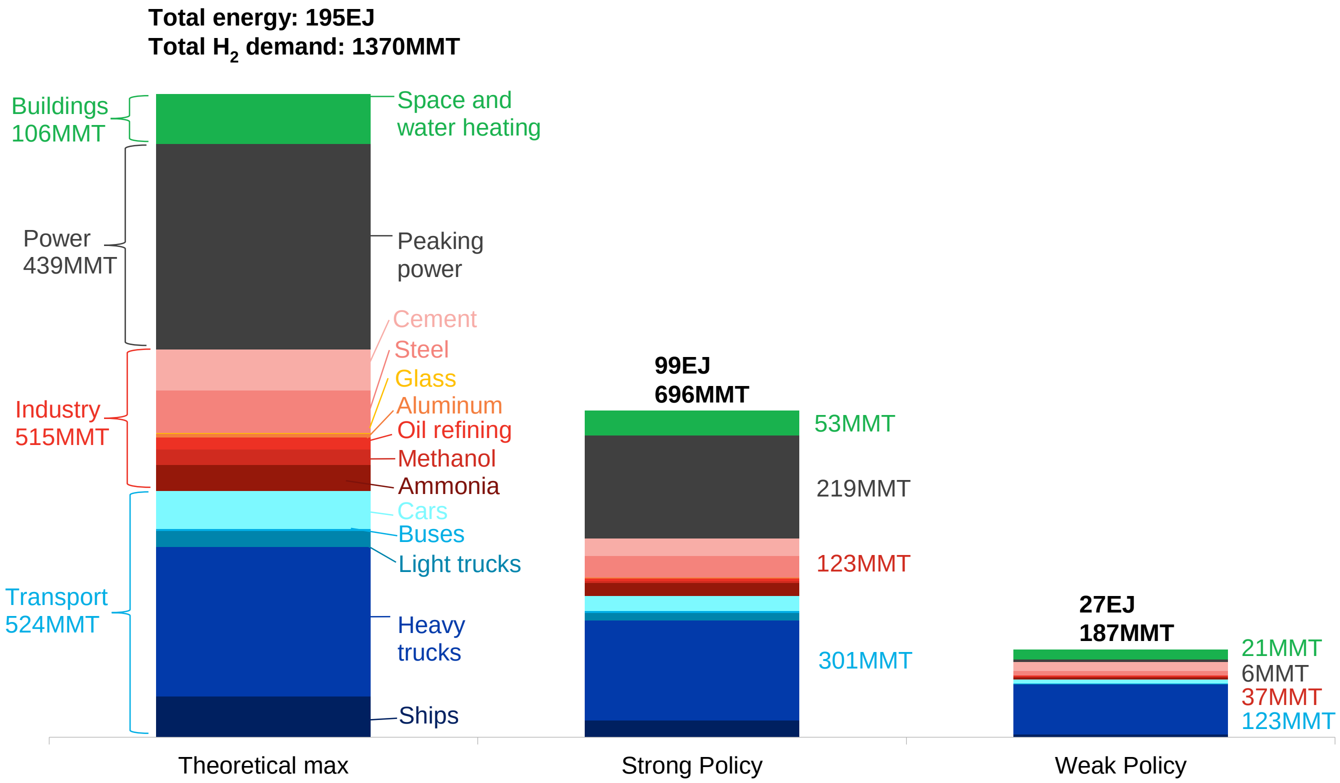


Source: BloombergNEF Note: 'N. Gas' is natural gas. Natural gas LCOEs vary with fuel price: $2 (low) to $7 (mid) and $12/MMBtu (high) and do not include a carbon price.

Hydrogen could meet up to 24% of the world's energy needs by 2050

If supportive but piecemeal policy is in place, we estimate that 187 million metric tons (MMT) of hydrogen could be in use by 2050, enough to meet 7% of projected final energy needs in a scenario where global warming is limited to 1.5 degrees. If strong and comprehensive policy is in force, 696MMT of hydrogen could be used, enough to meet 24% of final energy in a 1.5 degree scenario. This would require over $11 trillion of investment in production, storage and transport infrastructure. Annual sales of hydrogen would be $700 billion, with billions more also spent on end use equipment. If all the unlikely-to-electrify sectors in the economy used hydrogen, demand could be as high as 1,370MMT by 2050 (Figure 11).

Figure 11: Potential demand for hydrogen in different scenarios, 2050

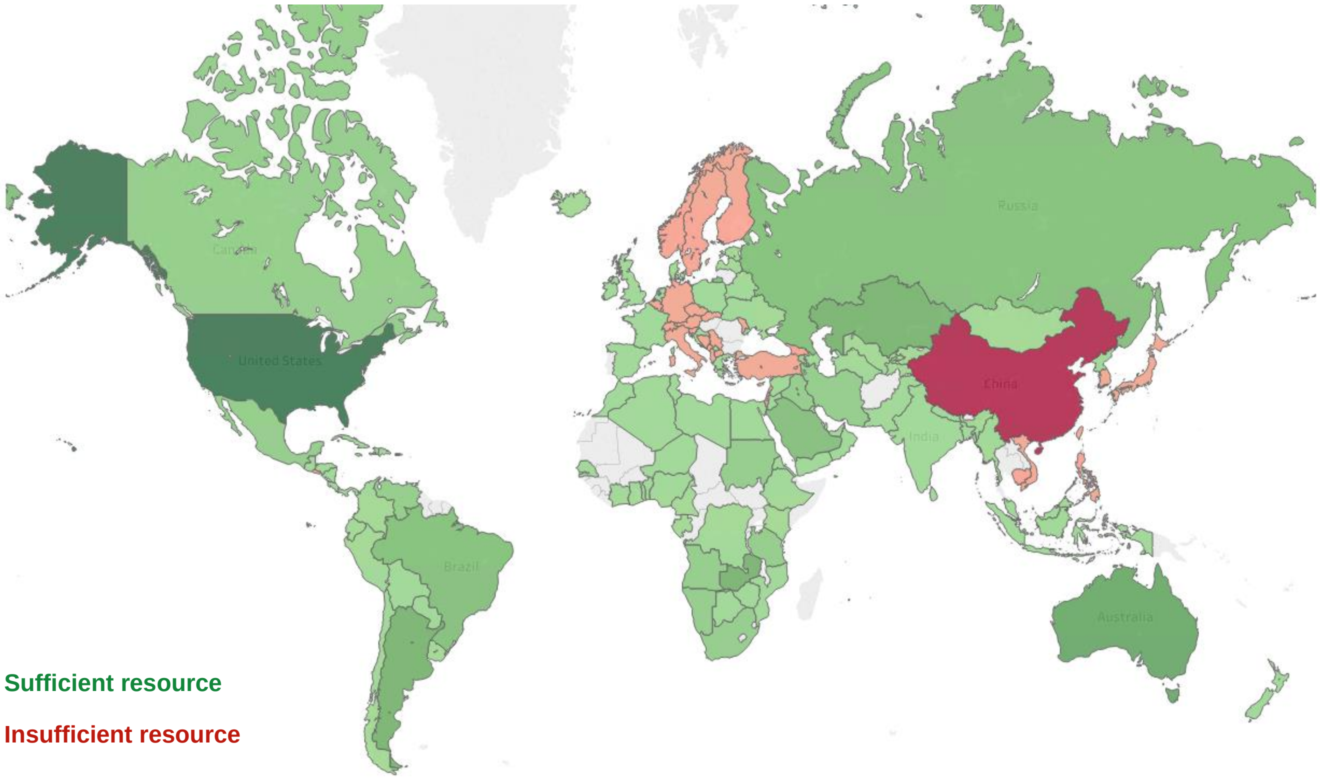


Source: BloombergNEF. Note: Aluminum demand is for alumina production and aluminum recycling only. Cement demand is for process heat only. Oil refining demand is for hydrogen use only. Road transport and heating demand that is unlikely to be met by electrification only: assumed to be 50% of space and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

Producing hydrogen at the scales required will, however, be challenging

Meeting 24% of energy demand with hydrogen in a 1.5 degree scenario will require massive amounts of additional renewable electricity generation. In this scenario, around 31,320TWh of electricity would be needed to power electrolyzers – more than is currently produced worldwide from all sources. Add to this the projected needs of the power sector – where renewables are also likely to expand massively if deep emission targets are to be met – and total renewable energy generation excluding hydro would need to top 60,000TWh, compared to under 3,000TWh today. China, much of Europe, Japan, Korea and South East Asia may not have enough suitable land to generate the renewable power required (Figure 12). As a result, trade in hydrogen would be necessary. Although more expensive, hydrogen production from fossil fuels with CCS may still need to play a significant role, particularly in countries like China and Germany that could be short on land for renewables but are well-endowed with gas and coal.

Figure 12: Indicative estimate of the ability for major countries to generate 50% of electricity and 100% of hydrogen from wind and PV in a 1.5 degree scenario



Source: BloombergNEF, Baruch-Mordo et. al, 2019. Note: ***Green*** *= Country has sufficient estimated solar and wind resources and* ***Red*** *= Country has insufficient resources to generate 50% of electricity and 100% of hydrogen by 2050. The methodology used to estimate potential renewable generation is conservative, and may underrepresent achievable generation in specific locations. In some countries the estimate for potential generation is below current levels. These countries are not given a sufficiency rating.*

The signs of scale-up are not yet there, but investors should keep watch for seven signposts

Hydrogen has experienced a hype cycle before, and right now, there is still insufficient policy to support investment and to scale up a clean hydrogen industry. But with a growing number of countries getting serious about decarbonization, this could change. Investors should watch out for the following key events to help determine whether a hydrogen economy is emerging: 1) net-zero climate targets are legislated, 2) standards governing hydrogen use are harmonized and regulatory barriers removed, 3) targets with investment mechanisms are introduced, 4) stringent heavy transport emission standards are set, 5) mandates and markets for low-emission products are formed, 6) industrial decarbonization policies and incentives are put in place and 7) hydrogen-ready equipment becomes commonplace (Table 2).

Table 2: Seven signposts of scale-up toward a hydrogen economy

Event	Effect
1) Net-zero climate targets are legislated	Makes it clear that the hard-to-abate sectors will need to decarbonize
2) Standards governing hydrogen use are harmonized and regulatory barriers removed	Clears or minimizes obstructions to hydrogen projects
3) Targets with investment mechanisms are introduced	Provides a revenue stream for producers, increases competition, builds capacity and experience, and gives equipment manufacturers confidence to invest in plant
4) Stringent heavy transport emissions standards are set	Provides an incentive for manufactures to produce, and users to buy, fuel cell trucks and ammonia-powered ships
5) Mandates and markets for low-emission products are formed	Provides an incentive for manufacturers to produce low-emission goods (e.g. steel, cement, fertilizers, plastics) that will often require the use of hydrogen
6) Industrial decarbonization policies and incentives are put in place	Helps to coordinate infrastructure investment and scale efficient use of hydrogen. Provides incentives for hydrogen use
7) Hydrogen-ready equipment becomes commonplace	Enables and reduces the cost of fuel switching to hydrogen

Source: BloombergNEF

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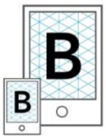

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