Carbon Tracker Initiative

October 2022

Clean Hydrogen's Place in the Energy Transition

Destined for dramatic growth if obstacles overcome

About Carbon Tracker

The Carbon Tracker Initiative is a team of financial specialists making climate risk real in today's capital markets. Our research to date on unburnable carbon and stranded assets has started a new debate on how to align the financial system in the transition to a low carbon economy.

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About the Author

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Kofi brings more than 10 years of experience in the renewable energy and climate change sector. Prior to joining Carbon Tracker in 2021, Kofi founded PVDATA, where he created bespoke technical, environmental, and financial software for the renewable energy sector. Additionally, he spent 2 years as an energy consultant developing renewable energy projects in Africa. Kofi worked for CDP (formerly Carbon Disclosure Project) at their investment research desk. He started his career working as a young professional at the Renewable Energy Department of a national oil corporation in Africa. He holds a PhD in Renewable Energy Investments from Imperial College London, where Tech Nation awarded him for his research innovation. Kofi also holds an MSc in Renewable Energy: Technology & Sustainability from the University of Reading, and a BSc in Biological Sciences from the University of Massachusetts, Amherst, USA.

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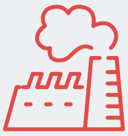
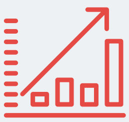
Key Findings



The war in Ukraine, yet another example of the high risk of dependency on fossil fuel supply chains, has driven the cost of fossil hydrogen (blue & grey) 70% above pre-war levels, now making these assets more expensive than non-fossil green hydrogen. The levelised cost of producing fossil hydrogen has now leapfrogged that of non-fossil green hydrogen in just under a few months amidst the Ukrainian-Russia war. This occurrence has accelerated investment commitments and capacity pledges to build out more green hydrogen assets on a global scale.

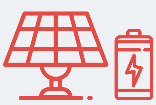
Fossil hydrogen assets, particularly in Europe and Asia, could be stranded before 2030. Carbon Tracker estimates that more than $100 billion worth of existing fossil hydrogen assets, particularly those exposed to Russian gas, could be stranded before 2030 due to supply insecurities, high gas prices, and the global north's commitment to reduce its natural gas usage in line with the IEA's and IPCC's net-zero scenarios.



Rapid capital investment for non-fossil green hydrogen over the next few years could see its levelised cost fall under $2/kg, making it one of the cheapest forms of energy. The outcome of the Ukrainian-Russia war has rapidly accelerated new investments and deployment of new non-fossil assets. With increasing learning rates, along with the right financial structure, future asset owners would be able to produce new non-fossil hydrogen at record costs lower than $2/kg before the end of 2030.

Technological inefficiencies along with green hydrogen's reliance on freshwater during its production process ought to be addressed. Technological innovations for green hydrogen electrolyser assets (Polymer electrolyte membrane (PEM) and Alkaline) are still in their novel phases, losing up to 35% of energy alone during their production phase. Additionally, current green hydrogen assets will require large volumes of freshwater annually to split hydrogen from water molecules. If not addressed, this can lead to future freshwater shortages.

Green hydrogen will play a key role in our energy transition, but its applications will have to focus on the incumbent agricultural sector (fertiliser production) in which it already serves and the hard-to-abate heavy industries until technological innovation for electrolysers improves and water concerns are addressed. The demand distribution of green hydrogen should follow a Carbon Tracker defined hydrogen pyramid of priority, whereby volumes are used predominantly for the agricultural sector and heavy industries (steel, heavy transport, shipping, mining) before then serving in the non-essential sectors.



Until renewable batteries become economically attractive, hydrogen can be used as a short-term measure to help solve power intermittency issues caused by renewable energy technologies, particularly wind and solar. This is only a short-term solution while the costs of batteries continue to fall. Carbon Tracker projects that by the early-to-mid 2030s, the global weighted average levelised cost of energy (LCOE) for renewables and batteries will be cheaper than the marginal cost for both gas and coal.

02

Executive Summary

For many decades fossil hydrogen has been an integral part of our energy society. From being an essential component for powering the first internal combustion engine more than 200 years ago, to becoming an essential part of the modern agricultural and oil refining industry. Fossil hydrogen, produced by splitting natural gas through a process called Steam Methane Reformation (SMR), is now experiencing a modern-day shift to a cleaner, non-fossil form, as we attempt to decarbonise our industries and reduce our dependency on fossil fuel products, mainly natural gas in this case.

Non-fossil green hydrogen today is growing in use as nations, particularly in the global north, have recognised its potential and are now developing policy and investment strategies to economically expand its production (~300% by 2030 from current 2022 levels[1]) and usage in certain high priority sectors like heavy industries, while innovation improves and environmental concerns in its production chain such as freshwater feedstock are addressed.

WAR IN UKRAINE HAS HIGHLIGHTED THE NEED FOR THE HYDROGEN INDUSTRY TO MOVE TO AN UNREGULATED NON-FOSSIL-BASED HYDROGEN SYSTEM

Russia's invasion of Ukraine is an example of how conflicts in our society can disrupt our entire fossil-based energy system — from the security of supply to rapid price escalations.

The war in Ukraine has re-emphasised the need for hydrogen asset owners and investors to shift to an unregulated non-fossil-based system, in this case, a green hydrogen system. In the space of a few months since the start of the war in February 2022, we have seen natural gas prices, a major feedstock for producing fossil hydrogen, skyrocket in price more than 70% from pre-war levels. The consequence of this on the global market will take many years to play out, even if the war ends sooner rather than later.

The effect of this price disruption has seen the levelised cost for blue and grey hydrogen assets skyrocket, leapfrogging that of green hydrogen. As a result, this makes green hydrogen a cheaper and more economically viable investment vehicle in most regional markets, particularly Europe and Asia.

Fears of spiking energy prices also sparked the global north, particularly those exposed to Russian gas, to increase their investment commitments in green hydrogen expansion, thus causing its global weighted average cost of production to commence a steady price fall, decades ahead of pre-war projections[2].

European fossil hydrogen asset owners, particularly those exposed to Russian gas supply, will see their cost of production rise roughly 50% ($7.6/kg) higher than their green technology counterparts.

In Asia today, new blue hydrogen would cost $6.4/kg, (35% higher than the base average green hydrogen cost), while grey hydrogen also leapfrogged roughly 29% above the base average green hydrogen costs.

1 This is according to the IEA's net zero expansion target for green hydrogen. The IEA, projects that the production volumes for green hydrogen is expected to grow rather rapidly by roughly 300% by 2030 from current 2022 levels.

2 Before the war in Ukraine, green hydrogen was calculated to fall at a steady price pace, competing in price with its fossil counterparts (Blue & grey) by the mid-2030s in most regional markets, and by late 2040 in the USA. After the war, thanks to rapid price hikes of natural gas, green hydrogen is already cheaper than fossil-based hydrogen in most regional markets.

Fossil hydrogen assets are not more expensive in the USA; however, they are now competitive in production cost with green hydrogen assets – 28 years ahead of pre-war calculations.

The price of green hydrogen today ranges between $3.8/kg to $5.8/kg, and the war has only acted as a catalyst to drive this cost further down in the near rather than distant future.

FOSSIL HYDROGEN ASSETS ARE AT RISK OF STRANDING

Existing fossil hydrogen assets, particularly those exposed to Russian gas, are at an immediate risk of stranding for several reasons:

1. Current assets are facing gas supply issues.
2. The global market has been plagued with record high gas prices making the cost of operating and running these assets the increase accordingly.
3. The global north is committed to reducing its gas demand over the next 30 years.
4. Gas expansion to support fossil hydrogen growth does not align with any net-zero scenario pathway.

Europe, particularly eastern and western Europe, along with Asia will be the most exposed to the risks of stranding, as large new fossil hydrogen capacity commitments (~8MT+) are expected to come online from 2022 onwards. With the state of the world now, and the global north's strong commitment to decarbonise and reduce its gas dependency, a large percentage of these new assets will not last 20 – 30 years (standard operational life cycle for fossil hydrogen assets), due to future shortages in gas demand.

As such, Carbon Tracker estimates that more than $100 billion worth of fossil hydrogen assets, particularly in Europe and Asia could be stranded before 2030.

SOARING NATURAL GAS PRICES HAS ACCELERATED NEW INVESTMENTS IN GREEN HYDROGEN

More investments and capacity pledges to scale up green hydrogen have resulted from the disruption of the gas and energy markets. The price of green hydrogen has steadily decreased over the past few months and this technology is gradually becoming more alluring to both public and private sector money. In response to the conflict between Ukraine and Russia, the world economy has committed around $ 73 billion to produce green hydrogen (committed by more than 25 countries mainly from the global north). The total capacity of green hydrogen production will be led and dominated by the global south (~50% of total production by 2050), with South Africa, Morocco, and Chile projected to control market share.

GREEN HYDROGEN COSTS CAN DROP TO $2/KG BEFORE 2030

If electrolyser manufacturing can scale up, and asset and production costs continue to fall, Carbon Tracker projects that green hydrogen could be produced under $2/kg in most parts of the world before 2030. Achieving an LCOH cost of $2/kg or lower without the help of subsidy schemes is possible but will be unattractive to private investors. This will require investors and hydrogen asset owners to accept electricity tariffs below $25/MWh, which will only bring about negative financial returns on any green hydrogen investment in today's market. Investors require a reasonable price subsidy on the capital cost of green hydrogen assets to make this sector more attractive to the private sector and boost its deployment.

The US recently introduced the Inflation Reduction Act (IRA) policy scheme aimed at reducing the capital cost of new green hydrogen assets in the US alone. This policy will subsidise the cost of all new green hydrogen assets by $3/kg, meaning that new assets can now achieve LCOHs lower than $2/kg (the current US average without subsidy is ~$4.5/kg). Such a scheme would not only make new green hydrogen assets affordable but would also mean that investors could generate very healthy returns and rapidly scale-up production in the US market.

UNADDRESSED INEFFICIENCIES IN ELECTROLYSER TECHNOLOGIES ALONG WITH ITS RELIANCE ON FRESHWATER COULD LIMIT THE FUTURE GROWTH OF GREEN HYDROGEN

About 30% to 35% of the energy required to produce hydrogen is wasted along the production chain. A further 13% to 25% is lost when liquefying or converting it to other carriers such as ammonia and then an additional 10% to 12% of hydrogen's own energy is needed to convey or transport the product. These inefficiencies, if not addressed, would require a considerable increase in the usage of renewable energy assets to bridge the inefficiency gap.

Green hydrogen production is not 100% environmentally friendly. In fact, large-scale hydrogen production introduces a new environmental challenge - freshwater availability. Hydrogen electrolysers require freshwater (or desalinated water) to be effective. This could pose a major challenge and cause water stress and shortage in certain regions in the long run.

Taking the IEA's projection targets for hydrogen (for all sectors of the economy), we estimate that by 2050, the total volume of freshwater required will likely surpass 25% of today's global freshwater consumption. Our report highlights 17 countries at risk of being exposed to extreme water scarcity, of which all petrostates in the Middle East and Northern African countries will be the most exposed to this risk.

UNTIL TECHNOLOGICAL AND ENVIRONMENTAL CHALLENGES ARE ADDRESSED, THE DEMAND DISTRIBUTION FOR GREEN HYDROGEN SHOULD FOCUS ON THE INCUMBENT AGRICULTURAL SECTOR AND THE HEAVY INDUSTRIES

Carbon Tracker recommends that until technological innovation improves and environmental concerns are addressed the future of green hydrogen should only focus on serving its current industries; agriculture and the heavy industries, or hard-to-abate sectors (i.e., steel, heavy transport, shipping, mining). This is because scaling up green hydrogen in all sectors of the economy will be a technological challenge due to inefficiencies in novel electrolyser technologies and possible future freshwater shortages because of future hydrogen electrolyser demand.

GREEN HYDROGEN CAN BE USED AS A SHORT-TERM MEASURE TO HELP SOLVE FUTURE POWER INTERMITTENCY

As we transit into a post-fossil fuel era heavily dominated by wind and solar technologies, we will be faced with the possibilities of supply intermittencies when the "sun don't shine and the wind don't blow". Although there is increasing data that suggests that this only becomes an issue at beyond 70% of total supply, and we are well short of that target globally, the intermittency question dominates the narrative, especially from the incumbent fossil fuel lobby. **Hydrogen offers a viable solution to bridge this "intermittency anxiety" gap in the power sector alongside batteries and smart grid solutions.**

Recommendations

INVESTORS AND POLICYMAKERS

- Recognise the limitations of hydrogen and suppress unrealistic expectations. These unrealistic expectations risk slowing down the energy transition by inviting procrastination and potential crowding out of investment in existing cheaper energy options.
- Focus the implementation of blended capital to accelerate the innovation and deployment of green hydrogen to decarbonise fertiliser production, heavy industries (i.e., steel, heavy transport, shipping, mining) and energy storage.
- Investment in hydrogen in non-ET essential sectors to be entirely left to commercial funding but with policy put in place to protect the precious resources such as land use and clean water from being 'dispossessed' from social and human rights needs.
- Understand that existing blue and grey hydrogen assets contribute to the carbon bubble and should only be seen as short-term bridging solution which may lead to stranded assets & financial loss.

INVESTORS

- Capitalise on the investment opportunities arising from a hydrogen economy: scaling up a green hydrogen economy in the priority sectors requires big investment. We estimate an investment size in excess of $3 trillion by 2050 to build a successful hydrogen economy under the NZE 2050 1.5c scenario. This investment however does not include the cost needed for other assets or materials needed to support a hydrogen economy such as refuelling stations, hydrogen storage, transportation, export facilities and water desalination facilities.

Recommendations

POLICYMAKERS

- Introducing green hydrogen certificates: green hydrogen certificates are required to certify that the hydrogen purchased is entirely from renewable sources. A certification system implementation and widespread use will be important to the deployment and uptake of green hydrogen, as well as a global green hydrogen market. Green hydrogen certifications will track hydrogen quality across the value chain, establishing transparency among purchasers, increasing demand and promoting transferability.

- Contract for difference: Contract for difference (CfD) is a government subsidy scheme aimed at boosting the growth rate of renewable energy technologies. The CfD is a financial contract between a government body and an investor, whereby the investor is guaranteed a favourable subsidy incentive that enables them to capitalise on returns. The CfD must also take into consideration future uncertainties such as the unpredictable price of steel and hedge such cost in the subsidy package.

- Tax credit schemes: Tax credit is a government-funded scheme that subsidises the cost of production of an energy asset to make it more accessible and affordable. This scheme is popular in the USA and other European countries.

- Establishing dedicated financial bodies to fund deployment: Setting up financial bodies (banks or private equity funds) dedicated solely to increasing green hydrogen deployment would help accelerate deployment rates and fast-track LCOH cost reduction for green hydrogen. The European Union has recently announced (Sept. 2022) its plans to create a new European Hydrogen Bank to invest EUR 3 billion worth of green hydrogen assets across Europe.

HYDROGEN TECHNOLOGIES

Grey hydrogen

grey hydrogen is produced by splitting natural gas or methane into hydrogen and CO_2, using a production process known as Steam Methane Reformation (SMR). The by-product (i.e., CO_2) is emitted into the atmosphere. The efficiency of SMR systems ranges from 74% to 85%.

Blue hydrogen

blue hydrogen follows a similar production process as grey hydrogen using SMR. The by-product (CO_2), however, is stored and trapped in sinkholes, coalbeds or deep saline aquifers. This method is also known as hydrogen carbon capture and storage or CCS. Blue hydrogen can also be produced by Auto Thermal Reforming (ATR). This method is well established and uses natural gas as a feedstock to produce syngas composed of hydrogen and CO_2. The syngas is then split into hydrogen and CO_2. Both processes are similar in terms of their output. They differ in how heat is introduced to their production unit. For the SMR system, the catalyst that causes the natural gas to split is contained in tubes heated by an external burner. In contrast, heat is introduced internally by burning a portion of the natural gas before reacting with the catalyst that splits the natural gas into hydrogen and CO_2 for the ATR system. The efficiency of ATR systems ranges from 74% to 85%.

Green hydrogen

green hydrogen (also referred to as low-carbon hydrogen) produces hydrogen by a process known as electrolysis, whereby purified and desalinated water (feedstock) is split into hydrogen and oxygen (by-product). Electrolysers run on electricity and, in the case of green hydrogen, this electricity source must be from a clean energy source (i.e., solar or wind power). The average efficiency of hydrogen electrolysers (polymer electrolyte membrane (PEM) and alkaline) ranges from 40% to 70%. Minimum efficiency of 40% is required to achieve optimal yield.

03

The war in Ukraine has demonstrated need for hydrogen industry to move to an unregulated non-fossil based system

Europe's ambition to economically scale up its fossil hydrogen (blue and grey hydrogen assets) production hit a major wrench after Russia invaded Ukraine in early 2022. The immediate short-term impact of the war saw the long-run marginal cost of fossil hydrogen production skyrocket by more than 70% (~$12/kg as of August 2022[3]) from its pre-war price. This price volatility has exposed the fossil hydrogen market, branding it as an unreliable and unsustainable energy source incapable of meeting its targeted net zero production volumes.

Fossil hydrogen asset owners must now factor in the price volatility of natural gas, and what the pending risks of price fluctuations and supply disruptions mean to their production facilities. This, particularly in Eastern and Western Europe, has unconditionally raised the operational cost of more than 20 existing fossil hydrogen assets (2MT+ of hydrogen produced per year)[4] and put the security of gas supply at the forefront of concern. To solve this issue, European fossil hydrogen asset owners, especially those exposed to Russian gas, are turning to other markets (i.e., Africa) to replace Russian gas and help bridge the supply gap to power their assets.

This is only a short-term measure for fossil hydrogen asset owners to guarantee supply volumes. The issue of gas reliance for power is that asset owners are subjected to the geopolitical powers of the countries that produce these natural resources. Thus, if a petrostate goes into conflict, the same effects regarding gas price fluctuations and disruptions (Russia-Ukraine) will more than likely happen again.

Fossil hydrogen is, therefore, no longer a low-cost solution as it will always be exposed to gas price market risks.

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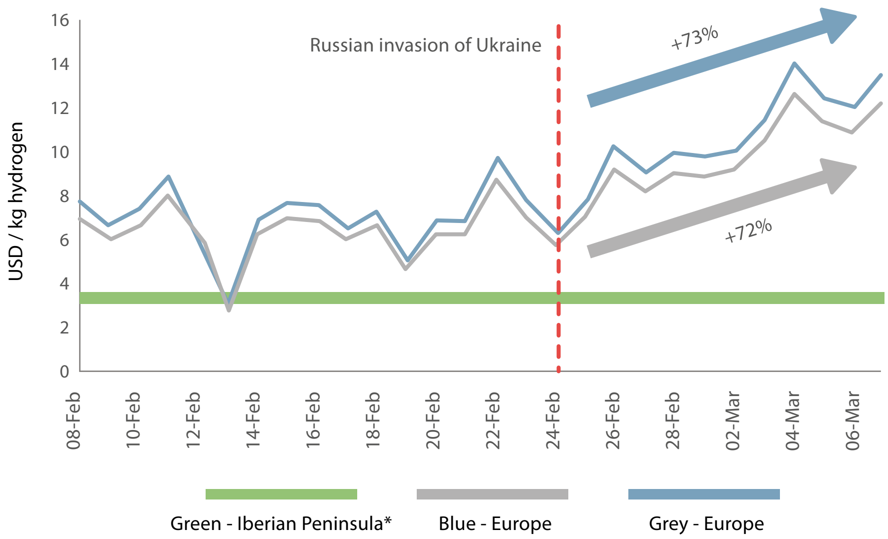
3 Data collected from Rystad Energy Hydrogen Cube.

Figure 1: Levelised cost of hydrogen in europe



Source: Rystad Energy

3.1 New fossil hydrogen is now more expensive to produce than non-fossil green hydrogen

New fossil hydrogen assets would cost more to produce across most regional markets based on today's gas and power prices. At the current gas prices the long run marginal cost of fossil hydrogen would be more expensive than green hydrogen in Asia and Europe (particularly eastern and western Europe).

Now in Asia (in 2022), new blue hydrogen would cost $6.4/kg[5] (35% higher than the base average green hydrogen cost). Grey hydrogen production (also produced from gas) would also cost roughly 29% more to produce compared to green hydrogen in this market. This economic feasibility and the ability for investors to guarantee favourable returns over a fossil hydrogen assets operational tenure is therefore questioned. The unpredictable rise in gas prices (along with gas supply disruptions), especially at current levels could automatically change a profit-making blue/grey hydrogen asset to a loss making one.

European fossil hydrogen asset owners exposed to gas supply from Russia will see their cost of production rise to up to 50% ($7.6/kg) more than their green counterparts. As Russia has recently indefinitely suspended natural gas supply to Nord Stream 1 pipeline (the pipeline that supplies gas to eastern and western Europe)[6], hydrogen asset owners in this region may end up stranded far sooner than expected on the grounds of the lack of gas supply if they cannot find suitable alternatives from neighbouring gas markets.

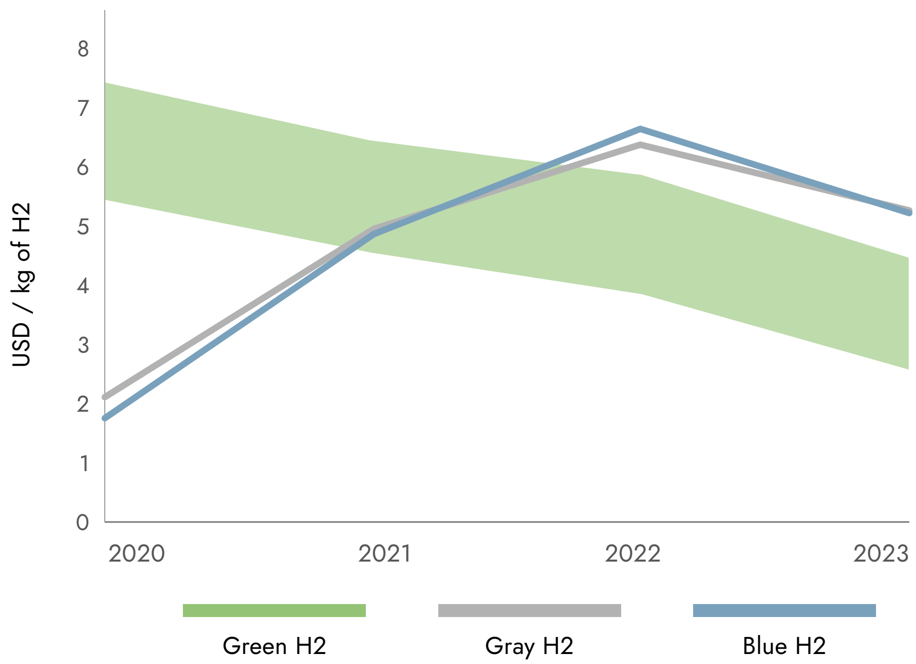
4 The result of record gas prices has seen the LCOH of blue and grey hydrogen assets in Asia and Europe become more expensive to produce compared to green hydrogen – Rystad Energy Hydrogen Cube.

5 Following the G7 summit by western nations to introduce a price cap on Russian gas exports, Russia followed up by indefinitely suspending gas supply to Nord Stream gas pipeline flagging maintenance issues. - Russia indefinitely suspends Nord Stream gas pipeline to Europe | Financial Times (ft.com)

Europe's thirst to revive its gas supply has seen it look at an unlikely candidate, Africa. Both public and private capital have estimated a total of $100 billion[7] needed to expand Africa's gas infrastructure to bridge the supply gap lost from Russian supply. As time is of the essence, it is still unclear when these funds will be released and when the expanded African gas pipeline infrastructure will be ready for exports to European fossil blue and grey hydrogen asset owners. Thus, it is very likely that if cheaper gas alternatives are not secured, fossil hydrogen asset owners in Europe will become stranded on these grounds. Alternatively, fossil hydrogen asset owners who are willing to pay for more expensive gas cargo from independent gas vendors will be hit by a negative cash flow for at least a year (end of 2023) until the regional gas price rectifies and the Nord Stream 1 gas pipeline is re-opened. Fossil hydrogen asset owners who cannot afford to wait a year will also become stranded.

In contrast to LCOH prices in Asia and Europe, fossil hydrogen prices in the USA are not higher than that of green hydrogen, simply because of the low gas production cost in the USA is projected to average at $7.3 MMBtu - $7.7 MMBtu at the end of 2022[8] (roughly three times lower than the annual gas price for Asia). Nonetheless, due to the relative rise in gas prices in the USA post the Ukraine-Russia war (which rose more than 50% since the start of the war in February 2022), gas prices initially projected to compete with green hydrogen in the early 2050s are now competing directly in price. Data collected from Rystad Energy shows that the long-run marginal cost for new blue hydrogen price in 2022 is now $3.2/kg (17% of the base average green hydrogen cost), while grey hydrogen is only 10% of the base average green hydrogen cost in this region.

Figure 2: Hydrogen LCOH FORECAST ASIA

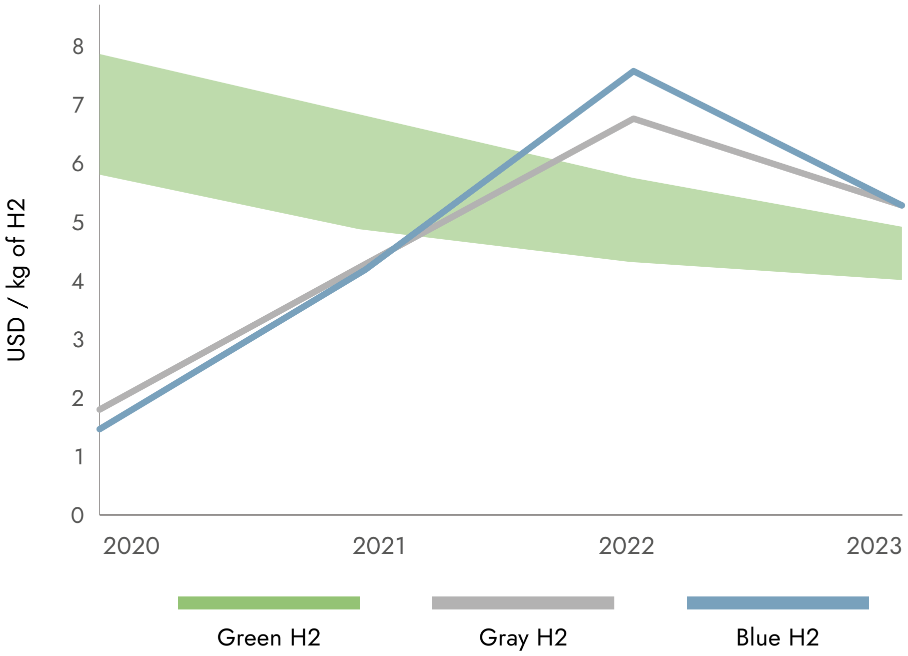


Source: Carbon Tracker, adopted from Rystad Energy Hydrogen Cube.

6 Energy firms have estimated a total of $ 100 billion will be needed to expand Africa's gas production to meet its needs. - Analysis: Ukraine war rekindles Europe's demand for African oil and gas | Reuters

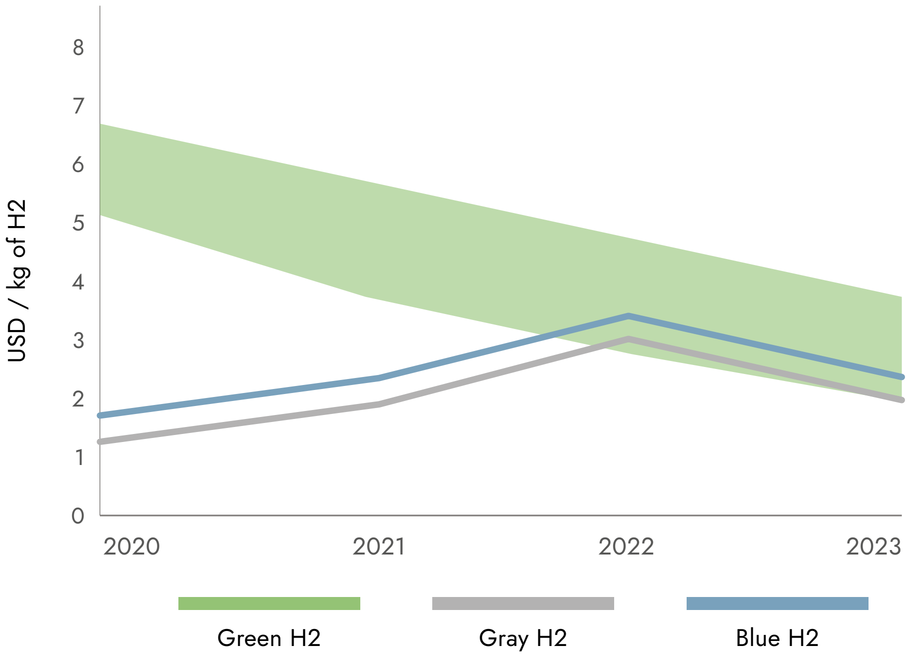
7 This projection is made based on gas prices from Jan – Sept 2022. Data is collected from trading economics.

Figure 3: Hydrogen LCOH FORECAST EUROPE



Source: Carbon Tracker, adopted from Rystad Energy Hydrogen Cube.

Figure 4: Hydrogen LCOH FORECAST USA



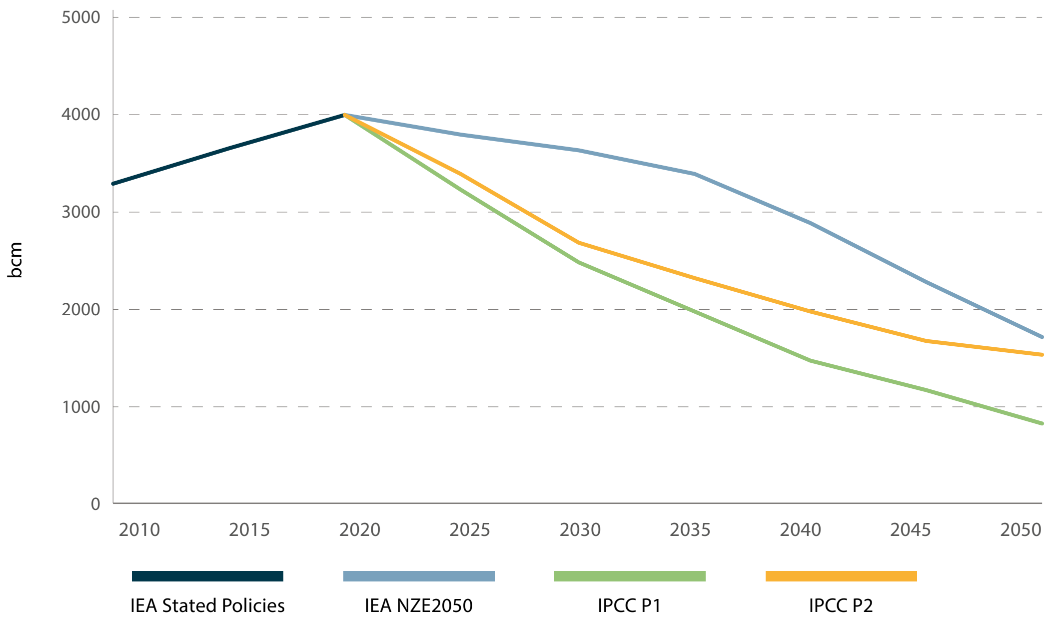
Source: Carbon Tracker, adopted from Rystad Energy Hydrogen Cube.

3.2 A Fossil hydrogen economy does not align with any net zero scenario

The notion of natural gas being considered as a transitional fuel was squashed by the International Energy Agency (IEA) in 2021. Thus, much like its fossil fuel counterparts oil and coal, natural gas faces a shrinking future in its demand. In the net zero scenarios presented in Figure 5, the global gas demand of all three net zero scenario pathways (IEA, IPCC P1, and IPCC P2) will shrink by more than 50% below 2020 levels by 2050.

Fossil hydrogen asset owners with long-term gas supply contracts beyond 2020 are therefore at risk of stranding, as none of the presented net zero scenarios supports for more gas expansion or supply. This, therefore, means that projected net zero fossil hydrogen volumes will be at stake and these volumes may never be met in a net zero world.

Figure 5: Scenario for gas demand



Source: IEA, IPCC.

3.3 Fossil hydrogen assets could be stranded almost immediately

All fossil hydrogen assets, particularly in Europe and Asia, are at risk of stranding on or before 2030. This is because:

1. Current assets are facing gas supply issues.
2. The global market has been plagued with record high gas prices making the LCOH of fossil hydrogen assets 29% or higher than green hydrogen in most regional markets.
3. The global north is committed to reducing its gas demand over the next 30 years.
4. Gas expansion to support fossil hydrogen growth does not align with any net-zero scenario pathway.

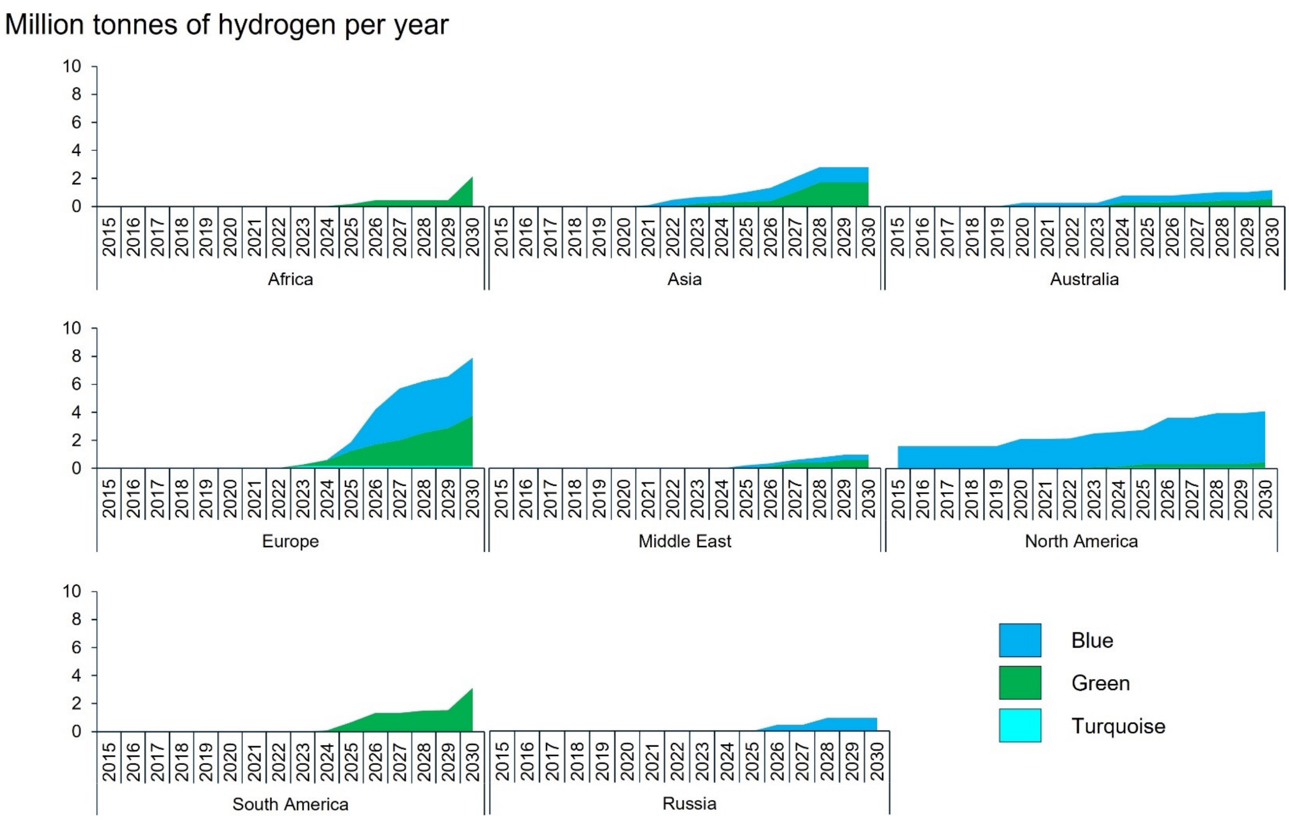
Europe and Asia will be hit the most as most new fossil hydrogen assets are set to come online from 2022, meaning that not all these assets will be able to secure 20-30 year long-term gas supply contracts as the gas demand market is expected to shrink by more than 50% below 2020 levels, by 2050. Carbon Tracker estimates that more than $100 billion[9] worth of blue and grey hydrogen assets in Europe and Asia could be stranded before 2030.

In contrast the US market will not be heavily affected as current gas prices, although still 50% higher than pre-war levels (February 2022), are still not more expensive than green hydrogen. Thus, there is a stronger case that as long as the LCOH of US fossil hydrogen remains lower than gas, asset owners can still capitalise on gas for their hydrogen production[10]. In Figure 6, we see that there is a higher demand for blue hydrogen in North America (the USA) than in any other continent in the world. This is because blue hydrogen is still cheaper to produce (or just barely competing with green hydrogen). This should however not be misconstrued by US investors to make new investments in fossil hydrogen. The US, like any other regional market, will still face global declining gas demand under the IEA and IPCC net zero scenarios and although US fossil hydrogen assets may not face imminent phase-out or stranded risk before 2030 like in Europe and Asia, the risk is still very present and will occur in the mid-2030s to early 2040s when the effect of reduced gas demand is felt by asset owners.

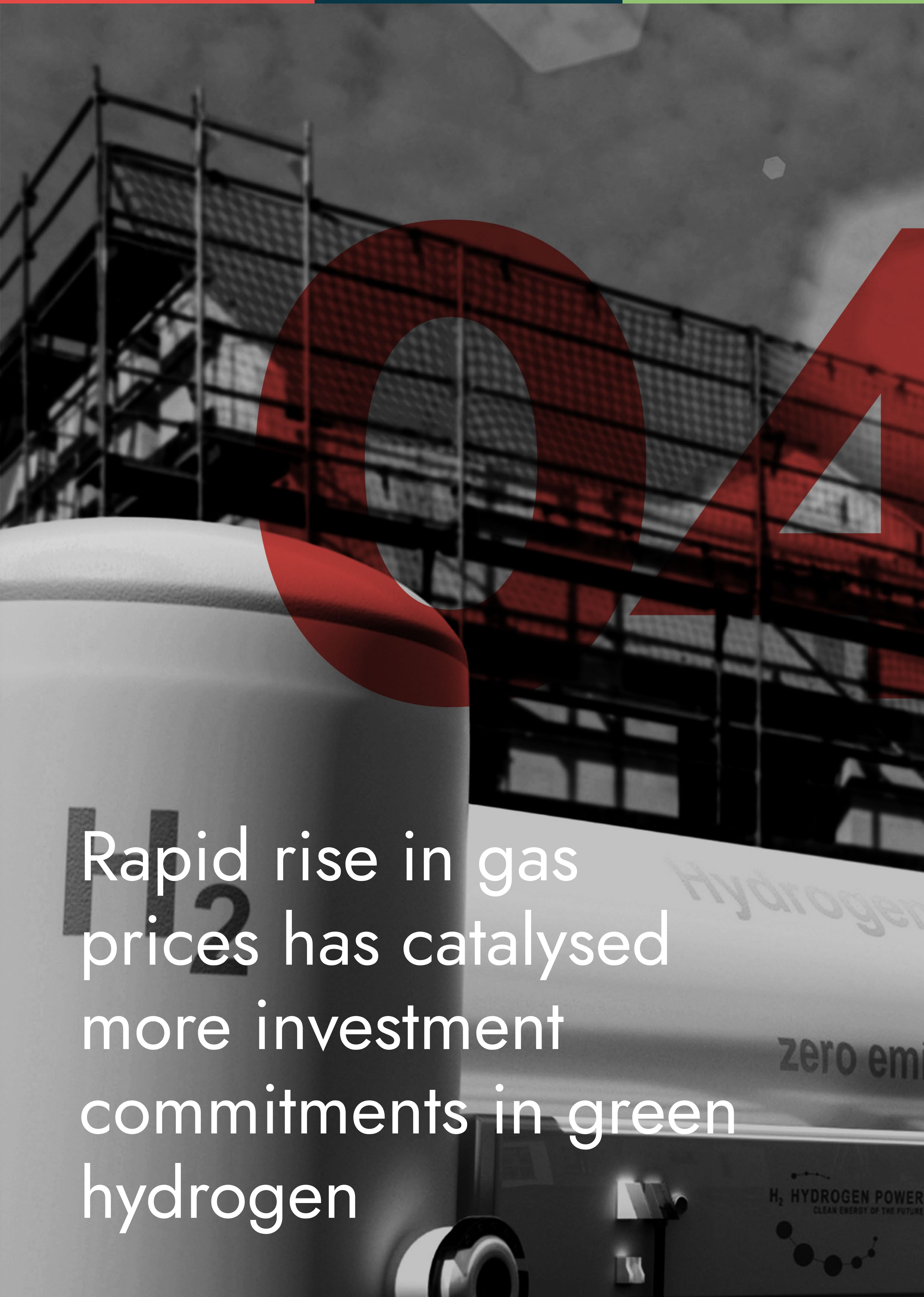
8 We estimated the value of existing and announced fossil hydrogen assets from 2020. Asset data was collected from Rystad Energy Hydrogen Cube.

9 In Figure 6, there is a higher demand for blue hydrogen in the US than any other continent in the world. This is because blue hydrogen is still cheaper than green.

Figure 6: Global hydrogen production pipeline by continent



Source: Rystad Energy Hydrogen Cube.



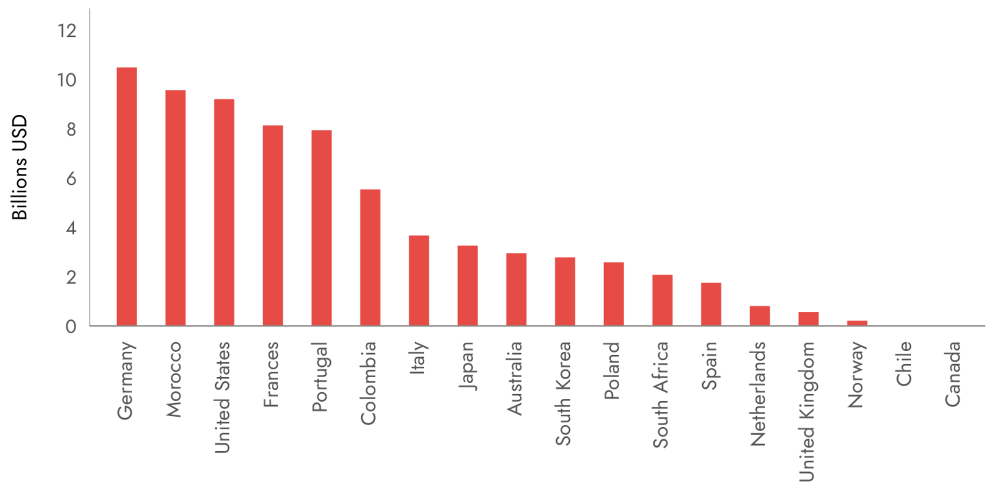
04

Rapid rise in gas prices has catalysed more investment commitments in green hydrogen

The disruption of the gas and energy markets have triggered more commitments and investments in green hydrogen. Over the last few months, the cost of green hydrogen has seen a steady drop, and this technology is quickly becoming more attractive to both public and private sector capital. In light of the Ukraine-Russia war, the global economy has committed roughly $ 73 billion towards green hydrogen production (committed by more than 25 countries – see Figure 7). As energy prices continue to exacerbate, we project more countries to explore green hydrogen as a bridging fuel to negate the high gas prices and as a transitional fuel to shift permanently from gas.

Countries, particularly in the Global South, have accelerated their pledges and targets toward green hydrogen production over the next 30 years. South Africa, Morocco, and Chile will control roughly 50% (68 MT) of total green hydrogen production by 2050 (see Figure 9). Although some of this volume will be used domestically to power industries (shipping, refinery, road transport, mining and chemicals), the bulk of the volume produced will be primarily tagged for the export market, particularly purchased by countries in the Global North like Germany, Belgium and the Netherlands[11].

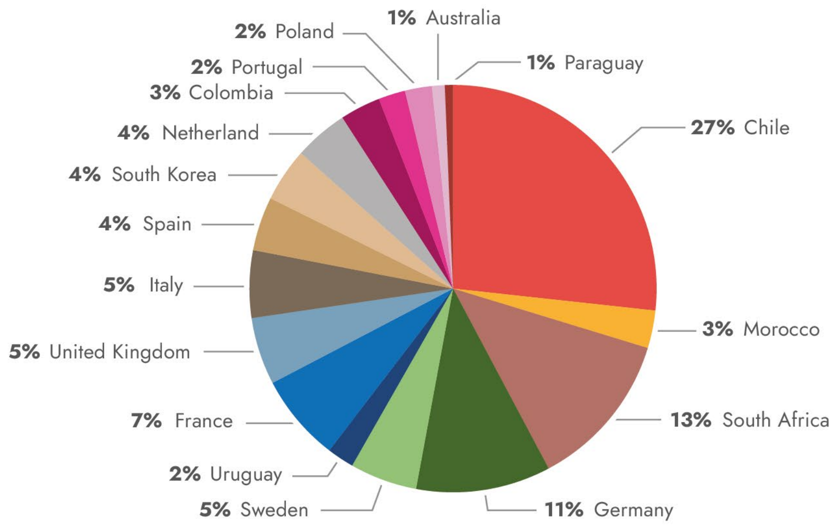
Figure 7: Financial commitments toward green hydrogen



Source: Rystad Energy Hydrogen Cube.

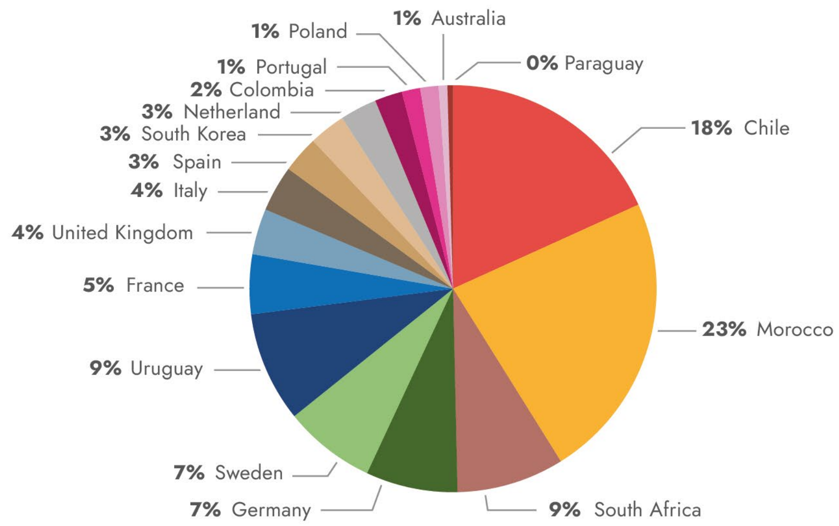
10 As producing large volumes of green hydrogen will be difficult in these countries (Germany, Belgium, the Netherlands) due to unfavourable weather conditions, both for solar and wind. The best practice is for the countries to rely of the export market for green hydrogen.

Figure 8: 2030 Announced green hydrogen target by country (GW)



Source: Rystad Energy Hydrogen Cube.

Figure 9: 2050 Announced green hydrogen target by country (GW)



Source: Rystad Energy Hydrogen Cube.

4.1 Rapid deployment of green hydrogen could push its production costs below \$2/kg years before 2030

With the right structure, the LCOH could potentially fall below \$2/kg at the site of production before the end of 2030 (in certain countries). This will be predominately driven by the continued rapid green hydrogen commitments, capacity pledges and deployment (as highlighted in figures 7 – 9), and the continued falling costs of renewable energy assets (solar and wind) and hydrogen electrolysers (costs already down more than 60% below 2020 levels[12]).

Based on current green hydrogen asset prices, the cost of electricity needs to be below \$25/MWh to achieve an LCOH lower than \$2/kg over the next 5-7 years (considering electrolyser efficiency)[13]. As this electricity cost is too low for the private sector capital to generate attractive returns on their investments, funding for green hydrogen assets with LCOEs lower than \$2/kg needs to be sourced from public/government capital only.

As the cost of capital for green hydrogen drops over the years, the electricity cost needed to achieve a production cost of below \$2/kg would increase – thus incentivising the private sector.

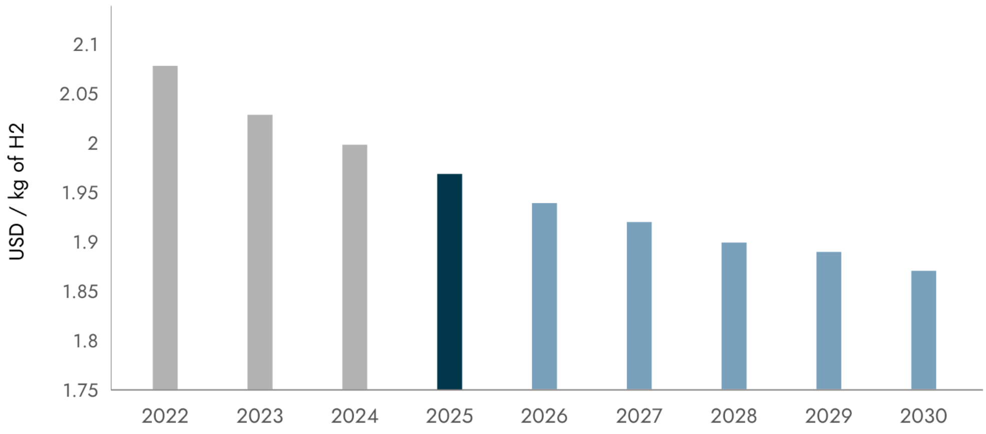
Alternatively, the introduction of tax credits on new green hydrogen production could quickly achieve a milestone cost of production under \$2/kg. For example, if a \$3/kg tax credit is applied to a green hydrogen asset with an LCOH of \$4.83/kg, it would have a revised production cost of \$1.83/kg. The US has recently introduced this tax credit scheme, the Inflation Reduction Act (IRA), for US-based green hydrogen manufacturers. The goal of this scheme is to make green hydrogen more accessible for fertiliser production and other heavy industries at a cheap rate. Such a scheme would rapidly scale-up the sector.


As the cost of capital for green hydrogen drops over the years, the electricity cost needed to achieve a production cost of below \$2/kg would increase – thus incentivising the private sector.

11 The cost of hydrogen electrolysers dropped more than 60% between 2020 and 2022 from an average cost of \$5450/kW to \$1200/kW – Rystad Energy Hydrogen Cube, Electrolyser overview: Lowering the cost of hydrogen and distributing its production – PV magazine USA (pv-magazine-usa.com).

12 Breakdown of data for achieving an LCOH below \$2/kg was collected from \$2 hydrogen: The goal of H2 to Australia | Wood (woodplc.com).

Figure 10: Aggressive cost forecast to $2/kg and below



Source: Carbon Tracker, Rystad Energy Hydrogen Cube.

Table 1: Parameters to forecast to achieve $2/kg and below

	INPUT PARAMETERS
Hydrogen Energy Source	Onshore wind
Wind CAPEX ($/MW)	1550
Electrolyzer CAPEX ($/kW)	1125
Electrolyzer Efficiency (kWh kg)	55
Electricity/PPA Price ($/kWh)	20
Electrolyzer Utilization rate (%)	50

4.1.1 Wind-powered hydrogen electrolysers are cheaper than solar-powered hydrogen electrolysers

Hydrogen electrolysers produce hydrogen from renewable energy sources, solar or wind power (onshore and offshore). Our analysis tells us that onshore wind power will be the most reliable energy source for powering hydrogen electrolysers on the grounds of high-capacity factors (>40%+) and therefore a higher volume of hydrogen dispatched from the electrolysers compared to a low-capacity solar asset.

The capacity factor needed to reach somewhat of an optimal electrolyser capacity ranges between 40% and 70% (for both PEM and alkaline electrolysers). Onshore (and offshore) wind technologies are the only clean energy technologies capable of reaching the high-capacity factors of 40% or more. Offshore though is somewhat at a slight disadvantage compared to onshore due to the higher cost resulting in a higher overall cost of capital for hydrogen electrolysers.

Solar-powered electrolysers on the other hand are not suitable as they cost roughly double than onshore wind-powered electrolysers. This is because the capacity factor for most solar photovoltaic systems ranges from 10% to 21% which is not up to par with the capacity required to meet optimal volume for hydrogen electrolysers.

Our findings also show that using a solar PV system as an energy source will cost roughly 49% more in CAPEX cost than using an onsite onshore or offshore wind system. This is simply because more solar panel installations will be needed to meet the required electrolyser capacity. This will result in higher LCOH values for solar.

4.2 Green hydrogen may be part of the energy transition, but technological inefficiencies and environmental concerns could limit its growth

Green hydrogen technologies (PEM and alkaline electrolysers) are quite novel, especially in large-scale applications. A major technological challenge facing green hydrogen production is its high energy losses. In the production chain approximately 30% to 35%[14] of the energy used to produce hydrogen is lost. Liquefying or converting it to other carriers, such as ammonia, results in a 13% to 25% loss and then transporting requires roughly 10% to 12% of the hydrogen's own energy. If not addressed these inefficiencies will necessitate a considerable increase in the usage of renewable energy assets to supply green hydrogen electrolysers.

From an environmental perspective the production of green hydrogen is not carbon-free. In fact, the production of large volumes of hydrogen introduces a new environmental challenge — water availability. In this section we use the IEA's NZE 2050 demand forecast for hydrogen in the power sector to highlight the impact of water on green hydrogen production.

13 Severe energy losses in the production and transportation of hydrogen https://www.weforum.org/agenda/2021/06/4-technologies-accelerating-green-hydrogen-revolution/.

Green hydrogen production assets require the use of water to separate hydrogen molecules from oxygen. This process is known as electrolysis and it requires fresh or desalinated water to be effective. Water desalinated facilities are carbon-intensive and until they begin to run on 100% renewable energy power, in alignment with net zero targets, the sourcing of clean water from such a plant may contribute to scope 2 emissions.

To measure the impacts on water resources we calculated the total volume of clean/fresh water per year required to produce green hydrogen in alignment with the IEA's NZE 2050 demand for hydrogen. For our analysis we only focused on the power sector due to available data (assuming hydrogen would be used to support baseload power generation). Our calculation of the volume of water was based on the atomic water principle for hydrogen that 1kg of hydrogen gas requires roughly 9 litres of water as a feedstock[15].

From our analysis we calculated that by 2030, a total annual volume of 136 billion litres per year of clean/fresh water will be required by electrolysers in this market. Our modelling shows that the required water volume will rise by roughly 100% by 2040 and 2050 (Figure 11).

Hydrogen demand forecast/RE capacity/cost for power generation

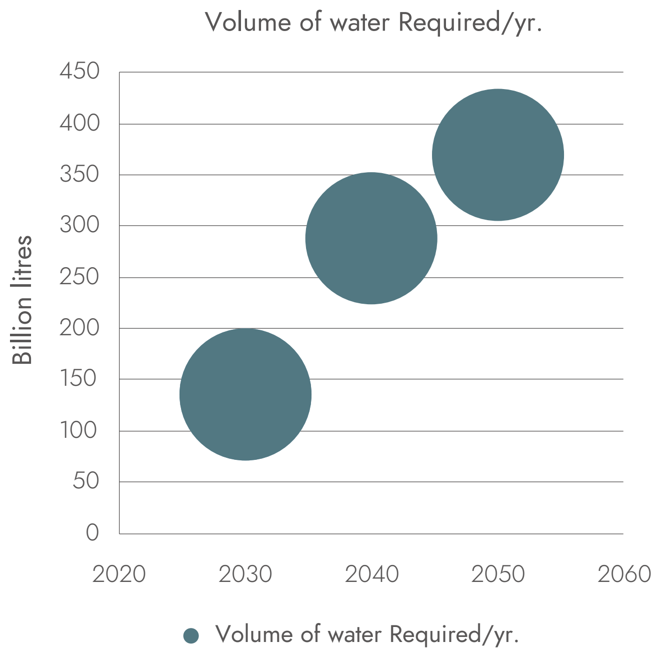
Year	Hydrogen demand/yr.	Renewable energy capacity	Investment cost
2030	15 Mt	240 GW	$ 522 Billion
2040	32 Mt	504 GW	$1,009 Billion
2050	41 Mt	649 GW	$ 1,401 Billion

Note: The renewable technology used for this analysis was onshore wind, as this is considered the cheapest among other forms of renewables.

Source: IEA, Carbon Tracker Analysis.

14 First Analysis of the Water Requirements of a Hydrogen Economy (phys.org).

Figure 11: Impact of hydrogen on water resources



Source: IEA, Carbon Tracker Analysis.

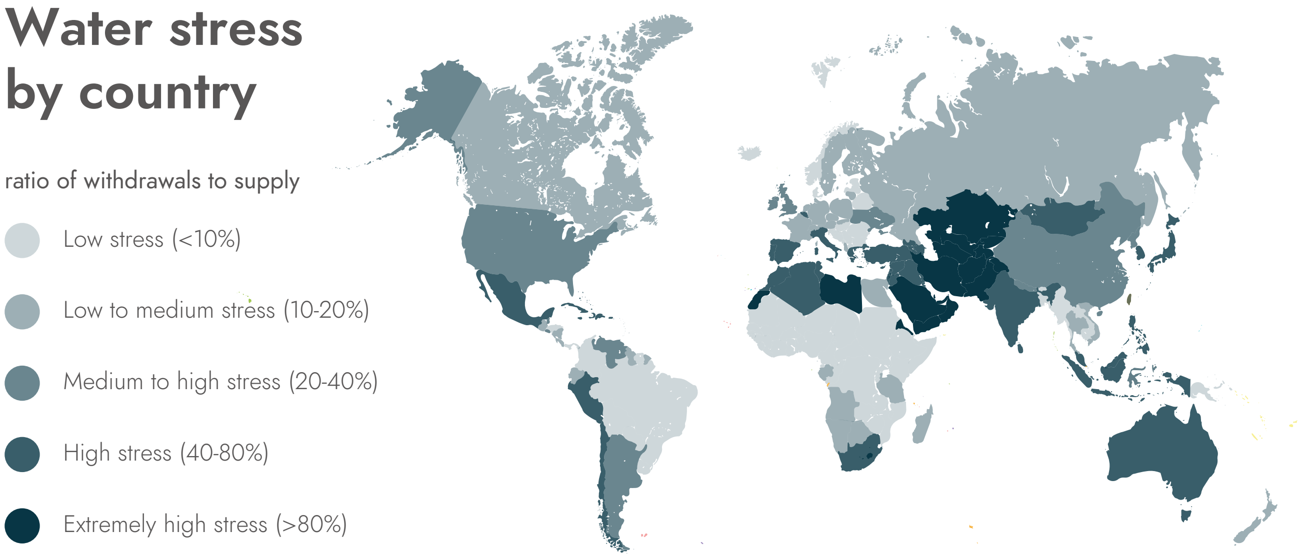
By 2025 about two-thirds of the global population may face water shortages, putting further stress on the demand market for freshwater (mainly in agriculture)[16]. The demand market for freshwater however is rising inexorably through a combination of population growth, economic development and changing consumption patterns. We assumed that if the 2050 IEA's NZE 2050 hydrogen projection stands, this will represent roughly 9% of today's global freshwater consumption per year. Further analysis shows that by 2050 the total volume of water required to satisfy the scaling up hydrogen in all required sectors will likely surpass 25% of today's global freshwater consumption per year.

A report published by the Water Resource Institute (WRI) flagged 17 countries at risk of being exposed to extreme water scarcity which includes all petrostates in the Middle East and North Africa amongst the listed countries[17]. Water stress has always been a concern in the selected red areas of the map provided in Figure 12 below. In these areas (mainly the Middle East and North Africa) freshwater is usually processed via desalination plants from seawater. Groundwater reserves, which account for nearly two-thirds of all water use, have been severely depleted in recent decades because of economic development, agriculture and population growth.

15 Water Scarcity | Threats | WWF (worldwildlife.org).
16 Countries, Home to One-Quarter of the World's Population, Face Extremely High Water Stress | World Resources Institute (wri.org).

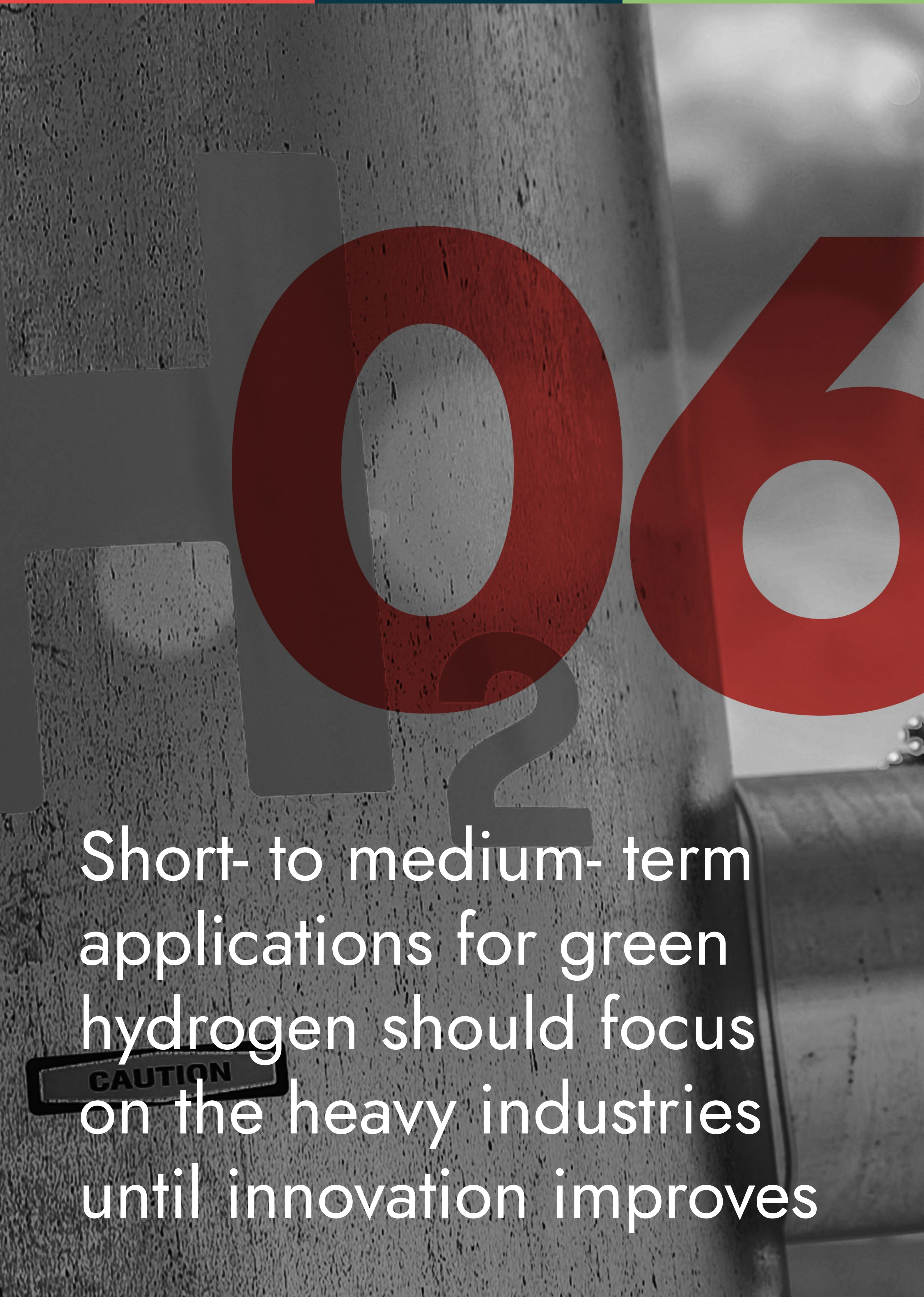
We can therefore conclude that as long as water scarcity remains prevalent in the Middle East and North Africa it will not be possible to scale green hydrogen in these regions, as asset owners will constantly face challenges in securing this resource on a long-term basis. This may result in possible future lost revenue and ultimately a forced shutdown, as assets will not be able to operate throughout their operational lifecycle.

Figure 12: impact of hydrogen on water resources



This map shows the average exposure of water users in each country to water stress, the ratio of total withdrawals to total renewable supply in a given area. A higher percentage means more water users are competing for limited water supplies. Source: WRI Aqueduct, Gassert et al. 2013

Source: World Resource Institute.

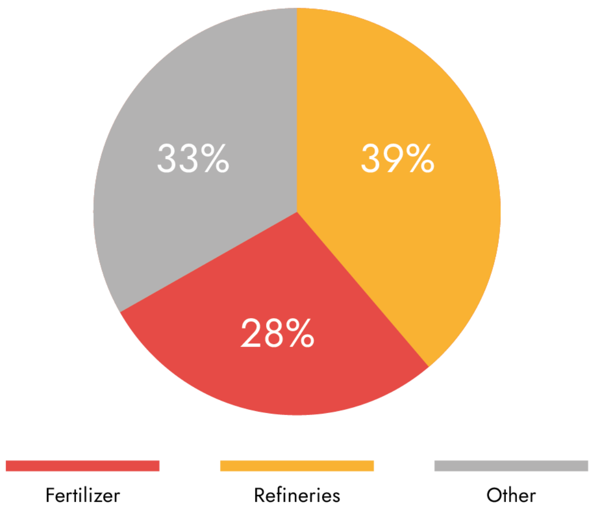


06

Short- to medium- term applications for green hydrogen should focus on the heavy industries until innovation improves

The current demand distribution for hydrogen has been predominantly used to serve both the agricultural sectors and oil refinery, particularly to aid in lowering the sulphur content of diesel fuel. As the demand for crude oil products decline in line with the IEA and UN Intergovernmental Panel on Climate Change (IPCC) net zero scenarios, the demand distribution gap will be filled by other wanting sectors. Technological inefficiencies and environmental concerns may however limit the projected global growth of hydrogen (~310 MT/yr. of hydrogen by 2050)[18].

Figure 13: Hydrogen demand distribution 2015 - 2022



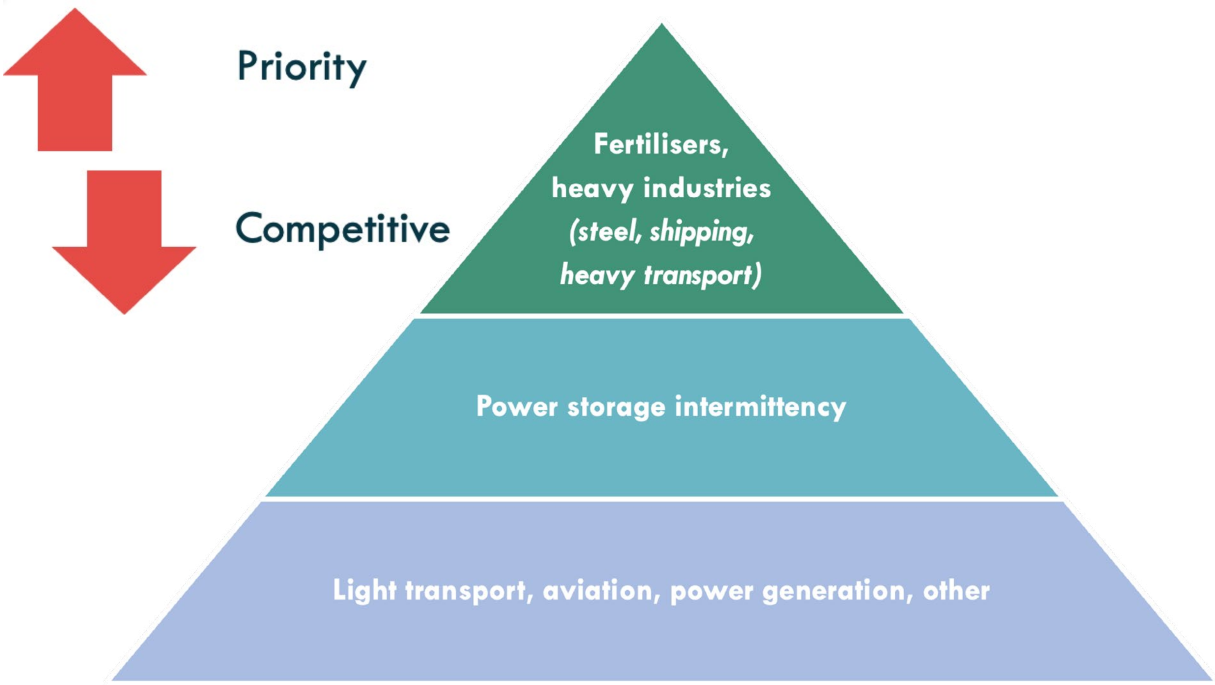
Source: Rystad Energy Hydrogen Cube.

Carbon Tracker therefore recommends that until technological innovation improves, and environmental concerns are addressed, the future of green hydrogen should only focus on serving its current industries; agriculture and the heavy industries, or hard-to-abate sectors (i.e., steel, heavy transport, shipping, mining). This is because scaling up green hydrogen in all sectors of the economy will be a technological challenge due to inefficiencies in novel electrolyser technologies and possible future freshwater shortages because of future hydrogen electrolyser demand.

Both governments and investors ought to be aware of the implications of a full-scale green hydrogen economy. Therefore, the scaling of hydrogen should be prioritised in the sectors of high necessity (agriculture) and those that have no strong alternative to decarbonisation.

17 By 2050, according to Rystad Energy, the global demand for hydrogen will be 310 MT/yr. This demand is said to serve all major sectors of the economy, i.e., road transport, aviation, fertiliser, power generation, shipping, steel production and other.

Figure 14: Hydrogen priority pyramid



Source: Carbon Tracker Analysis.

5.1 Hydrogen's application in heavy industries

5.1.1 Steel

Steel production is an extremely carbon-intensive activity, accounting for roughly 7% of global emissions. Sectors requiring steel indirectly inherit what is known as accumulated emissions, measured by a metric called emissions payback or energy payback. This is essentially a tag on the amount of carbon used during the production process to produce the steel being used. Emissions payback in the context of low carbon hydrogen assets is the number of years required for a hydrogen electrolyser asset (including the renewable energy asset powering it) to pay back CO2 emissions accumulated during the manufacturing stage of the steel used to build these assets. The higher the efficiency and capacity factor of the asset, the quicker the payback. The average payback time for most hydrogen assets powered by renewable wind energy would range from 3-5 years (depending on the location), while a solar-powered hydrogen asset would range between 4-8 years[19].

Adopting hydrogen, with the help of renewable energy electricity, to the steel manufacturing process could see emissions payback become nil, meaning that there will be no indirect emissions accumulated by hydrogen assets and both the steel and hydrogen asset would have zero-emission payback.

Replacing coal with hydrogen, therefore, seems a promising option for decarbonising the steel production process. Although initially it would increase the price of steel due to the high cost of hydrogen compared to coal, this gap is likely to fall over the coming years and could become cheaper before 2030[20], as the deployment of hydrogen is more than likely to increase, leading to the reduced cost of production over time.

5.1.2 Shipping

Ammonia is a potential solution to decarbonising long-haul shipping. Ammonia (NH3) is a gas compound produced via a reaction of nitrogen and hydrogen at high temperatures and pressure. As a gas ammonia can be compressed under pressure to form a clear liquid. Ammonia has a liquid density 1.5 times higher than liquid hydrogen, thus, liquid ammonia is easier to both store and transport (and an excellent fuel type for shipping).

As the shipping industry is under pressure to decarbonise and shift away from reliance on fossil fuels, ammonia is emerging as an appealing alternative. Ammonia, however, will not be the dominating fuel type for the future of shipping.

As decarbonisation regulations are becoming more stringent in the shipping sector, there is currently no clear fuel type that is favourite to dominate the sector. Ammonia is projected to grow only by 20% in the next 30 years and other fuel types such as methanol, biofuels, batteries and nuclear power will all play a role in assisting to decarbonise shipping.

18 Energy payback time and carbon footprint of commercial photovoltaic systems - ScienceDirect.
19 The potential of hydrogen for decarbonising steel production (europa.eu).

5.1.3 Heavy Transport

Hydrogen-powered vehicles (or fuel cell electric vehicles – FCEVs), are unlikely to play a major role in decarbonising passenger vehicles. In fact, according to the IEA, it is anticipated that FCEVs will account for no more than 3% of global road transportation by 2030 and slightly over 10% by 2050 only because of the phasing out of internal combustion engine (ICE) vehicles. Battery electric vehicles (BEVs) on the other hand are projected to dominate light passenger vehicles, controlling more than 40% of the future market cap by 2050[21].

Fuel cell vehicles, particularly heavy transport, have one major advantage over BEVs and that's on both range and fast refuelling times. BEV solutions may be less practical in for heavy transport, due to the prohibitive weight and expense of the lithium-ion battery needed to deliver the daily-duty cycle. Therefore, there needs to be a stronger priority on hydrogen as the preferred energy fuel of choice to help decarbonise heavy transport.

5.2 Green hydrogen can be used as a short-term measure to solve future power intermittency issues until the LCOE for renewables + batteries is cheaper than coal and gas

Until the cost of batteries is economically advantageous and cheaper than coal and gas, short-term future power intermittency issues can be alleviated with the help of green hydrogen. This is because of the intermittent nature of the electricity generated from renewable energy sources (wind and solar). Hydrogen can be an excellent energy storage medium alongside batteries and smart grid technologies to support the future grid in times of low generation yields from renewable sources.

5.3 Nonessential applications of hydrogen

- Nonessential means hydrogen, for now, it is not a necessity to decarbonise these sectors as they already have strong decarbonisation plans which will be powered and dominated by other clean energy technologies.
- After hydrogen has satisfied the top priority sectors and both innovation and environmental challenges have been addressed, then large-scale capital deployment for nonessential sectors should be encouraged. Carbon Tracker however does not see this occurring in the short-term term.

Hydrogen can be an excellent energy storage medium alongside batteries and smart grid technologies to support the future grid in times of low generation yields from renewable sources

20 Net Zero by 2050 - A Roadmap for the Global Energy Sector (windows.net).

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