A TECHNOLOGY'S TAKE-OFF: SPEED-SCALING HYDROGEN

PIONEERS AND ADOPTERS: HYDROGEN'S BEST PRACTICE

GLOBAL HYDROGEN PERSPECTIVE: THE BIG PLAYERS' STRATEGIES

HYDROGEN

IMPACT 2023

AN FII INSTITUTE PUBLICATION

HIGH$_2$WAY TO ZERO

HUMANITY'S PATH INTO THE AGE OF HYDROGEN

FII INSTITUTE
Future Investment Initiative Institute
Impact on Humanity

FACTS AND FIGURES

A TECHNOLOGY SET FOR TAKE-OFF

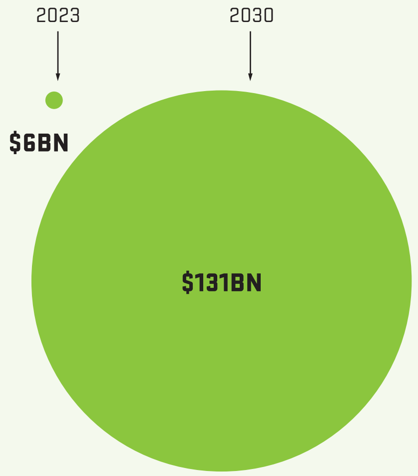
Pushed by the policy goal of achieving energy security, the green hydrogen market is taking off. Figures vary, but one estimate is that the global market will increase from $6 billion in 2023 to $131 billion in 2030, with a compound annual growth rate (CAGR) of 54.98% from 2023 to 2032.

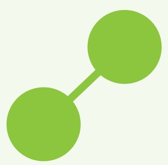
Producing green hydrogen through the electrolysis of water is expensive, but that will change. According to the Hydrogen Council, this year there are more than 1,000 projects in development globally, to the value of $320 billion (see p.23).

At the moment the world's functioning electrolyzer capacity is small, but that too is changing. A plant at NEOM in Saudi Arabia (see p.28) will be generating 600 tonnes of green hydrogen a day from 2026. A proposed plant in Mauritania, Aman, will produce almost eight times as much.

GLOBAL GREEN HYDROGEN MARKET

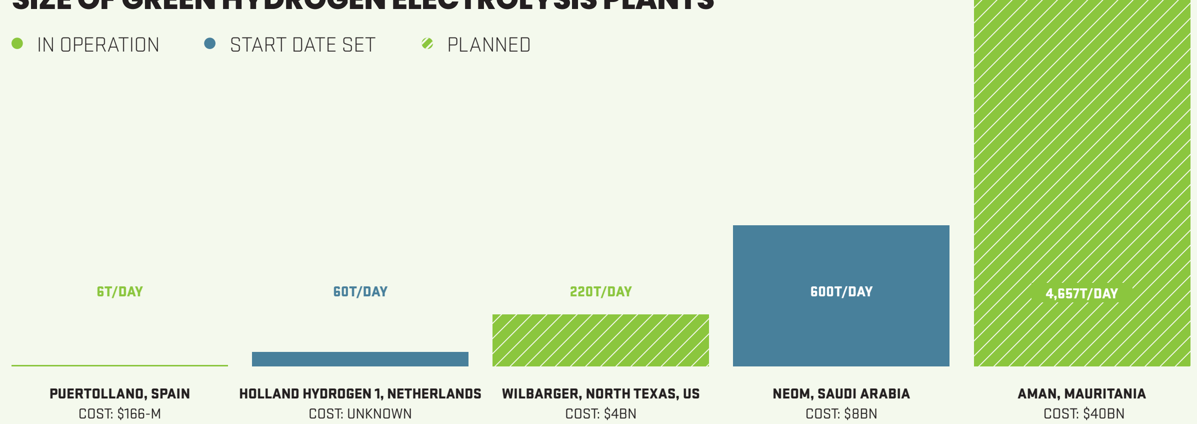
54.98% projected 2023–2030 market share growth





HYDROGEN IS THE MOST ABUNDANT ELEMENT IN THE UNIVERSE

SIZE OF GREEN HYDROGEN ELECTROLYSIS PLANTS



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EDITORIAL

THE NEW COLOURS OF HYDROGEN

GREEN HYDROGEN offers the world a route to carbon-neutral energy security amidst a global drive for sustainability. Recent discussions at the G20 summit and the approval of new trade routes, such as the one connecting India, Arabia, and Europe, have elevated green hydrogen from a futuristic concept to today's indispensable energy source.

Unlike oil or gas, green hydrogen is not a mere substitute; it is a versatile player seamlessly integrating into diverse supply chains, from energy storage to transportation. Its potential stretches far beyond the ordinary, with the potential to revolutionize industries such as steel production and chemical fertilizer manufacturing, making them more environmentally friendly.

One of the most remarkable aspects of green hydrogen is its universal accessibility. Regions like Africa, South America, Asia, and the Middle East are on the brink of a new era, where abundant and renewable resources like sun and wind translate into significant revenue streams, leveling the global energy playing field.

By 2050, green hydrogen is poised to redraw the world's trade boundaries. Nations that were once reliant on fossil fuels will have the opportunity to transform into energy superpowers in this post-oil era. This shift is not solely about power or the economy; it's about securing a sustainable future for every nation.

We find ourselves at the outset of an unprecedented journey—one that promises to not only redefine energy trade but also reshape global perspectives on sustainable energy. Green hydrogen represents more than just an energy source; it signifies the world's commitment to a cleaner, brighter future.

Richard Attias
CEO, FII Institute

COVER: MALAIKA PROJECT / ILLUSTRATION: ANJE JAGER/ SOOTHING SHADE

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HYDROGEN FOR NET ZERO

Green hydrogen is one of main elements of the world's energy transition. But only global cooperation will ensure its optimum use.

HUMANS CREATED THE CLIMATE change crisis and we have now embarked upon solving the problem by human means. Last year, Bill Gates stated the task succinctly in his book, How to Avoid a Climate Disaster. He wrote: "We add 51 Gt of carbon to the atmosphere every year and we need to get that number to zero."

Three main steps are needed to reach net zero, or at least get close to that target. These three steps are included by the International Panel on Climate Change in its most ambitious climate change mitigation pathways:

- generating more electricity from renewable sources
- exploiting the energy uses of zero carbon (green or pink) hydrogen and
- scaling up global carbon capture utilization and storage (CCUS).

What if all three were pursued to the maximum extent between now and 2050? We could reduce human CO_2 emissions by 95% by the middle of the century.

55% COULD BE ACHIEVED by an eight-fold increase in renewables for electricity generation up to 2050, estimates the Ellen MacArthur Foundation.

20% COULD COME from CCUS. The International Energy Authority (IEA) has estimated that CCUS could account for 7.6 Gt of carbon reduction.

20% – ANOTHER 7 GT – of CO_2 emissions annually, could be the contribution of clean hydrogen, according to the IEA.

And this final 20% is the percentage we will focus on here.

FROM GRAY TO GREEN

Right now, we are still very far away from that hydrogen target– in volume as well as in color. Each year, 94 Mt of hydrogen is used, so just a bit more than 1% of the 7 Gt to achieve. And more than 95% of this 94 Mt, primarily used to make chemicals, is gray. It produces 2% of the world's carbon emissions. Green hydrogen is made by applying electricity from renewable sources to water in a process called electrolysis. This produces no carbon emissions. Blue hydrogen is made, like the gray kind, from natural gas, but the resulting carbon emissions are captured. Pink hydrogen is made by electrolysis using nuclear power. This also releases no emissions.

Experts agree we won't reach net zero without scaling up production of green, blue and pink hydrogen. So how much will it cost? It has been estimated by the International Energy Authority that financing the clean hydrogen element of reaching as close to possible to net zero by 2050 will require global investment of at least $1.2 trillion by 2030.

To put these numbers into context, the Hydrogen Council calculates that clean hydrogen can reduce the cost of the energy transition by $6 trillion. It says that spending $1.4 billion a year on its use in transportation will save at least four times as much in annual systems costs.

We cannot afford not to make this investment. The World Meteorological Organisation (WMO) estimates that extreme weather events have been responsible for the deaths of 2 million people and about $4.3 trillion in economic damages over the past five decades.

> "We add 51 gigatons of carbon to the atmosphere every year and we need to get that number to zero."
>
> **BILL GATES**
> Cofounder of Microsoft and the Bill & Melinda Gates Foundation

MULTIPLE BENEFITS

The benefits won't just be reducing CO_2 and slowing down climate change. Increasing the role of clean hydrogen to meet global energy needs will help to level up inequalities between countries, increase the GDP per capita of the poorest and reduce food insecurity and hunger. However, to avoid duplication of effort there is an urgent need for stronger global cooperation on plans, production facilities, ports, shipping routes, equipment manufacture, subsidies and offtakes. This could be assisted by a global hydrogen strategy.

Numerous uses of clean hydrogen and its derivatives are poised to take off between now and 2050. With the price of green hydrogen set to match that of gray by 2030, it will increasingly be adopted for heavy transportation and industry, including iron and steel and chemical manufacture, and storing off-peak electricity (see page 12).

Vaitea Cowan, cofounder of green hydrogen company Enapter, explains: "The world is turning to green hydrogen because it is coupling hard-to-decarbonize sectors with green electricity from solar and windpower. Green hydrogen is converting this green electricity into a highly versatile energy carrier."

But, she adds: "To make green hydrogen the fuel of the future, ↘

it needs to be cheaper than fossil fuel." The main factors are the cost of the electrolyzers used to make green hydrogen and the cost of renewable energy. Both are falling steeply (see p.22).

SHADES OF GREEN HYDROGEN

Green hydrogen has many advantages over fossil fuels. It is not dependent upon geology and can be made closer to where it's needed. Unlike oil reserves, the sun and wind won't run out. As the world transitions from fossil fuels, a lot less oil and coal will be moved around as rail and sea freight, producing double savings.

As well as by electrolysis, green hydrogen, along with biofuels and synthetic fuels, can also be made from other abundant sources – waste and biomass. Several processes can be used, including pyrolysis, gasification and anaerobic digestion (AD). Sources could be green waste from farms or households, municipal rubbish, including plastics, and human and animal waste.

Mani Sarathy, professor of chemical engineering at King Abdullah University of Science and Technology (KAUST) notes: "Green H_2 made from waste and biomass will certainly be important, for example as syngas converted into green aviation fuels. The technology exists and is scalabe. The issue is that waste management and recycling practices are very poor – more than 90% of waste is currently landfilled."

Anthony Boden, principal in the energy practice of Charles River Associates, notes that biogas from sewage and animal waste, a green form of methane, is increasingly valuable both as a fuel source and for conversion into other fuels. Countries that graze animals have an abundant material for anaerobic digestion. Policy and investment choices determine how far they go down this route.

Boden says: "While the UK sources only a few percent of its energy from AD, in Denmark they produce 20% of their gas from this source, using farm waste." Circular economies are rare. We live in a world in which most waste is burned, buried or washed out to sea. Bio and e-fuels are not being made anywhere on a significant scale from waste.

SHIPPING AND GREEN FUELS

It may be unglamorous but shipping is set to be a key entry point for the world's initial adoption of green fuels, argues Sam Mackilligin, Hydrogen Director for Europe & India for global infrastructure consulting firm AECOM. Shipping is a major source of greenhouse gas emissions. It is estimated that 80% of all consumer goods pass through a port of some type. And one-third of global maritime cargo is oil.

Mackilligin says that,

> "If we want to go to net zero globally, there is no other way than hydrogen."
>
> **AHMAD AL KHOWAITER**
>
> CTO of Saudi Aramco, at FII V in October 2021

in terms of green fuels, "Aviation is 15 years away from doing anything at volume, but shipping is getting there now." Biomethanol, he notes, a stable, energy-dense liquid, has been approved by the International Maritime Organisation (IMO) for zero carbon shipping. Danish company Maersk, which is responsible for one-fifth of the world's container ships, has 20 biomethanol-ready container vessels on order, and Sweden-based Stena Line already has methanol-ready ferries in service.

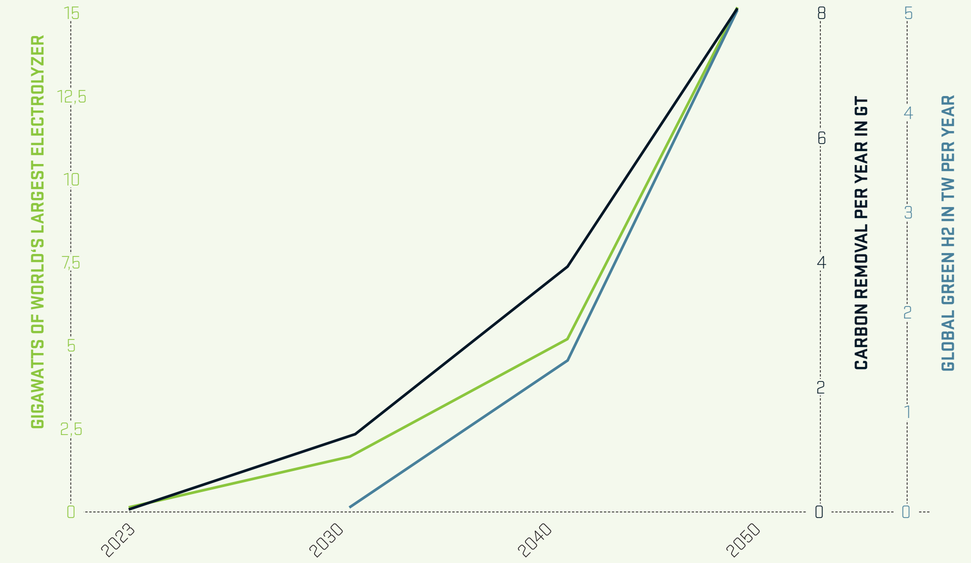
Mackilligin says: "Maersk is working to create from seven to ten 'green shipping corridors' globally. One of these routes would be from Singapore to Los Angeles, with a focus on green fuel bunkering to support zero carbon shipping."

At the moment, there isn't enough biomethanol and e-methanol to fuel green shipping demand, but he predicts that by 2030, subject to increased production, there could be hundreds of ships running on these fuels. He predicts that that these green shipping fuels will be joined by ammonia and, potentially, green hydrogen as low-to-zero carbon fuel sources, as they become approved by regulators.

While shipping only makes up about 3% of global CO_2 emissions, the increased availability of liquid e-methanol, made from green hydrogen and captured carbon, which is stable at ambient temperatures, will make it attractive for hard-to-decarbonize land applications such as agriculture and temporary power.

FROM ZERO HYDROGEN TO ZERO CARBON

The path to a green hydrogen world: The decisive factor for hydrogen's contribution to net zero carbon is the growth of the size of electrolyzers.

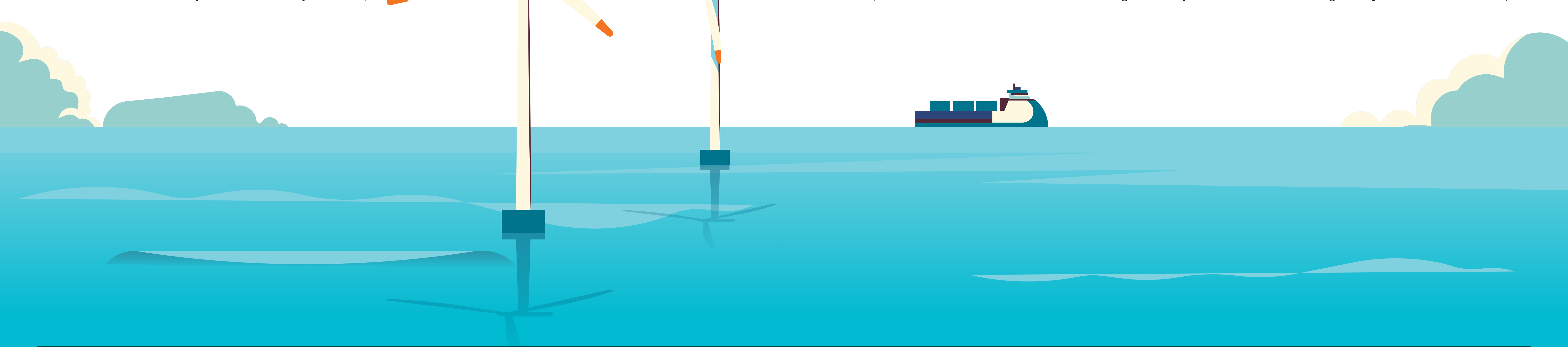


SOURCES: MCKINSEY, INTERNATIONAL ENERGY AGENCY, INTERNATIONAL RENEWABLE ENERGY AGENCY

POTENTIAL OF BLUE AND PINK

Blue hydrogen is yet not being made anywhere at scale, because it depends on CCUS, and these carbon capture technologies have yet to be further developed and widely adopted. Currently, there are 30 CCUS facilities in operation, 11 under construction and 153 in development. The US has more CCUS projects than any other country, and its Inflation Reduction Act of 2022 is expected to drive further deployment.

Countries with well-developed oil and gas and petrochemical industries,

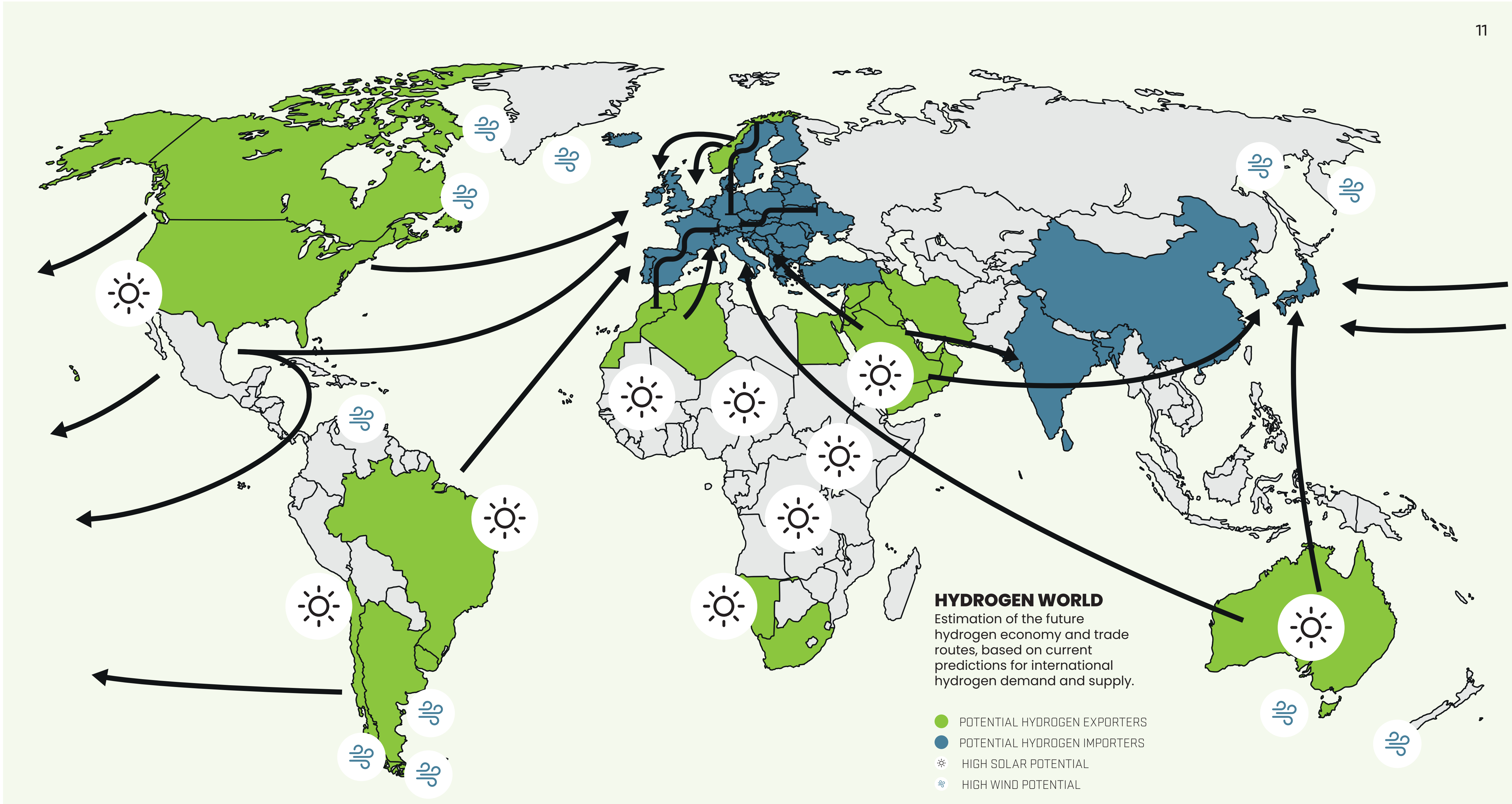


such as the US and Saudi Arabia, will be the main blue hydrogen adopters, substituting it for gray hydrogen in their chemical industries to make methanol and ammonia, precursors for fuels, fertilizers and plastics.

What about pink hydrogen produced by electrolysis using nuclear energy? Sarathy says, "Pink hydrogen could be viable in places with existing nuclear energy assets, but it will be too expensive for new builds only to make pink H_2."

Boden comments, "Nuclear energy could be a contributor to clean hydrogen, but it isn't generally cheap." He adds: "There have been studies in the US, looking at adding hydrogen production to existing reactors on site. Small modular reactors, made in factories, are the ones to watch, as their economics become more favorable. They may play a role, but they are not likely to become available until after 2030."

Boden sees a chance to get away from color coding: "Agreed standards and certification on hydrogen will help to drive progress, for example on whether hydrogen is green. Then you won't need to ask for colors, but simply, 'is it renewable or not?'"



SOURCES: FLOW VOLUMES: HYDROGEN COUNCIL/MCKINSEY & COMPANY; ROUTES: IRENA; SUN AND WIND MAPS: IRENA

NEED FOR COOPERATION

By 2050, according to the International Renewable Energy Agency (IRENA), the global trade in hydrogen will be worth more than global trade in oil. Hydrogen hubs or valleys (see p.18) will colocate complementary processes, often in places with existing infrastructure. As well as generating green hydrogen, many will capture carbon emissions from gas turbine power stations and factories, and energy from waste plants. Some will serve as collection points for organic waste that can be made into biofuels and e-fuels.

Some, like Neom (see page 28), will be global hubs. Green hydrogen from North Africa and Spain will travel by tanker and pipeline to Italy, Germany and Central Europe. There will be North Sea-based offshore hydrogen from Belgium, Germany, the Netherlands and the UK. But these countries' clean hydrogen demand will outstrip supply, making them importers from Africa, South America, the Middle East and Australia. Japan will also be an importer.

The Hydrogen Council notes an up-to-fivefold differential in production costs between the lowest and highest-cost locations. To maximize impact, infrastructure must be built in the right places, countries will need to incentivize R&D in equipment using clean fuels and enter into partnerships and long-term offtake agreements.

The hydrogen industry is still in a very early stage of its development. It will be implemented and scaled around the globe, and it is in the interest of producers and consumers alike to scale it in the most efficient way – at the best locations, with the best technology and the best logistics. And more than that, this is in the interest of humanity, as clean hydrogen is one of our best weapons to fight climate change.

The best way to maximize the efficiency and productivity of clean hydrogen would be to coordinate the development of green hydrogen industries on a global level. There are already steps in that direction. Japan has hosted a Hydrogen Energy Ministerial Meeting since 2018. There is the Clean Energy Ministerial Hydrogen Initiative, Mission Innovation, a global initiative to promote clean energy, and Bill Gates' Breakthrough Energy and the Global Partnership for Hydrogen of the UN Industrial Development Organization. All of them are promoting global cooperation.

Nevertheless, ever more countries are pursuing their own national hydrogen strategies. Germany has elaborated its strategy, as have Oman, Morocco, Chile and others. But the sum of many national optimizations leads to worse results than one global optimization. The rollout will be slower, as supply and demand match less, and more expensive, as facilities will be constructed at less appropriate locations.

It's difficult to calculate how big the price tag for hydrogen nationalism would be. Given the huge efficiency differences between potential locations, we estimate at least 20% higher investment costs than would be necessary for a globally coordinated hydrogen strategy – so, futile extra costs of at least $240 billion in this decade alone.

Humanity should make good use of hydrogen investments. Sarathy says: "Green hydrogen democratizes energy production. There should be policies which would enable wealth distribution to developing economies while benefitting climate reduction targets in the developed world."

CALL TO IMPACT

1 The three main steps to net zero CO_2 from energy are exploiting renewable electricity, developing zero carbon hydrogen and scaling up carbon capture utilization and storage (CCUS).

2 Countries should promote R&D in clean fuels and enter into partnerships and long-term offtake agreements.

3 Agreed-on standards and certification will help to harmonize progress and avoid futile extra costs.

4 A global hydrogen strategy would build on current cooperation and help to coordinate countries' efforts and optimize investment.


H2

FROM GIGA TO BIGGER

There are signs that green hydrogen investment is reaching its escape velocity. The costs of building and running new electrolyzer plants are falling sharply.

IT'S COLD IN DAVOS IN WINTER. Posing for a picture in January 2017, leaders of 13 major energy and auto companies, as well as French-headquartered gas multinational Air Liquide, were wearing puffer jackets and overcoats as they stood in a snow-covered field.

They were at the World Economic Forum's annual meeting to launch the Hydrogen Council – a high-level industrial pressure group designed to put the need to increase green hydrogen production on the agenda of national leaders.

It was not a high-profile topic at the time. The world had only just been chastened by the dire warnings of the 2015 Paris agreement. The scale of the cuts that would be needed in greenhouse gas emissions were a huge reality for politicians and the public to absorb and dominated discussion of climate change. Few people at that time were thinking, in detail, about the role that hydrogen would play in what came to be called "the transition."

That has changed. The Hydrogen Council now includes in the region of 150 multinational companies, representing the entire hydrogen value chain. Over the last two years, in the wake of the war in Ukraine threatening energy security worldwide, national hydrogen strategies covering more than half of the world's leading economies have been announced.

ENGINE OF GROWTH

The council's latest Hydrogen Insight report, produced with McKinsey & Company, reveals that about 0.8 Mt of clean hydrogen supply is operational today, and that 3 Mt per year has passed final investment decision. There are now globally over 1,000 projects requiring $320 billion of investment. North America is ahead, committed to $10 billion in investment, followed by Europe at $7 billion and China at $5 billion. China is recording the fastest growth.

The last two years have seen the US commit to $400 billion from its Inflation Reduction Act and a $10 billion of package of tax credits for green hydrogen. The EU has signed up to €430 billion investment over the next decade. Fiscal incentive in the US and emissions trading and carbon taxes in the EU will also see the cost of carbon continue to rise, incentivizing green hydrogen production.

Bernd Heid, Senior Partner at McKinsey, says: "North America has been a real engine of growth. it now accounts for 30% of committed funding and 70% of committed clean hydrogen production."

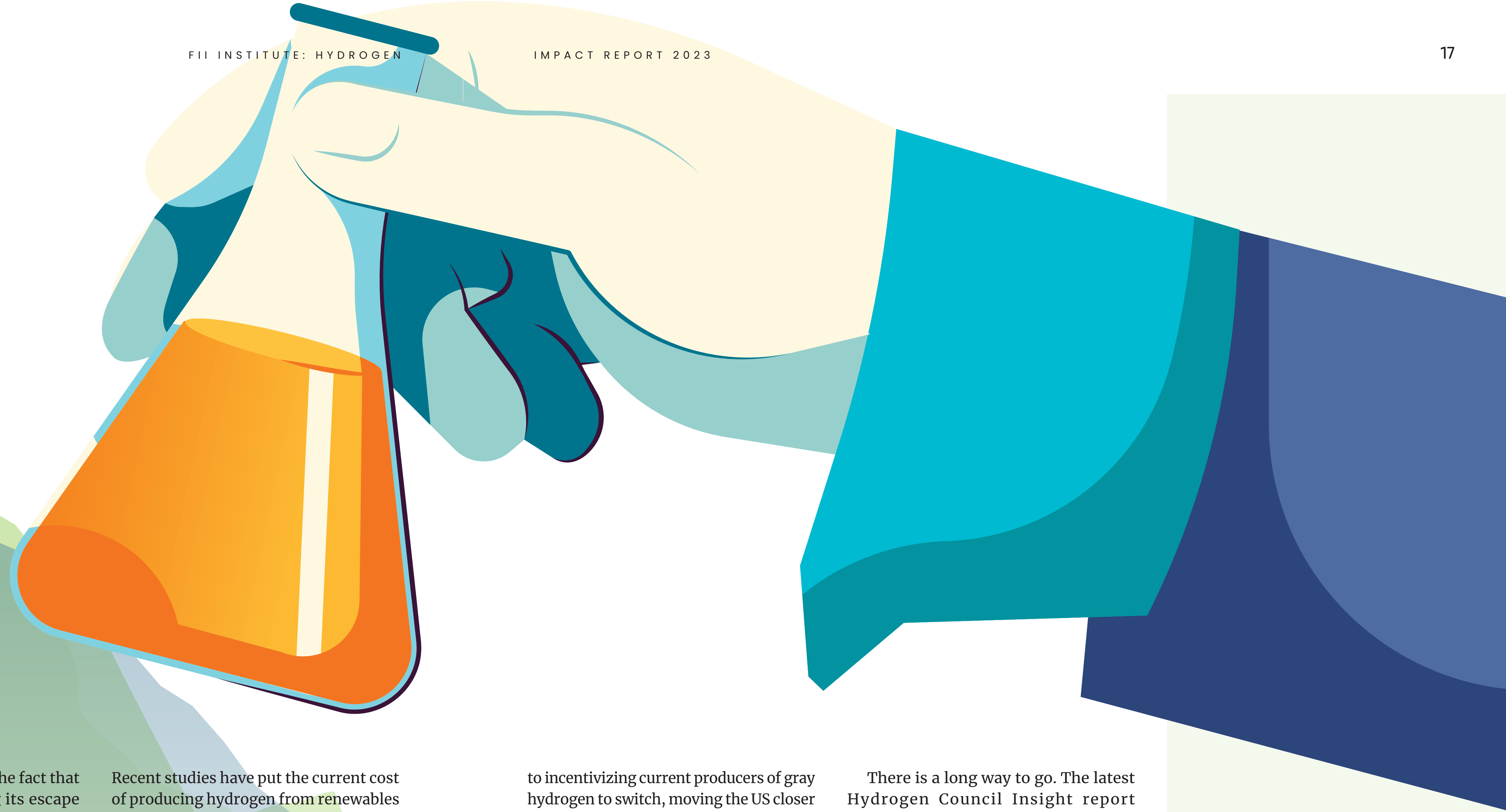
India, which has "skin in the game," is not pleased by the largesse of President Biden propelling the country's green hydrogen economy with tax dollars. India aims to produce 3 Mt of renewable H_2 production and around 15 GW of electrolyzers over the next five years under its National Hydrogen Mission. In the month that India announced it first "giga scale" green hydrogen electrolyzer investment, renewable energy minister RK Singh complained that the developed world, an alleged supporter of free markets, is creating barriers to global trade. "Of course, they have the advantage that they can print money. I also see this barrier mentality in Europe."

SIGN-OFF DELAY

There is a slight caveat in the Hydrogen Insight report, in that that some large projects are taking longer than previously to reach sign-off – only 10% of last year's investment volumes, it says, have passed a final investment decision.

This year, for example, the Danish government announced it is postponing a final investment decision on the prestige joint Danish and Dutch North Sea Wind Power Hub – a series of green hydrogen islands in the shallow Dogger Bank area that would export green hydrogen and grid power to the rest of Europe.

This could either be a market blip – after all, the cost of money has risen sharply – or signal a genuine slowdown in "big ticket" investment. But overall, the Hydrogen Council analysis points to a healthy pipeline of committed projects, in 2023, helping the green hydrogen economy to achieve momentum.



Green electricity, one of the biggest factors in scheme viability is becoming cheaper across the world. Between 2010 and 2018, the average global cost of solar energy fell by almost 80% from $250/MWh to $56/MWh. Onshore wind dropped from $75/MWh to $48/MWh in 2018. Record low prices were observed in 2019 and 2020 around the world, according to the International Renewable Energy Authority (IRENA).

The cost of ectrolyzers is also falling. The International Energy Authority reports that electrolyzer manufacturing capacity has doubled since last year, reaching nearly 8 GW per year, pointing to a capacity of 134–240 GW by 2030, twice the expectation from last year.

IRENA says that larger production facilities, design standardization and insights from early adopters could cut electrolyzer costs by 40% in the short term and up to 80% in the long term, reducing the price of green hydrogen to parity with gray within a decade.

All these factors point to the fact that green hydrogen is reaching its escape velocity. As costs fall, countries that have made expensive initial investments will benefit from an escalating global demand for green hydrogen. Experts say that the conversion of road heavy goods transport to hydrogen will be the first market to mature, followed by shipping and short-haul aviation.

The steel industry, oil refining and chemicals – which are at the beginning of the world's value chains – will be the next sectors that are reached. The jury is still out on whether it will be economic for cold countries to use green hydrogen to heat their houses with adapted natural gas grids, or to blend some hydrogen into their grids, proportionately reducing CO_2 emissions.

COLD, HARD NUMBERS

The speed of adoption of green hydrogen will depend ultimately on cold, hard numbers. In 2020, gray hydrogen could be produced for around €2 per kilogram. Recent studies have put the current cost of producing hydrogen from renewables in Northern Europe within a rough range of €6–€8, but it is continuing to fall.

Factoring in costs of production, conversion into other energy forms and transport via ship, pipeline or truck, US technology company Aurora has calculated that clean hydrogen in Germany will cost €4–€5 per kilogram by 2030. The same study says the cost of the gas from Australia, Chile and Spain will reach €3.1, Morocco €3.2 and the United Arab Emirates €3.6. It predicts that liquid ammonia and hydrogen from Chile and Australia into Europe will match domestic production costs by 2030.

It is explicit US policy to reduce the cost of producing clean hydrogen by electrolysis to $2 per kilogram by 2026 and $1 per kilogram by 2030. A recent government report states that the US is on course to reach $1.50 per kilogram in 2035. The production tax credit of up to $3 per kilogram, introduced in the Inflation Reduction Act, will be the key to incentivizing current producers of gray hydrogen to switch, moving the US closer to the goal of decarbonizing the refining and ammonia sectors.

THE CARBON FACTOR

The price of carbon is another factor governing the speed of green hydrogen adoption. The EU's Emissions Trading System and carbon taxation policies are two price levers. According to the World Bank, regional, national and subnational carbon-pricing initiatives in 2021 covered 22% of global GHG emissions.

A KPMG reports suggests the carbon price would have to be higher than $235 per tonne of CO_2 to make green H_2 cost-competitive with gray. The UN Global Compact believes that $100 is the minimum price needed to spur innovation, unlock investment and shift market signals in line with the 1.5–2 °C pathway. This is far from being achieved.

The current average explicit carbon price in the world economy is estimated to be only $2 per tonne of CO_2.

There is a long way to go. The latest Hydrogen Council Insight report issues a timely warning that the green hydrogen industry is "maturing during a time of strong headwinds which could slow deployment, including strained supply chains, labour shortage, energy performance contracting (EPC) capacity, increasing inflation and interest rates, and permitting delays."

The report says, soberingly, that "by 2030, an increase of more than twenty-fold in current investment would be required to track toward net zero objectives. Resource and equipment needs remain critical to prevent infrastructure bottlenecks."

Yoshinori Kanehana, chairman of Kawasaki Heavy Industries and co-chair of the Hydrogen Council, comments: "Taking action at the scale required is a learning journey for governments, industry and the public. Maintaining strong communication and relationships will help us to achieve our goals for the energy transition, together."

CALL TO IMPACT

1 The current average carbon price is $2 per tonne of CO2. It needs to rise to $100 to unlock investment in green hydrogen.

2 A more than twentyfold increase on current investment in green hydrogen is required by 2030 to put the world on track towards net zero objectives.

3 Strong international communication and relationships will help the world to reach its goals.

THE NEW WORLD OF HYDROGEN

A common architecture is developing for the world's fast-emerging hydrogen economy: country-level hubs or valleys, connected by pipelines and, for shipping, international hydrogen corridors.

A HYDROGEN "HUB" OR "VALLEY" is a location in which clean hydrogen-related processes and industries are concentrated. It's proving a popular model worldwide. A hub can also be understood as group of buildings linked by a pipeline serving different functions in the hydrogen value chain. Hubs often feature carbon capture utilization and storage (CCUS), usually associated with geological disposal of unwanted carbon dioxide.

Mission Innovation (MI), a global clean energy initiative launched at COP 21 in 2015, has identified more than 80 hubs worldwide. Three-quarters are in Europe, followed by the Americas and Asia Pacific, with the fewest in the Middle East and Africa. Germany has the most hubs of any country. The number of hubs does not correlate with the number of individual projects, including those on a gigawatt scale, in a given country.

In Europe and the US, hydrogen hubs are often located in traditional areas of heavy industry, power generation and petrochemicals, frequently in coastal locations with deep-water ports. Some are set to be the nodes of the world's "hydrogen corridors."

Hubs have internal synergies and attract government funding, subsidies and investment. They have good PR value as symbols of future-facing strategy and can be promoted nationally and locally, often as the "first" or the "largest in the world." In the hubs of cold countries, renewable energy for green hydrogen comes primarily from offshore wind farms. Warmer countries – for example, in Africa, South America and the Middle East – also have access to substantial solar power.

UK HYDROGEN CAPITAL

In the UK, Net Zero Teesside on the northeast coast has been nominated by the government a "low-carbon industrial cluster." The initiative began in 2016 before the UK's hydrogen strategy of 2021. But this, and subsequent developments, have led to Teesside being described as the UK's "hydrogen capital."

The industrial area lies at the mouth the River Tees, close to the oil and gas fields of the southern North Sea, which were developed from the 1960s and are now coming to the end of their lives. Typical of many areas in Northern Europe, this is a densely populated conurbation, with a history of coal mining, iron and steel manufacture and shipbuilding. A once thriving steel industry, supporting more than 90 blast furnaces next to the Tees, had virtually disappeared by the end of the 1970s.

Known as a center of gray hydrogen production and oil refining, Teesside, with a population of half a million people, has reinvented itself as an area at the forefront of the UK's carbon reduction plans. A ten-point green industrial strategy, which included low-carbon hydrogen as point two, was announced in 2020.

The founding partners of Net Zero Teesside include oil companies BP, Equinor, Shell and Total; France-based EDF energy; the UK's largest gas company, BOC; Saudi electrical company alfanar; and French-based waste giant, Suez.

Offshore wind turbines will deliver energy to BP's HyGreen Teesside facility, which is targeted to produce 600 MW of green hydrogen by 2030, fuelling a hydrogen transport hub able to power 10,000 trucks a year. BP's H2Teeside will manufacture blue hydrogen to decarbonize local industry. It will share pipework with NZT's 840 MW state-of-the-art gas-fired power station to store 12 Mt of CO_2 a year beneath the North Sea.

Alfanar's Lighthouse project will manufacture green fuels. The Suez 30 MW Teesside energy-from-waste plant is already turning 400,000 tonnes of waste a year into power and heat for local homes. In a connected project, Redcar on Teesside has been selected as a trial "hydrogen town."

Northern Gas Networks is to supply 2,000 homes with locally produced green hydrogen from 2025. With the electric heat pumps providing an alternative, experts are still debating whether it will be economic to use green hydrogen as a partial or total replacement for natural gas for home heating in northern Europe. The outputs of the Redcar Hydrogen Community are keenly awaited.

It's estimated that, together, the UK's six industrial CCUS areas will be able to store more than 35 Mt of CO_2 a year – a substantial proportion of the UK's industrial emissions. On a global scale, this model of industrial decarbonization could make a significant impression on reducing global warming.

PARAGUAY'S GREEN PLANS

Far away from Teesside, Paraguay is a landlocked country in South America with a population of some 7 million people and a windy tropical and subtropical climate. Its topography is swampland, forest and savanna. The country's Itaipu hydro electric dam in the southeast of the country was built jointly with Brazil in 1984 – one of the largest and most expensive civil engineering projects ever constructed. The dam's 14 GW hydroelectric power plant is the second-most powerful in the world. China's 23 GW Three Gorges Dam, spanning the Yangtze River, in Yiling District, wins the top spot.

Paraguay has an abundance of low-cost renewable energy, providing more than its entire power needs. It exports electricity to Brazil – at an unfavorable price, a continuing source of controversy – but there is a lot left over. Excess electricity generated by the Itaipu plant is key to an innovative project devised by ATOME Energy, the first green fertilizer production company to be listed on the London Stock Exchange. Set to open in 2025, ATOME's green hydrogen, ammonia and fertilizer facility will be located in Villeta, 35 kilometers from Paraguay's capital Asuncion, connected by the Paraguay River to fertilizer distribution companies and the Port of Buenos Aires in Argentina. It will produce up to 250,000 tonnes of green calcium ammonium nitrate a year. The energy used will be baseload renewable power from the Itaipu dam. US engineering consultancy AECOM designed and is managing the project. ATOME has secured a 120 MW Power Purchase Agreement and land for the facility, making it one of the world's first commercial-scale green ammonia schemes. It will be the largest green ammonia facility in South America, supplying agricultural fertilizers.

Synthetic fertilizers made from gray hydrogen produce 2.6 Gt of carbon a year – more than global aviation and shipping combined. Green ammonia, manufactured from clean hydrogen, could greatly reduce agriculture's contribution to global warming. Locally produced, it could shield countries in the Global South from the volatility of fertilizer prices, which are currently linked to the oil-based petrochemical industry.

ATOME has plans to duplicate its South American model in Costa Rica and Iceland. It's a good example of green hydrogen being used to generate export income. ■

CALL TO IMPACT

1. Hydrogen hubs can be promoted as symbols of future-facing, low-carbon industrial srategy.
2. Hubs can also provide a geographical focus for inward investment, trial projects, subsidies and tax breaks.
3. Since they are often located in areas that relied on coal or oil-based industries, their development can help to level up parts of countries that have economically fallen behind.

NEOM
PUTTING THEORY INTO PRACTICE

The world's largest green hydrogen facility is coming to life in NEOM in Saudi Arabia. We interviewed Prof. Mani Sarathy, one of the project leaders.

MANI SARATHY

Professor of chemical engineering at King Abdullah University of Science and Technology (KAUST) and associate director of Kaust's Clean Combustion Research Center, the Canadian Mani Sarathy holds a doctorate from the University of Toronto. Working for ENOWA.NEOM, a one-third shareholder in the Neom Green Hydrogen Company (NGHC), Sarathy has assisted in translating a theoretical plan into a world-class physical asset for the past three years. NGHC's electrolyzers are set to begin producing green hydrogen in 2026.

The statistics are impressive. A joint venture among NEOM, Air Products, ACWA Power and energy and water company Enowa, the project will use nearly 4 GW of renewable energy from a mixture of solar and wind sources to supply alkaline electrolyzers manufactured by the German company Thyssenkrupp.

The electrolyzers will produce 600 tonnes per day of carbon-free hydrogen. This will be converted into an extremely valuable commodity – up to 1.2 Mt a year of green ammonia. Production is scheduled to begin in 2026.

Nadhmi Al-Nasr, chairman of NGHC and CEO of Neom, says, "In scale, this project is the first of its kind internationally, leading the world in the hydrogen revolution." In this interview, Prof. Sarathy talks about the perspectives of the NEOM facility and of the global markets for green hydrogen.

Prof. Sarathy, is the Neom Green Hydrogen Company plant really the world's largest green hydrogen facility?
It will be. These are expensive projects. None of the other large projects have announced this level of progress.

So this is not about size, but about implentation?
It is easy to say, "We're going to build this" or "We're going to build that." But then it gets complicated. First, you have to secure the land and the necessary permits and permissions. Then you have to design the facilities and secure contracts for all your suppliers. After that, you have to get the investment. The investors want to see a good return, so you have to provide a lot of information to them before they will commit. A project may be well-advanced but have no backers. NGHC is the world's largest project to have secured and signed off financial commitment with an $8.4 billion investment. In addition, the engineering is more than 30% complete.

Can you put the planned production of NGHC into a global perspective?
Currently, the world uses about 94 Mt of pure hydrogen a year and it's virtually all gray, coming from natural gas, with related CO_2 emissions. In this plant, planned production is 600 tonnes of green hydrogen a day, let's say 180,000 tonnes a year. That's a drop in the bucket. The International Energy Agency estimates that, to get to net zero, the world will need 200 Mt of clean hydrogen a year by 2030. So, we'll need not one, or five, or ten, but at least a thousand plants like the one at NEOM in the next ten years. By 2040, we will need 650 Mt of clean hydrogen, which will require more than 3,500 hydrogen plants like at NEOM.

With 3,500 plants like the one at NEOM, will mankind have wiped out the use of fossil fuels?
Not completely. Even with 80% renewable energy, you still need nuclear and fossil fuels for demand when renewables are unavailable. You're going to need carbon capture and storage because 10% to 15% of power will come from fossil fuels for peaking and reserve needs. Geological hydrogen storage will be useful for countries that have a wide seasonal variation in renewable supply.

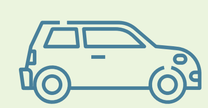
Let's do the math: One plant like yours costs $8.4 billion, as you just told us. Multiplied by 3,500, that's a whopping $30 trillion just for the construction of the green hydrogen plants mankind should build by 2040?
If you do the math with today's prices, yes. But that's not what will happen. For green hydrogen, I think the price will begin to drop steeply from where it is today. At least half of the production cost comes from renewable energy and those prices keep coming down. For deployment of solar energy and wind energy, the price is now 100% lower than the late 1990s, and prices continue to decrease. That's why Saudi Arabia is a good place for green hydrogen, because it's one of the cheapest places to obtain renewable energy.

And the other half of production costs?
The major part of it is the initial cost of building the electrolyzer facility. That's expensive today, but prices will decrease significantly. Over the next 10 to 15 years, the cost of electrolyzers should come down by about 50–60%. That's when we'll start seeing green hydrogen ↘

HOW MUCH HYDROGEN IS THAT?

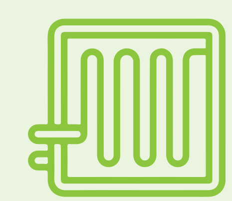
1 kg of hydrogen is enough to travel up to 100 km in a **Hyundai Nexo**

Travelling in a **Hyundai Santa Fe** uses 7.5 L of diesel or 9.3 L of gasoline



Driving a Hyundai Nexo compared to a diesel Hyundai Santa FE avoids **0.2 kg CO_2-e / km** driven or **20 kg CO_2-e per kilogram** of hydrogen used.

Hydrogen delivers 33.6 kWh of usable energy per kg, versus diesel which only holds about 12–14 kWh per kg.



In 2021, a Toyota Mirai hydrogen fuel cell vehicle covered **more than 1,000 km on a single tank of fuel.** Hydrogen consumption was 0.55 kg/100km

↘ being used widely in many applications.

And in which applications? Buildings? Cars? Ships? Planes? Factories?
In my opinion, the green hydrogen market will start off with heavy transportation, because that segment is hard to decarbonize – trains and trucks and ships. Then steel making, because the cost of the energy to make the steel is not the major contributor to the final price of steel sold on the market. The green steel made with clean hydrogen will go into automobiles and buildings.

You didn't mention airplanes.
For the synthetic and e-fuels market, mainly for aviation, the price of clean hydrogen will need to come down more, because every time you transform hydrogen into something else, there are losses and additional capital cost requirements. In aviation, you can't use hydrogen for long-haul aircraft and that's unlikely to happen any time soon. But for short-haul aviation – say regional flights of up to 1,500 kilometers – hydrogen is not only theoretically applicable, but already in the market.

Flying with hydrogen?
Some companies, like ZeroAvia and Universal Hydrogen, are using turboprop technology. They load hydrogen storage tanks into the fuselage, and they have fuel cells, powering props run by electric motors.

That's again lots of energy transformation. Space rockets use hydrogen as fuel – why can't planes do it?
Of course they can. Or better: they could. You could have hydrogen running combustion engines turning the props. But you can't store that much hydrogen. It would take up 20% of the cargo space. Freezing hydrogen cryogenically to make it more energy dense, as you do it for rockets, is super expensive. That technology has a long way to go. A company called Kawasaki is working in that area.

Is hydrogen safe?
What's dangerous about hydrogen? Millions of tonnes of gray hydrogen are produced safely today. Hydrogen is already safely transported in trucks and pipelines. We just don't see it since the scale is still small compared to the distribution of fossil fuels. Green hydrogen storage tanks are made out of proven carbon-fiber composite technology. They can store hydrogen at 700 bar, they are rated up to 1.25 times that pressure, and they are fireproof. They also have pressure relief valves. They won't explode.

Will the car market be for battery electric or hydrogen?
Right now, research and development go both ways, and for good reasons. Toyota and Hyundai are developing hydrogen fuel cell electric passenger vehicles. Toyota is more on the route of battery electric hybrids and fuel cell electric vehicles. I think Europeans are going more towards purely battery electric, mainly driven by regulations. Japan and Korea will give more support to hydrogen for light passenger vehicles, because they are limited in the amount of electricity they have. Even in Europe, predictions have started indicating that if you want 100% battery electric, there won't be enough power for anything else.

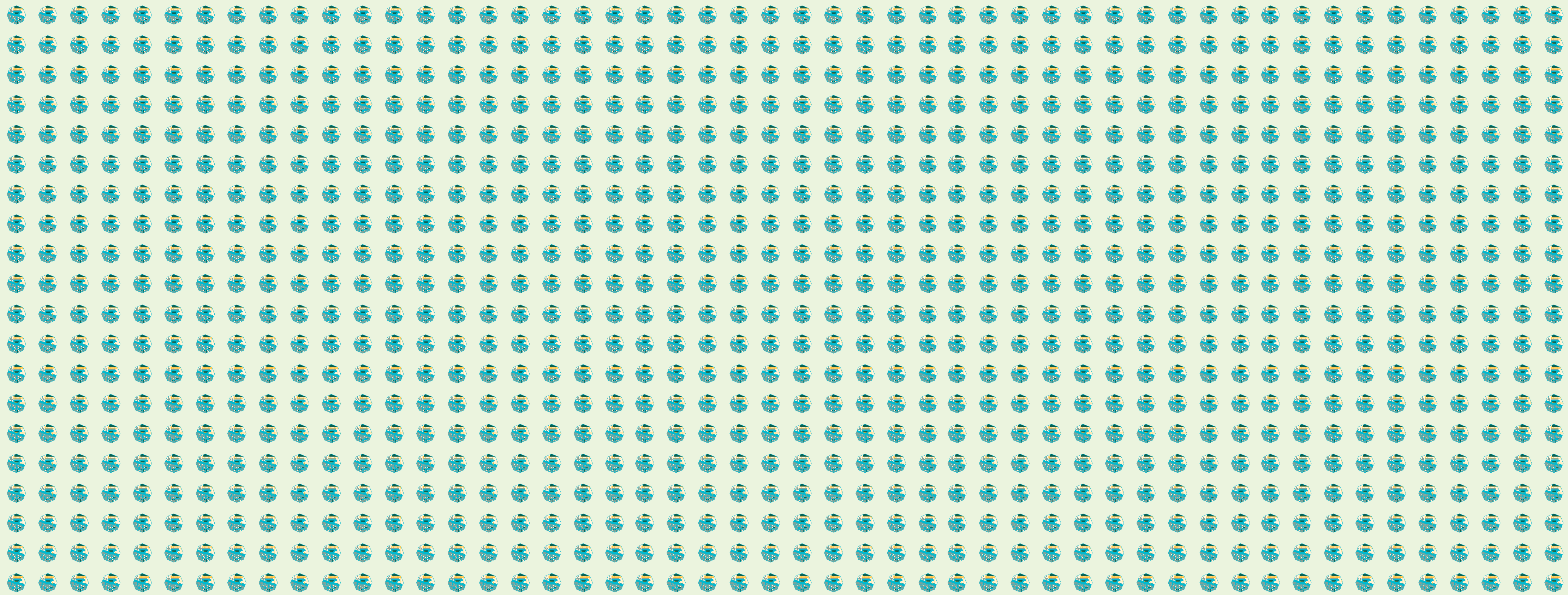
> **"The green hydrogen market will start off with heavy transportation: trains, trucks and ships. Then steel making will follow."**

Do I detect some skepticism about electromobility?
I'm just doing the math. Right now, battery electric is the trend. Battery electric vehicles account for almost 10% of new car sales and this is growing, but the overall share of vehicles on the road is still small – they account for less than 3% of the total automobiles on the road.

You don't think this growth can continue?
Once you start reaching penetrations of 40–50% of the automotive market, there will be material constraints in making so many batteries for electric vehicles. Additionally, there will be issues with lack of charging stations and electricity availability on the grid.

And then the bad old combustion engine will rise again like the phoenix?
Technologically, there's always the option to return to fossil fuels. But it is not a good idea, neither today nor tomorrow. The better idea is to use another kind of combustion engine: hydrogen in fuel cell electric vehicles.

Just because of their ecologic advantages?
There are more positive aspects. Hydrogen can be readily dispatched, and vehicles can be refilled in a couple of minutes, as opposed to 30-60 minutes for battery electric vehicles. But for the time being, fuel cells are not expected to dominate the passenger car market. It really makes the most sense for heavy duty applications for which batteries are not viable, because of their weight.



1000X NEOM IN 2030 NECESSARY
Each dot represents one electrolyzer like the one under construction at NEOM. All the dots combined show the amount of hydrogen the world should produce in the year 2030 to stay on track for its climate targets.

A DREAM THAT'S COMING TRUE

It's been touted as a "wonderfuel" for 150 years. Why has it taken so long for hydrogen to begin fulfilling its potential?

HYDROGEN, THE SIMPLEST AND most abundant element in the universe, is set to change how humans move around, heat buildings, grow their food, and make concrete, glass and steel. It will help to reshape the world as we move into the post-oil era, from the middle of this century and into the next.

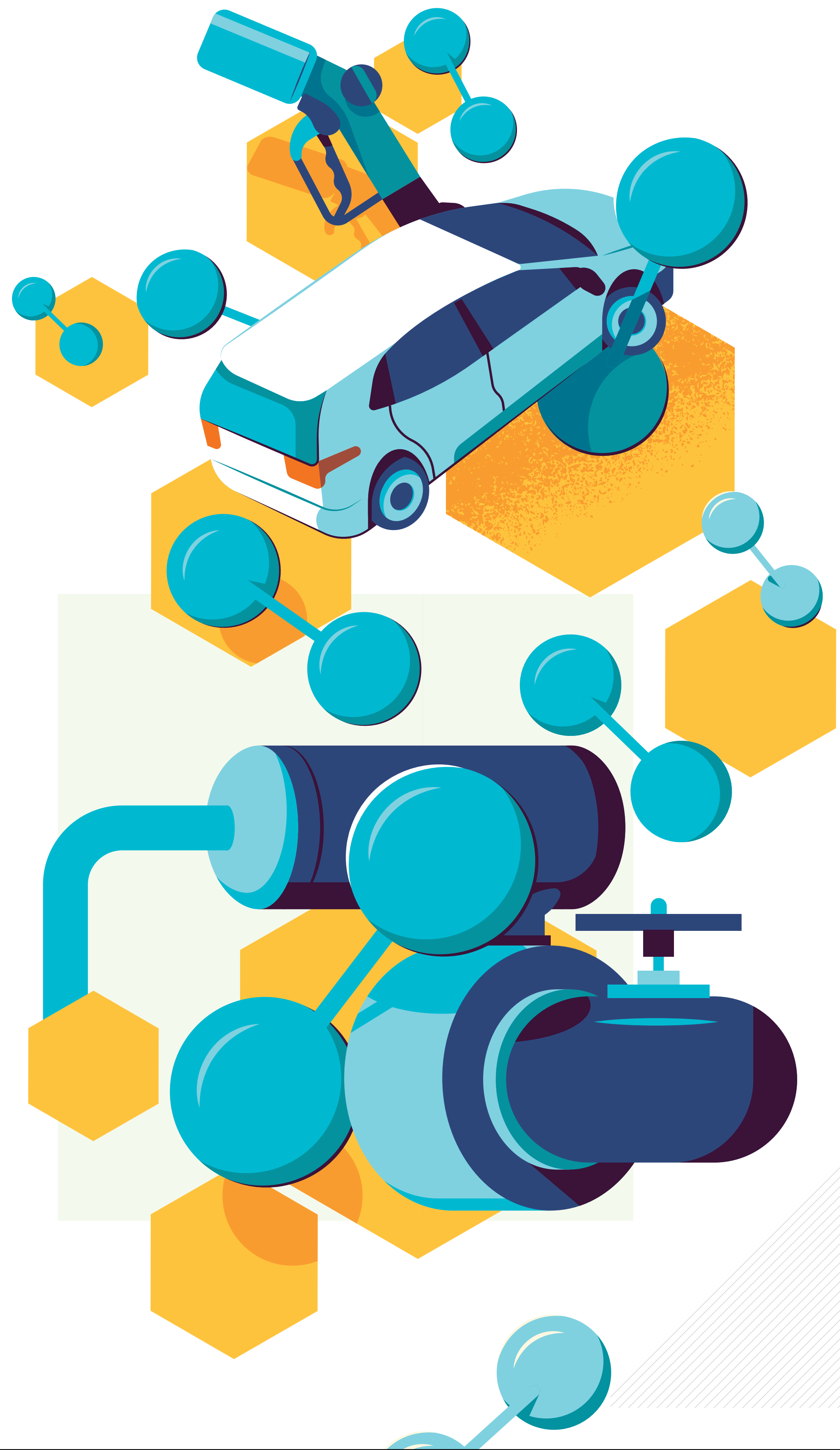
It was predicted a long time ago. In 1875, science fiction author Jules Verne wrote in his novel, The Mysterious Island: "I believe that water will one day be employed as fuel, that hydrogen and oxygen, which constitute it, will furnish an inexhaustible source of heat and light of an intensity of which coal is not capable. Someday the coal-rooms of steamers and the tenders of locomotives will, instead of coal, be stored with these two condensed gases."

Verne was right. But it has taken 150 years for his prediction to even begin to become true. To understand why it has taken so long, it's helpful to know some history and some chemistry. Although it began with the universe, humans did not identify hydrogen as a discreet substance until alchemists and natural philosophers came along in the 16th century. One day in 1766, Henry Cavendish, a wealthy English gentleman and pioneer chemist, made a breakthrough.

Cavendish added zinc particles to chloric acid. He observed a bubbling gas being formed. Through meticulous experimentation, he discovered its properties – it was insoluble in water, lighter than air and could be ignited by a spark. When it burned, it produced water. Cavendish named his discovery "inflammable air." He correctly calculated that water was composed of two parts hydrogen to one part oxygen.

He thought that he had encountered "phlogiston" – a substance thought by 18th-century chemists to exist in all combustible bodies. In fact, he had inadvertently isolated the simplest, lightest and most abundant element in the universe, making up 75% of its mass. Hydrogen's nucleus consists of one proton orbited by a single electron. At standard temperature and pressure, it is a colorless, odorless and tasteless gas. Free hydrogen simply escapes into the atmosphere and dissipates. Most of the hydrogen on earth exists in molecular forms, such as water and organic compounds.

In 1783, Cavendish's "inflammable air" was named hydrogen ("water-former") by the father of modern chemistry, Antoine Lavoisier. It has proved pretty useful, both theoretically and practically. Because of its simple atomic structure, the study of the hydrogen atom was central to the development of the theory of the conservation of matter and understanding atoms and quantum mechanics in the 20th century.



Hydrogen gave us the first form of commercial long-distance air travel – the airship – including transatlantic passenger services through the 1930s. The Hindenburg disaster, in which a German airship caught fire in 1937 in New Jersey, causing the deaths of 36 people, led to the end of the airship era.

The Haber-Bosch process, invented in 1918, which converts nitrogen and hydrogen to ammonia that can be used for fertilizer, gave rise to an agricultural revolution that vastly increased crop yields and made life possible for millions who would otherwise have starved. Vast quantities of hydrogen are used by the world, particularly to make ammonia (NH_3) and methanol (CH_3OH) for the world's chemical industries, but they are the black and gray kind. Paradoxically, hydrogen manufacture has been a major cause of global warming. In its green and blue forms it can make an enormous contribution to slowing global warming.

CHEMICAL CHARACTERISTICS

Hydrogen has the highest energy per mass of any fuel – three times more energy per kilo than petrol. But, as a fuel, it is problematic. Why? Because of of its low energy per unit volume and the smallness of its molecules. If you stored hydrogen gas in a plastic jerry can and kept it in your shed, there wouldn't be enough of it to burn for very long, and the gas would escape through the tiniest holes. By the next day, the can would be empty. But your jerry can of petrol would still be full and ready to be used.

Hydrogen is too leaky to be moved around in grids built for natural gas, methane (CH_4). One way around this is to line them with plastic, or you can simply blend a proportion of hydrogen into your gas grid – up to 20% without it escaping. For storage, hydrogen must be compressed to very high pressure (generally 5,000 to 10,000 PSI) or stored as a liquid. That means cooling it to less than -253 °C, known as a cryogenic temperature, which requires specialist and expensive equipment – and a lot of energy. There is another way to store and transport it – you can convert it ↘

EVOLUTION OF ENERGY

Lower Palaeolithic (up to 1.5m years ago)
humans begin using fire

↓

200 BC
Chinese use coal for heating

↓

1712
Invention of steam engine leads to deep coal mining

↓

1766
Henry Cavendish discovers hydrogen, "inflammable air"

↓

1800
Electric battery: voltaic pile. Discovery of electrolysis

↓

1804
Steam-powered locomotive, Richard Trevithick

↓

1807
Rivaz car uses combustion engine powered by hydrogen and oxygen

↓

1832
Electric motor, Willam Sturgeon

↓

1838
Sir William Gove invents fuel cell

↓

1838
SS Great Western, transatlantic steamship service

↓

1859
Lead acid battery, Gaston Planté

↓

> “Taming liquid hydrogen is one of the significant technical achievements of 20th century rocketry.”
>
> **NASA**
>
> Official NASA website

into ammonia or methanol. Both have a higher volumetric energy density than hydrogen and are easier to store and transport.

Another way to convert hydrogen to energy was discovered in 1838 – the fuel cell. Like a battery, a fuel cell has a positive electrode, a cathode; a negative electrode, an anode; and a chemical medium between them, an electrolyte. But it only produces electricity when a fuel is added – in this case hydrogen gas. The three outputs are electricity, water and heat. This can be understood as the reverse of the electrolysis process in which electricity and water produce green hydrogen and oxygen.

Using noble metals such as platinum for anodes, because of their resistance to corrosion, fuel cells last a long time – as long as the vehicle that they are installed in, unlike lead and acid and lithium-ion batteries, which must be periodically replaced. Fuel cells’ vehicles are highly efficient, but they are expensive to build and buy and, as hydrogen is not easily available and its production and distribution costs are high, they can only function in an environment that has an industrial infrastructure to manufacture green hydrogen. In most countries, such infrastructure will take decades to install.

So that should be the end of the story. The reason it isn’t is global warming. Unlike hydrocarbons, hydrogen burns without producing the greenhouse gas carbon dioxide. It burns at a very high temperature and its only ignition product, as Cavendish discovered back in 1765, is water vapor.

For transport, it’s a great fuel for moving large, heavy objects, such as trucks, trains and ships, for which the lithium-ion batteries required would be too cumbersome. Green hydrogen or its variants can be used in the engines, or green hydrogen can power cells powering large electric motors.

For the passenger and cargo ships of the future, which will take over from those vessels burning “bunker fuel” today, prototypes are being made that run on liquid hydrogen or liquid ammonia and biomethanol or e-methanol. Manufacturers are building experimental models of aircraft using both technologies, in some cases blending biofuels and conventional fuels.

Not surprisingly, hydrogen, especially combined with oxygen, makes a great propellent. Rocketry exposed the difficulties of using hydrogen to the full. It has been said by NASA that “taming liquid hydrogen is one of the significant technical achievements of 20th century American rocketry,” and that the lack of Soviet liquid-hydrogen technology was a serious handicap in the race of the two superpowers to the moon.

Cryogenically frozen hydrogen made metal fuel tanks brittle and its small molecules were found to leak through

1860
Lenoir Hippomobile. Car powered by electrolyzing water

1882
First coal-fired power station, Edison Electric Light Station, London

1886
Karl Benz patents gasoline-powered automobile

1888
Andreas Flocken, first real electric car

1903
First powered flight, Wright Brothers

1910
Haber-Bosch process for ammonia

1919
Non-stop transatlantic flight, Alcock and Brown

1932
Alkaline hydrogen-powered fuel cell, Francis Thomas Bacon

1938
Atomic fission, Lise Meitner and Otto Frisch

1939
First jet-powered flight, Heinkel He 178

1945
US tests atom bomb

1947
First supersonic flight, Charles Yeager, USAF

welded seams. The gas must be protected from heat from engine exhaust and air friction during flight through the atmosphere and, in space, the radiant heat of the sun. Liquid hydrogen expands and must be vented. The problems were solved. Liquid oxygen and hydrogen were burned in the main engine of the Space Shuttle from 1981 to 2011.

EVOLUTION OF THE ELECTROLYZER

Like the fuel cell and the hydrogen-powered car, electrolysis has been around for a long time. In 1800, the same year that the electric battery appeared as the Voltaic pile, using copper and zinc and salt water as an electrolyte, English scientists William Nicholson and Sir Anthony Carlisle discovered that applying electric current to water produced hydrogen and oxygen gases.

Akaline water electrolyzers were industrialized by the beginning of the 20th century, but as it became more economic to make hydrogen by steam methane reforming, the electrolysis method declined. That changed with new technology. In the 1960s, the space race, soon followed by a global oil crisis, turned the attention of US science and industry to improving the efficiency of both the electrolyzer and the fuel cell. It seemed at the time – the perception was a hundred years early – that space flight would soon become commonplace and that US roads were set to be filled with hydrogen-powered cars.

The alkaline electrolyzer using a liquid electrolyte solution had been in use for more than a century. Invented in the 1960s by General Electric, the proton exchange membrane (PEM) electrolyzer

was a huge improvement. Compact, matching the intermittency of renewable energy and producing high-purity hydrogen, PEM technology has further evolved since then. It forms the basis of today's "super electrolyzers," such as Air Liquide's 20 MW PEM electrolyzer in Bécancour, Canada, which produces up to 8.2 tonnes of low-carbon hydrogen a day.

Technology never stands still. Solid oxide electrolysis cell (SOEC) electrolyzers use solid ceramic electrolytes and operate at a high temperature (between 500 and 850 °C). They could be more efficient than PEM electrolyzers. NASA successfully deployed this technology for its Perseverance rover on its 2020 Mars mission, but it is not yet being used commercially. Photoelectrolysis, using only sunlight to separate water molecules, is still at an experimental stage and other technologies look promising, including the pyrolysis (heating without oxygen) of methane, which produces a carbon-sequestering soil additive called biochar.

In the last two decades, the combination of larger and more efficient elecrolyzers and ever-evolving and cheaper wind turbines and solar panels has put green hydrogen in the running, but we are still only at the beginning. Cost remains a factor (see p.32). Less than 1% of the hydrogen being made today is green or blue. ■

CALL TO IMPACT

1 If we are to win the battle against global warming, gray hydrogen must be substituted for the blue and green kinds, manufactured without CO2.

2 Solid oxide electrolysis cell (SOEC) technology looks like providing the next generation of electrolyzers and fuel cells.

3 Production costs mean that green hydrogen is still not competitive with gray. But that is changing as technologies are scaled up and the cost of renewable solar and wind energy goes down.

1952
US tests hydrogen bomb

1954
First nuclear power plant, Obninsk, USSR

1954
Bell laboratories silicon solar cell

1961
NASA rockets use alkaline fuel cells for heat and power

1967
NASA's Saturn V rocket powered by liquid hydrogen and oxygen

1967
General Motors' Electrovan, first hydrogen fuel cell car

1974
Japanese hydrogen-fueled car, Musashi 1

1976
Lithium-based battery patented

1986
Chernobyl nuclear disaster

1991
First offshore wind farm, Ørsted, Denmark

2004
Musk's Tesla Roadster, powered by lithium-ion batteries

2011
Fukushima nuclear disaster

2013
First commercial fuel-cell car, Hyundai ix35 FCEV

MIXED ADOPTION

Experts hope that the 2020s will be the key decade for the scaling up of hydrogen technologies to the point at which they take off. However, progress internationally is mixed and varied.

TOBY UPPINGTON IS GLOBAL hydrogen leader at one of the world's largest infrastructure consulting firms, AECOM. He explains that the adoption of green hydrogen is happening at a different rate and pace across the world.

AECOM is Fortune 500 company that employs about 50,000 people in more than 150 countries. Its stated mission is to solve the world's most complex infrastructure challenges and deliver sustainable legacies for future generations, so hydrogen fits the bill.

AECOM's first activity in this area was building hydrogen filling stations for cars in northern Europe. Uppington says: "Hydrogen-powered cars were easy for consumers to understand. But the market has changed. In Europe, the car market has shifted to electric vehicles. It is now heavy-duty lorry fleets, trains, ships and short-haul aircraft that are moving to hydrogen or its derivatives like ammonia or e-methanol."

In many countries, the war in Ukraine and the ensuing energy crisis have led to a reevaluation of energy needs and security of supply. Strategic decisions need to be made. In cold countries, how much do you spend retro-insulating your draughty buildings and how do you pay for that? Do you put green hydrogen, which is still scarce, into your country's gas grid? Or use it to decarbonize your heavy vehicles? How quickly do you retire your oil and gas reserves? How big a role do you assign to carbon capture, utilization and storage? In most developed countries, the growth in grid demand caused by electrification will raise questions about the role of nuclear power.

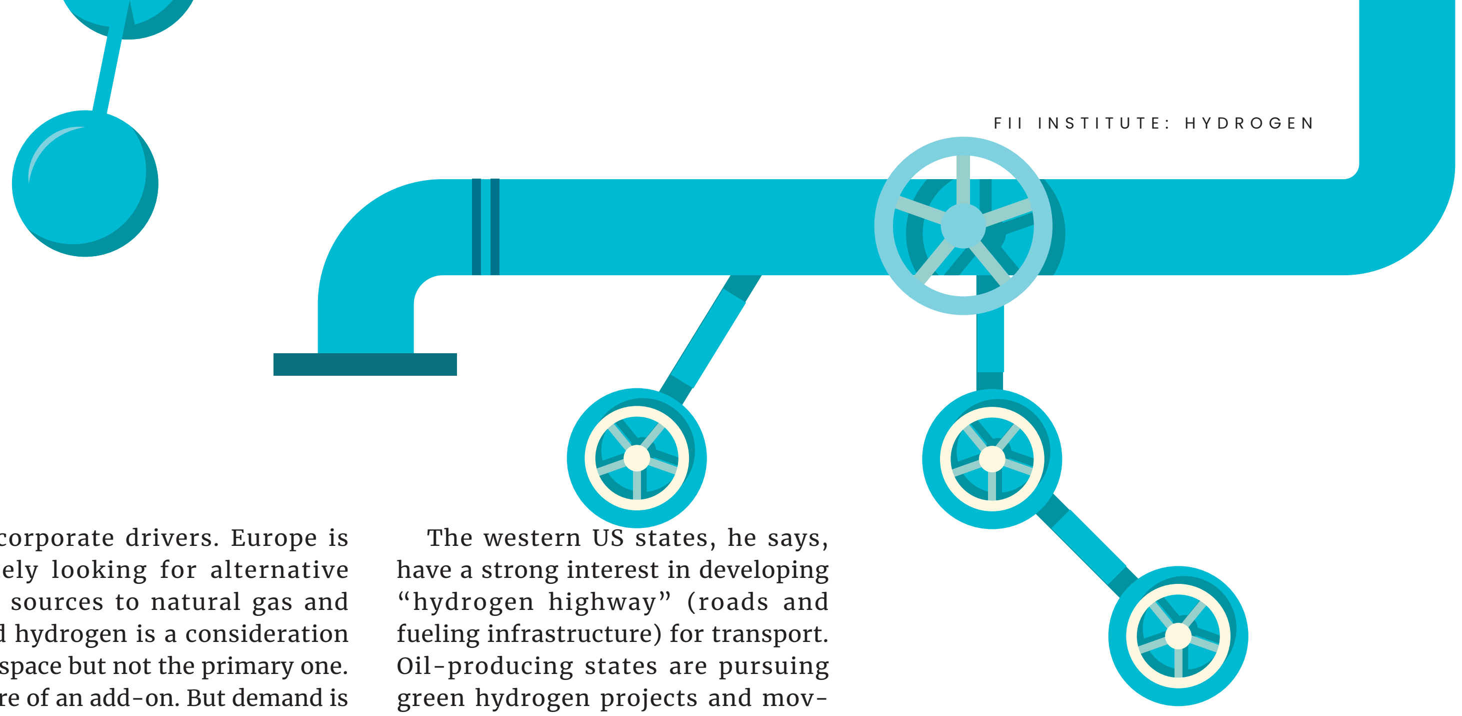
Such questions require specialized help. Companies like AECOM, which have engineering and policy expertise across multiple global markets, are well equipped to help. Uppington explains: "We aim to provide an end-to-end service. We can advise governments on incentivizing decarbonization and we explain their technology choices. For green hydrogen, we'll help them evaluate the right electrolyzers to adopt. We'll help with planning, permitting and meeting regulatory requirements, concept design, and then selecting and managing technology vendors. We can also manage the non-process infrastructure, such as road and water connections."

VARIABLE SPEED DEVELOPMENT

From AECOM's point of view the world is moving ahead at variable speeds. It's an unusual and fast-moving market with lots of players of different kinds and sizes. Uppington says: "You have the traditional oil and gas majors and energy companies. You also have public bodies, such as councils, which are decarbonizing their fleets. And you have new entrants that have come from nowhere and are growing fast."

A common development model for hydrogen, and a feature of most national plans, is the hydrogen "hub" or "valley" (see p.18). Uppington describes a hub as a place where "there is a nexus of public incentives and private sector generation, for production, distribution and offtakes." In the UK, AECOM is working with companies participating in two English hubs – Net Zero Teesside and Zero Carbon Humber. For Aberdeen, a smaller hub in Scotland, it is the overall infrastructure coordinator.

Uppington adds: "For us, it's definitely a worldwide market. But some regions and countries are moving faster on hydrogen than others. Northern Europe has been the fastest to develop and where we have got the deepest in terms of our delivery and customer relationships. It's due to regulatory ↘



and corporate drivers. Europe is definitely looking for alternative energy sources to natural gas and oil, and hydrogen is a consideration in that space but not the primary one. It's more of an add-on. But demand is growing quickly."

US IS PICKING UP

He adds: "The US market was a little slower to develop. But as often happens, when the US decides to do something, it does so very quickly. We are currently seeing opportunities and incentives pulling us towards the US very rapidly, particularly since the stimulus that was provided by President Biden's Inflation Reduction Act."

The western US states, he says, have a strong interest in developing "hydrogen highway" (roads and fueling infrastructure) for transport. Oil-producing states are pursuing green hydrogen projects and moving to incorporate blue hydrogen into petrochemical processes with new carbon capture and storage infrastructure. The US is favored with good sites for solar and offshore wind farms that can be used to produce green hydrogen.

In South America, one of AECOM's projects is for Atome Energy, the first green hydrogen and ammonia production company listed on the London stock market. Uppington says: "Atome has developed a sophisticated green hydrogen electrolysis process and is looking at Paraguay as its first project. We did all the advisory and design work and are the owner's engineer, acting as the client's eyes and ears to manage the contractor doing the construction.

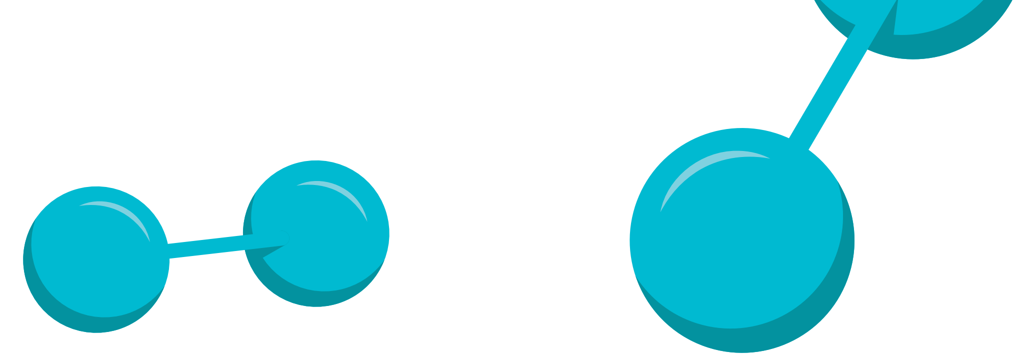
TSUNAMI OF OPPORUNITY

In Australia, AECOM has done high-end advisory work at state level. It is very interested in where Canada is going – the country is evaluating pink hydrogen produced via nuclear power – and in pursuing opportunities in Southeast Asia and the Middle East.

Christoph Noeres is head of green hydrogen at the German engineering company Thyssenkrupp Industrial Solutions, which has a contract to help deliver Saudi Arabia's Neom facility, one of the largest green hydrogen projects in the world.

Noeres told an energy conference last year that green hydrogen production is being bolstered by an additional 200 GW of solar and wind energy capacity annually, and that costs for both are falling rapidly.

Fiscal stimulus, development finance and private investment are being drawn to this area. Noeres says: "There's a tsunami of hydrogen opportunities coming up worldwide. We have never seen such a wave of projects in the past 10 to 20 years."

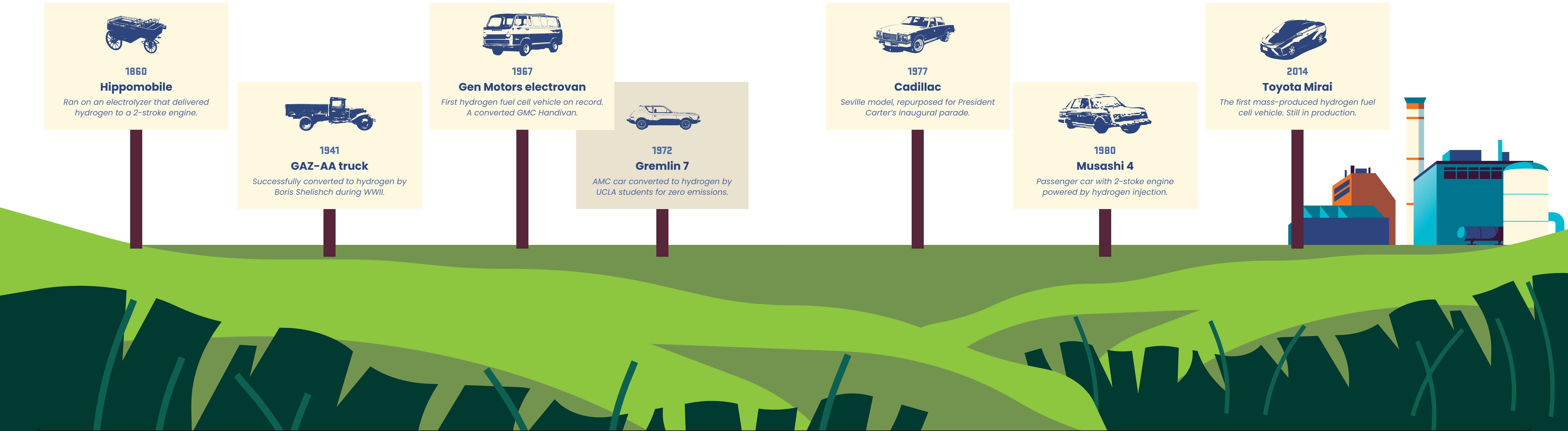


CALL TO IMPACT

1 Green hydrogen is being adopted at different rates across the world

2 The war in Ukraine has led to a global reevaluation of energy needs

3 A common development model is the hydrogen "hub" or "valley." These hubs can become a useful tool for the rapid scale-up of clean hydrogen production.



THIS TIME, LET'S GET IT RIGHT

Clean hydrogen is expensive and tricky to handle. It's not an easy fix for climate change. Care, due diligence and humility will be required in its deployment.

THE LAW OF UNINTENDED consequences has been around since the 17th century. It has been a factor in several of the strategies that humans have applied to anthropogenic climate change. One example is diesel. It was thought by European legislators to be a "cleaner" fuel than gasoline in global warming terms, and variable taxes in the late 1990s resulted in a mass switch to diesel cars. This had a disastrous effect on air quality, particularly as several manufacturers were lying about the emissions produced by their vehicles.

Biofuel offers another example. Its supporters argue that biofuels do not cause a net increase in carbon dioxide, because of the absorption of carbon through the life cycles of plants. The oil crisis of the 1970s led to the US applying large subsidies to new fuels from plants, including bioethanol, an alcohol made by fermenting crops.

The subsidies grew, as the world sought alternatives to fuels that produce greenhouse gases. Today, the US is the world's largest producer of corn ethanol, which accounts for 26% of corn-producing land. But to many environmentalists, the widespread adoption of biofuels produced by monoculture has been an environmental disaster. They argue that the downsides – diverting huge areas of land from food production and using intensive farming methods and chemical inputs that reduce biodiversity and degrade soil quality – have far outweighed the benefits to the planet.

DANGER OF LEAKAGE

So could green hydrogen be the biofuel of the future – a solution to climate change that harms the planet in unforeseen ways? A report produced for the European Geosciences Union explains that hydrogen's small molecules can escape across the entire value chain, including from electrolyzers, compressors, liquefiers, storage tanks, geologic storage, pipelines, trucks, trains, ships and fueling stations. Furthermore, some hydrogen is deliberately vented and purged from systems. The report warns that the amount of emissions from leakage, venting and purging from existing hydrogen systems is unknown.

It notes that hydrogen is an "indirect greenhouse gas." When it escapes into the atmosphere, up to 80% of hydrogen is estimated to be removed by soils via diffusion and bacterial uptake. The remaining gas is oxidized by reacting with the naturally occurring hydroxyl radical (OH). The oxidation of hydrogen leads to increased concentrations of methane, ozone and water vapor –all greenhouse gases – in the troposphere and stratosphere.

The report concludes: "A growing body of research has affirmed that the warming effects from hydrogen emissions are consequential, with new work showing that hydrogen's indirect warming effects are twice as high as previously recognized."

Hydrogen leakage across the value chain is a concern, it says, regardless of production method. But blue hydrogen "is subject to additional impacts on the energy balance due to residual emissions of CO_2, as well as emissions of methane from the natural gas supply value chain."

The report concludes: "Minimizing leakage will be essential to the effectiveness of hydrogen as a climate change mitigation strategy. It is easier to address and minimize hydrogen leakage when designing a system vs. retrofitting one, we have the rare opportunity to get ahead of this issue before the infrastructure and systems are widely deployed."

A report commissioned by the UK government from the universities of Cambridge and Reading also found that the presence of atmospheric hydrogen could increase concentrations of greenhouse gases. "There is great potential using hydrogen to save a lot of emissions of carbon dioxide, but it's really important to keep the hydrogen leakage rates down," says Nicola Warwick, lead author of the UK study and a National Centre for Atmospheric Science research scientist at the University of Cambridge.

> "It's really important to keep hydrogen leakage rates as low as possible."
>
> **NICOLA WARWICK**
> Research scientist, Cambridge University

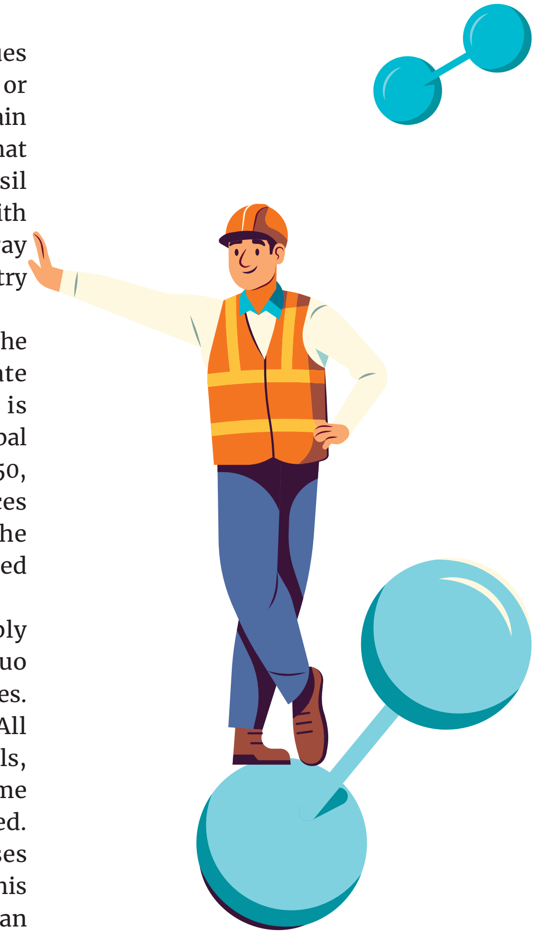
Combusting hydrogen at high temperatures produces nitrogen oxides (NOx), toxic gases whose emissions need to be permitted by an environmental regulator. It's not an issue for fuel cells, and in hydrogen-fired power stations the NOx could be scrubbed. But what about someone heating their home with hydrogen? The potential impact for air quality needs more research.

Some environmentalists believe that the technology enabling blue hydrogen, carbon capture utilization and storage, should be ruled out of any climate change mitigation strategy. The US NGO Environmental Working Group argues that it has "not been proven feasible or economic at scale and can only contain a fraction of source emissions" and that it will "prolong dependence on fossil fuels and delays their replacement with renewable alternatives." They portray CCUS as a ploy by the oil and gas industry to keep itself in business.

It's an easy argument to counter. The Intergovernmental Panel on Climate Change has concluded that CCUS is essential to all scenarios reducing global warming to a maximum of 1.5 °C by 2050, and it's clear that from green sources alone we won't be able to supply the quantity of clean hydrogen we'll need for the energy transition.

A hydrogen economy can't simply be a way of preserving the status quo – the profligate use of finite resources. It's too expensive. The IEA says: "All energy carriers, including fossil fuels, encounter efficiency losses each time they are produced, converted or used. In the case of hydrogen, these losses accumulate across the value chain. This makes hydrogen more expensive than the electricity or gas used to produce it."

Because it is costly and has to be made, using hydrogen in new ways will oblige the world to reevaluate its relationship to energy production and consumption. That's where humility comes in. It will require us to learn from our mistakes and look at the world in a new way. ■

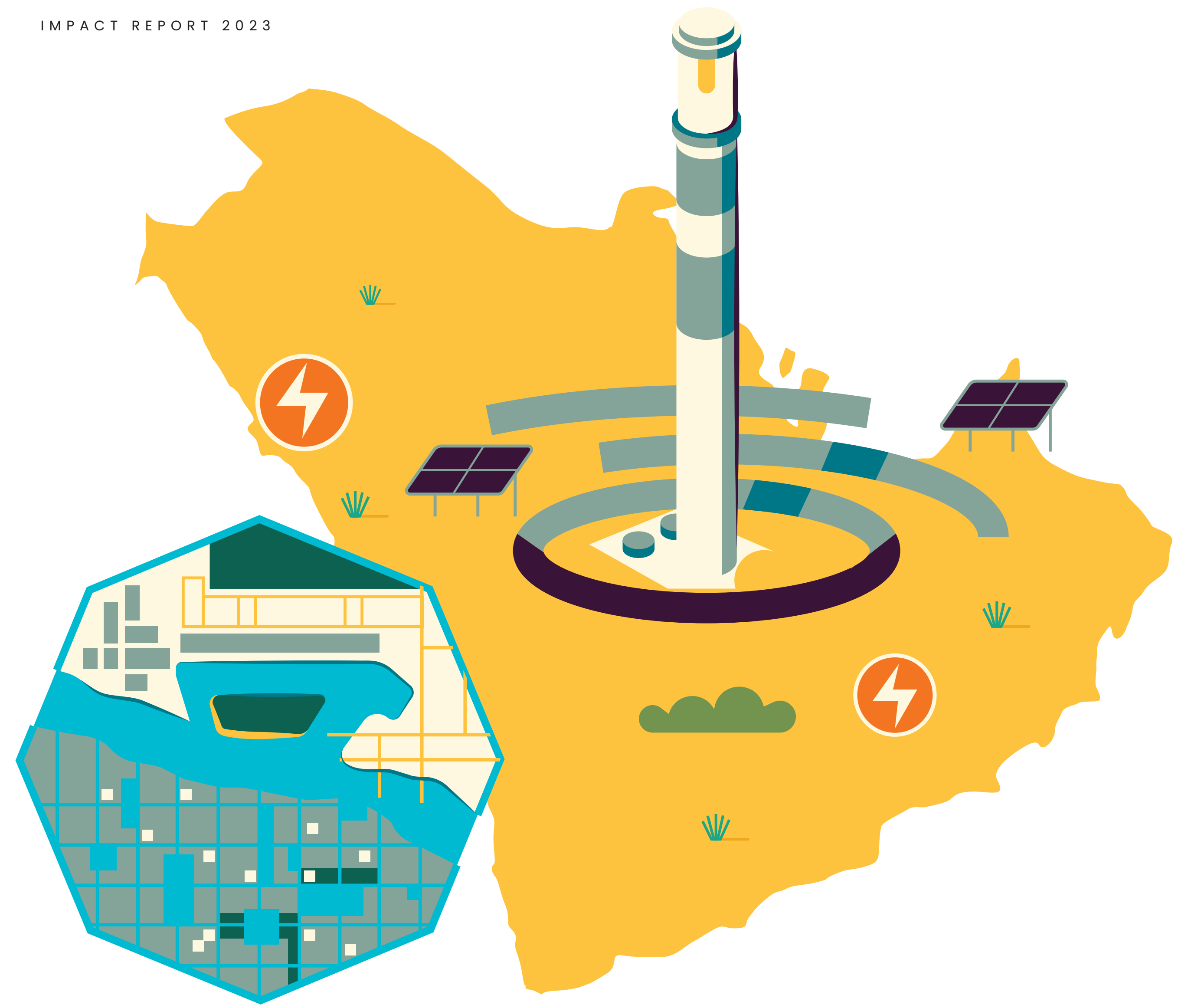


CALL TO IMPACT

1. Hydrogen is an indirect greenhouse gas when it escapes into the atmosphere.
2. Reducing leakage from all parts of the value chain will be essential.
3. The best time to address hydrogen's environmental issues is now, before take-off.

POWER PENINSULA

Arabia is one of the world's best-positioned regions for green hydrogen production. The competitive strategies of Saudi Arabia, UAE and Oman are likely to increase the productivity and the scalability of the sector.



ADVANTAGE MIDDLE EAST: On the Arabian peninsula, the cost of producing solar and wind energy and green hydrogen is estimated to be about one-third of the global average. Its renewable energy capacity doubled to 40 GW between 2010 and 2020 and is set to double again by 2024.

While all six countries of the Gulf Cooperation Council (Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, UAE) are strong players in the fossil fuel economy, just three of them have made significant steps into green hydrogen production: Saudi Arabia, UAE and Oman.

The Dubai-based project database MEED has calculated that Saudi Arabia and the UAE are home to hydrogen projects worth $10.5 billion and $10.3 billion respectively. Oman looks even more ambitious, with potential hydrogen sites estimated to have a combined worth of $49 billion.

SAUDI GREEN INITIATIVE

Under its Green Initiative, a part of the nationwide Vision 2030, Saudi Arabia plans to generate at least half of its power from renewable sources by 2030 and to become the world's largest supplier of green and blue hydrogen. It has set production targets of 2.9 Mt per year by 2030, rising to 4 Mt by 2035.

Saudi Arabia's flagship hydrogen project is NEOM, with the world's biggest electrolyzer facility to date under construction. The NEOM plant, NGHC, hopes to provide a model that other parts of the world will follow. Nadhmi Al-Nasr, chairman of NGHC and CEO of NEOM says: "Harnessing the energy of NEOM's abundant natural resources, NGHC's project will pave the way for the large-scale adoption of green hydrogen, while driving Saudi Vision 2030's sustainable development goals."

The country is also ahead of the curve on transitioning its infrastructure to clean hydrogen. In 2020, when the mostly state-owned oil company Saudi Aramco shipped 40 tonnes of blue ammonia from to Japan, it was the world's first demonstration of a blue ammonia supply chain.

PROJECTS IN MASDAR AND DUBAI

The UAE is also pursuing a massive build-up of renewable energy production. At 1.2 GW, Noor Abu Dhabi is the world's largest single-site solar plant, while the 2 GW Al Dhafra solar farm set a world record low price for solar energy of $0.01/kWh in December 2020. The country, host of COP 28 in December 2023, wants to demonstrate that the combination of transitory fossil fuel production and rapid growth of renewable energies is a reliable and sustainable strategy to fight climate change.

Green hydrogen is just one of the possible use cases for solar and wind energy. The replacement of fossil-powered electricity generation and desalination plants are equally important for carbon emissions reduction. Green hydrogen, though, is the most promising technology to generate exports with renewable energies.

In the UAE, France's Engie and Abu Dhabi's renewable energy business Masdar plan to invest $5 billion in the green hydrogen industry, aiming at 2GW of electrolyzer capacity by 2030.

Siemens Energy, the Dubai Electricity and Water Authority and Expo 2020 have collaborated to build a solar-powered green hydrogen plant at the Mohammed bin Rashid Al Maktoum Solar Park in Dubai, with a 1.6 GW capacity. Green hydrogen will be converted to electricity to power Dubai with sustainable energy at night.

OMAN'S EARMARKED 50,000 KM2

High-flying and advanced green hydrogen plans are being made by the Sultanate of Oman. The sparsely populated country in the southeast of the Arabian peninsula has already earmarked a whopping 50,000 km^2 for hydrogen projects - about one-sixth of its whole area, or the size of Costa Rica.

The projected hydrogen areas are of course not needed for the construction of electrolyzers or hydrogen infrastructure. They are necessary for the solar and wind plants that will generate the electricity for electrolyzers. This also needs a lot of money. The state-owned hydrogen company Hydrom predicts that up to $140 billion will be invested in Oman's hydrogen industry by the year 2050.

The targeted capacity of Oman's hydrogen industry in 2050 is 8 Mt of hydrogen per year. To produce this amount of hydrogen, renewable energy power plants with a capacity of 185 GW are needed.

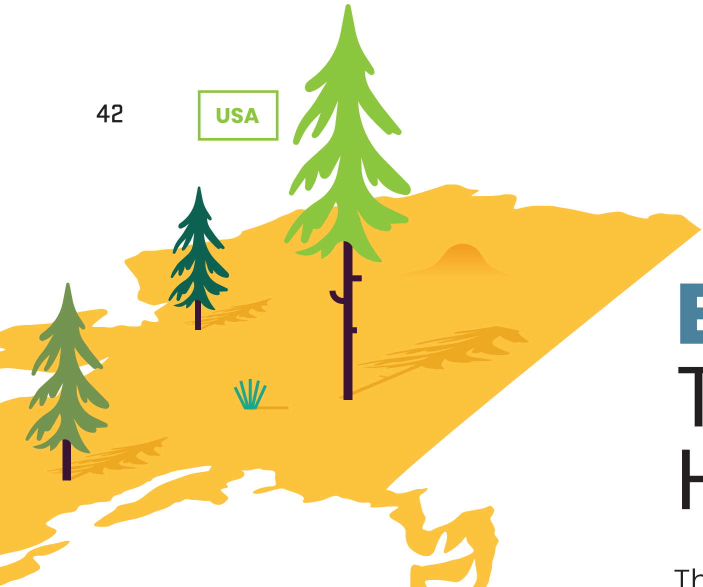
The biggest chunk of the projected hydrogen areas is located in Oman's southernmost provinces of Al Wusta and Dhofar. These two provinces combined cover an area bigger than Tunisia, but count less than one million inhabitants. They have lots of available space - so lots of potential for renewable energy production.

In 2023, the first five projects in Al Wusta province were awarded to international consortia, most of them with Omani participation. Three more projects in Dhofar will follow in 2024. The companies in these consortia are based in a wide range of countries, from the UK, Denmark and Germany to Japan, South Korea and Thailand.

While most of Oman's hydrogen production is designated for export as ammonia, a part of it will increase the country's manufacturing base. In the port city of Duqm, a plant for the production of five million tonnes of steel is to be constructed. Green steel of course, powered by hydrogen.

HYDROGEN PERSPECTIVE

1. Saudi Arabia plans to generate half its power from renewable sources by 2030, and to become the world's largest supplier of green and blue hydrogen.
2. In UAEs energy strategy, hydrogen is also produced for domestic use-cases.
3. Oman has ambitious and advanced hydrogen plans. One-sixth of the country is earmarked for green hydrogen production, mainly designated for export.



BRAVE AMBITION TO LEAD THE HYDROGEN RACE

The US has given major backing to clean hydrogen production, and big projects in related industries are cropping up across the country. Will this be enough to hit ambitious targets not far in the future?

IN 1969, WHEN HUMANS FIRST SET foot on the moon, the Apollo Command Module's primary internal power source was three hydrogen fuel cells, which produced the electricity needed to run systems, as well as water for the three-man crew to drink.

This US-made technology became the ancestor of modern hydrogen systems, which have grown in number and evolved in sophistication. Thousands of hydrogen and fuel cells have been developed and deployed to power systems across industry in the US alone, while money from the Department of Energy (DoE) has contributed to more than 1,100 related patents and 30 commercial technologies, with many more in the pipeline.

Launched in 2021,the US 1 1 1 Hydrogen Shot expressed a clear goal – to produce 1kg of hydrogen for $1 in the course of a decade. Published the following year, the draft National Clean Hydrogen Strategy and Roadmap, gives more explict detail. It states an aim to generate 10 Mt of clean hydrogen annually by 2030, double that figure by 2040, and 50 Mt by 2050, to reduce US carbon emissions by 10% that year compared to 2005.

The ambition is to realise the true potential of green hydrogen, which, while offering extraordinary potential for decarbonization, is currently expensive, tricky to manage and requires a lot of infrastructure.

Achieving cost competitiveness with carbon-based energy production is a must, particularly for decarbonizing key US sectors that would otherwise struggle,

> **"We can't allow these green hydrogen projects to incorrectly incentivize fossil fuel generators to increase their output on the grid, in order to meet the needs of electrolyzers."**
>
> **PETE BUDDEN**
> Natural Resoures Defence Defence Council

like metals manufacturing, chemicals and forms of transport, such as shipping and aviation, for which direct electrification is unworkable.

If the attempt is successful, the rewards will be huge and the US could become a net exporter of a valuable commodity. The DoE says that the global hydrogen market could generate $2.5 trillion in annual revenue by 2050, employ 30 million people and result in a 20% drop in global carbon emissions.

The strategy states: "The country can strengthen its energy leadership, create significant new investment and job opportunities, and help the world decarbonize by advancing and harnessing hydrogen technologies in a sustainable, competitive and equitable manner. The nation is in a unique position to lead, given its research, development, and deployment prowess, along with abundant supplies."

Acceleration is the key to reaching this future, facilitated by investors, business leaders, engineers and consumers. To this end, the 2021 Infrastructure Investment and Jobs Act included just under $10 billion funding for clean hydrogen, while the 2022 Inflation Reduction Act enacted supportive policies and incentives, including a production tax credit valued at just under $400 billion.

The DoE has promised to build on these foundations, responding to dialogue with industry, and revisiting its strategy every three years. That sounds like a plan, but are the targets attainable? Is green hydrogen truly viable in a country so fond of oil? And do the financial figures stack up?

POLICY IN MOTION

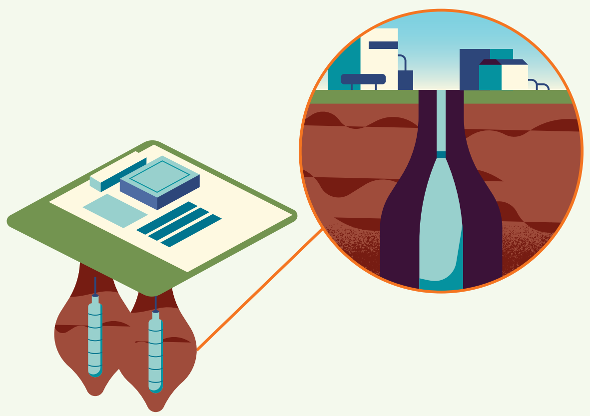
The key target, to generate 50 Mt of clean hydrogen annually within 27 years, sounds impressive, but perhaps less so in the context of a country which consumed more than 1,500 Mt of electricity-related CO2 in 2021 alone, despite a 37% decrease in power sector emissions since 2007. Nevertheless, with other green energy solutions in use and in the pipeline, it could make a highly significant contribution.

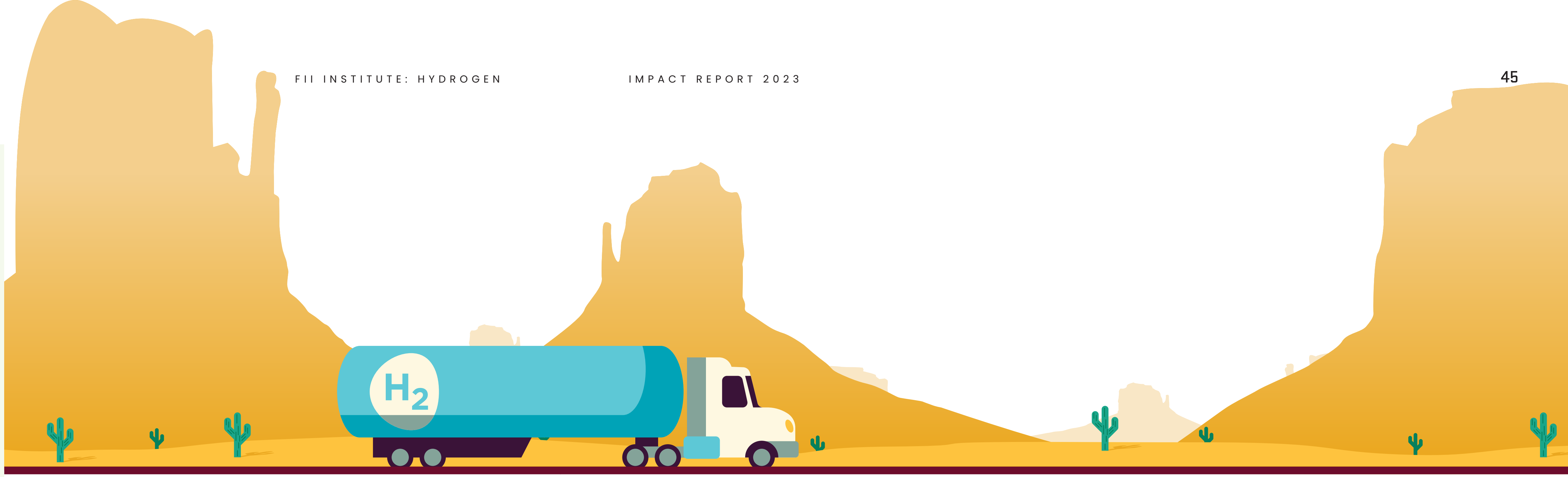
Industry appears to be playing ball, with several major projects being signed or in the works in 2023. New York-headquartered Plug Power, a Hydrogen solutions business that began as a manufacturer of forklift trucks, is working on a joint venture with Olin Corporation, which specializes in chlor-alkali production, to build a plant capable of producing 15 tonnes of green hydrogen per day in St Gabriel, Louisiana.

"The venture advances our commitment to transform Olin's hydrogen business into a value stream, as we seek to grow the value of our hydrogen production capacity," said Olin CEO Scott Sutton, announcing the tie-up in October 2022. Plug Power's national hydrogen network will extend to 1,000 tonnes of daily production by 2028, according to its stated goals.

Smaller plants are under construction across the country. The five-acre Sauk Valley plant in Illinois, built by Invenergy and featuring electrolyzer technology from Ohmium International, is set to begin production this year. Producing a planned 52 tonnes of green hydrogen annually, the project will help to power Invenergy's 584 MW Nelson Energy Centre, with surpluses being shipped for use off-site.

Speaking in July 2022, Invenergy's vice president of origination new technologies, Matt Nicholls, said ↘





FROM COAL TO GREEN HYDROGEN

The Advanced Clean Energy Storage project is a groundbreaking initiative led by Mitsubishi power Americas.

The project was launched early in 2022. In June that year it secured a $500 million government loan guarantee to provide long-term, seasonal energy storage via clean hydrogen – the first loan guarantee issued by the DoE to a clean energy project in nearly a decade.

Located in Delta, Utah, the scheme will combine 220 MW electrolysis capacity and 4.5 million barrel capacity in salt caverns to store green hydrogen. Green hydrogen will be piped to the Intermountain Power Agency's IPP power plant, which will transfer to renewable energy from fossil fuel, towards a target of 100% by 2045.

The hybrid plant will help to prevent more than 125,000 tonnes of carbon dioxide emissions annually with just a 30% green hydrogen fuel blend.

By adding advanced storage technology, Utah will enhance grid reliability, improve energy affordability, and significantly reduce carbon emissions associated with fossil fuel-based energy generation.

The DoE is backing the project, which is being run cooperatively with Magnum Development with backing from Haddington Ventures. The project is expected to create around 425 jobs, split between construction and operations.

Jigar Shah, head of the DoE's Loans Program Office (LPO), told reporters that the idea was to create a "multiplier effect".

He said: "The goal is to not just provide stimulus in the short term, but to create an institution that entrepreneurs and energy leaders can rely upon to help commercialize their technologies and build robust industries."

there was scope to grow: "Green hydrogen projects can scale rapidly and efficiently to reach megawatt to gigawatt applications."

A partnership between CF Industries and German electrolyzer manufacturer Thyssenkrupp seeks to integrate a new electrolysis plant into an existing ammonia production loop, eventually enabling the production of 20,000 tonnes of green ammonia per year.

The Donaldsonville green ammonia project in Louisiana, due to come online in 2023, will be the largest of its type in the US. Underlining the commercial scope of these business plans, in June Thyssenkrupp announced its intention to issue an IPO for its green hydrogen arm Nucera.

"Our goal is to participate significantly in the growth of one of the key enablers of the green transformation," said Thyssenkrupp chief executive, Miguel Lopez. "A potential IPO would enlarge the financial flexibility of Thyssenkrupp Nucera and raise its profile as a leading supplier of technology for the production of green hydrogen." Nucera's IPO in July 2023 raised about €600 million, valuing the company at about €2.5 billion.

The DoE is thinking big in the homegrown projects it is incentivizing. The Bipartisan Infrastructure Law includes up to $7 billion funding for between six and ten H_2 hubs across the US, creating new regional networks of producers, consumers and local connective infrastructure.

Out of 79 applications to the DoE, the 33 it encouraged have asked for nearly 60% of the total investments, with an average ask of $1 billion. The agency is prioritizing large, ambitious endeavors, rather than pilot-scale projects. Neighboring hydrogen hubs have strong incentives to partner with each other to decrease the number of applications per region.

BEWARE COLLATERAL DAMAGE

In essence, the US green hydrogen strategy focuses on hard-to-abate industrial sectors, energy storage and grid balancing, as well as solutions for heavy duty transportation.

But challenges remain in getting green hysdrogen to a scale that will allow it to make a significant difference to global emissions. In some quarters in the US, there are concerns that the amount of effort needed to promote large-scale green hydrogen production could ultimately do harm as well as good.

So generous are the grants, incentives and tax treatment of green hydrogen production that they may, some fear, drive private sector investment away from more attainable renewable energy solutions, potentially causing return to hydrocarbon-fuelled power stations to meet the increased energy demands of green hydrogen.

Achieving 50 Mt of green hydrogen production by 2050 would necessitate a vast increase in electricity generation and a massive investment in infrastructure, creating, in itself, an increase in short-term carbon emissions.

Based on current figures, production of that amount of hydrogen would need an additional 2,500 TW hours of electricity, a near two-thirds increase in the nation's total annual production.

"We can't allow these green hydrogen projects to incorrectly incentivize fossil fuel generators to increase their output on the grid, in order to meet the need of electrolyzers," Pete Budden, hydrogen lead at the Natural Resources Defense Council, told Reuters.

The target also assumes rapid technological progression, particularly in the construction and operation of electrolyzers which, according to the US clean hydrogen strategy, "will require high-volume manufacturing, innovations in electrolyzer stacks and balance of plant components, and electrolyzer integration in next-generation systems."

There is a strong emphasis in the national hydrogen strategy on collaboration and coordination to find the right way forward. Nothing is set in stone. Everything is open to review.

A national H2Hub scheme will crunch data from successful green hydrogen plants and identify "optimal approaches to market lift-off," so that they can be widely shared across the country.Despite its potentially circuitous and complicated road to a future powered by green hydrogen, the DoE says the US "can and must" succeed in fashioning a sustainable and resilient hydrogen sector.

"Though much remains uncertain, the potential for hydrogen is clear," states the strategy. "Focused investment and action in the near, mid-, and long-term are needed to lay the foundation for broader clean hydrogen adoption, to drive down cost, and increase scale in a sustainable and holistic manner."

It sounds a bit like the "space race," which history records the US won when NASA put a man on the moon in 1969. Generous funding, careful planning, honest assessment and readiness to adapt will all factor in the strategy's ultimate success or failure.

HYDROGEN PERSPECTIVE

1 Simple goals have powerful impacts. The US 111 Hydrogen Shot, launched in 2021, aims to produce 1kg of hydrogen for $1 in one decade.

2 The US Department of Energy is focusing on scale. It is funding the largest applications for plants and hubs, rather than demonstration-scale projects.

3 Reaching the target of producing 30 Mt of hydrogen a year by 2050 correlates to a near two-thirds increase on current national electricity supply.

EU PUTS MONEY IN THE HYDROGEN BANK

Eye-watering investment, high-level cooperation and the willingness to start yesterday are all needed for the EU's 27 member states to achieve their ambitious green hydrogen targets.

UNLIKE THE US, CHINA OR India, the EU has an added complication when it comes to formulating a renewable energy strategy, namely that 27 independent countries must agree on it, potentially having to compromise on their own priorities for generation and consumption.

A case in point was the renewable energy targets being negotiated in June this year, which involved rounds of wrangling and concessions to member states. At time of writing, no deal had been struck, despite the EU controversially allowing nuclear energy to qualify as a renewable source and potentially exempting from the target the use of fossil fuels for ammonia production in certain cases.

States like Germany, Denmark and Ireland lobbied for the EU to quickly resolve the quarrel with nuclear-powered states like France and Bulgaria, arguing that delay endangered investments in renewable technologies because of the uncertainty it creates. Meanwhile, several states in east and southern Europe complained that converting ammonia-producing facilities to use green hydrogen would require major industrial rebuilds, and so deserved extra time to hit carbon reduction targets.

All this is designed to enshrine in the rulebook a collective goal for the EU to derive 42.5% of its energy from renewable sources by 2030, and that net carbon emissions should plunge 95% by 2040, compared to 1990 levels.

Perhaps the need to negotiate everything is why the EU had no strategy on green hydrogen until July 2020, and that it took the pandemic, the war in Ukraine and the subsequent shock to energy markets to bring a sense of urgency to proceedings, with the so-called Fit for 55 package launched in the summer of 2021.

The original strategy includes 20 key actions to create a supportive framework, stimulate production, support strategic investment, scale demand and production and encourage cooperation with neighboring states.

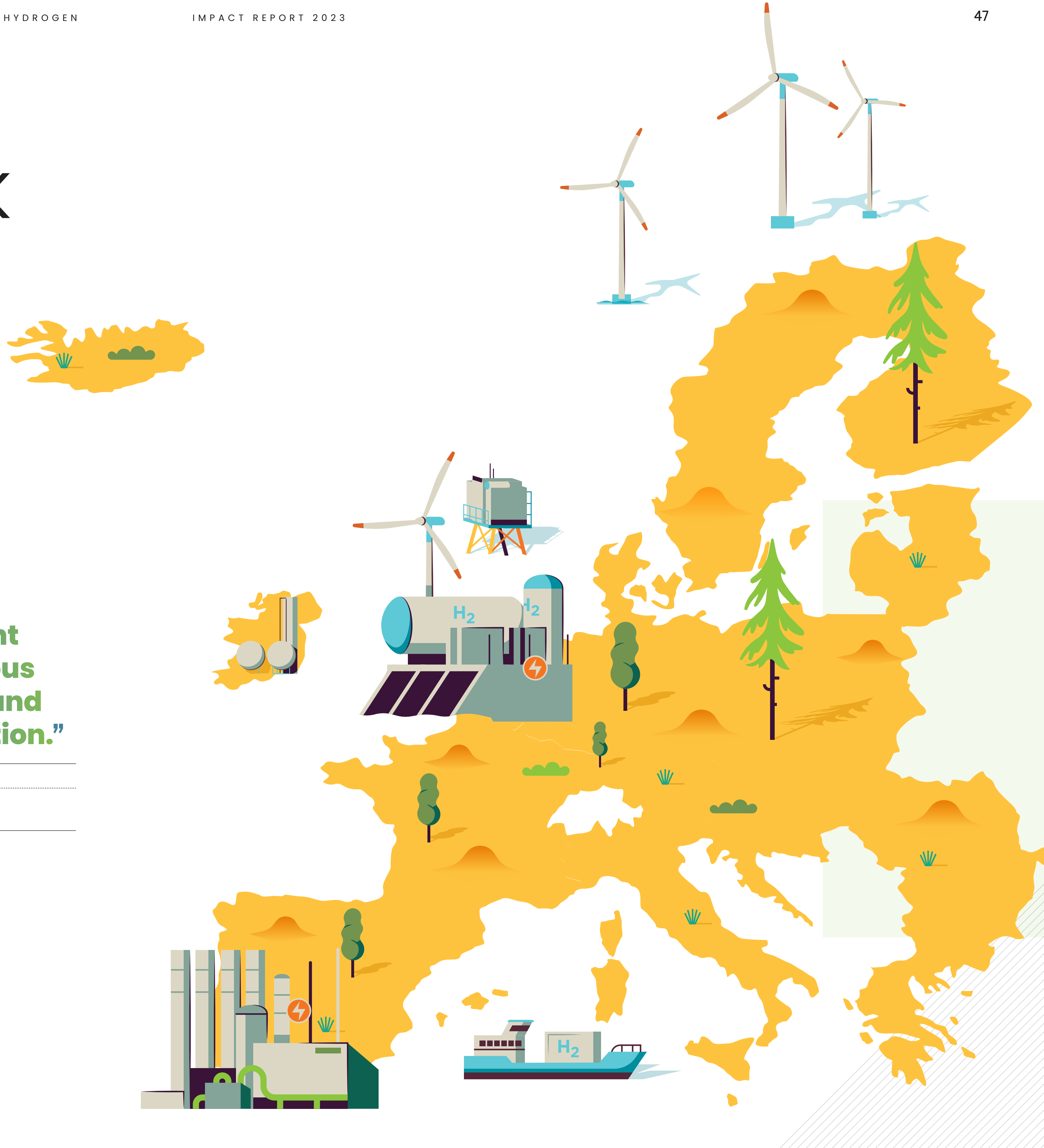
The European Commission's website suggests all 20 action points were implemented and delivered by the first quarter of 2022, although it's not completely clear how it measures delivery.

What did happen was the creation of a green hydrogen alliance involving scores of industry chiefs across the continent, a target of 10 Mt capacity by 2030 and the founding of a €3 billion "hydrogen bank" – a subsidy vehicle to stimulate the hydrogen value chain.

In its first funding round, billed for the autumn, the bank will allocate €800 million to projects capable of producing green hydrogen that can go online within three-and-a-half years, with subsidies capped at $4 per kilogram for the gas. Projects must aim for more than 5 MW of production.

According to Independent Commodity Intelligence Services (ICIS), producers awarded the full subsidy could regain their capital investment over the ↘

> "Initiatives require ongoing investment and rigorous research and collaboration."
>
> **MANISH NAYAR**
> Managing partner, OYA Ventures



↘ subsidy timeframe by charging buyers under €1 per kilogram of hydrogen.

These are tempting numbers – the catch being that the overall hydrogen bank budget is tiny. Speaking to news website Politico, Jorgo Chatzimarkakis, CEO of industry lobby Hydrogen Europe, said building 40 GW of electrolytic capacity across the EU carries a price tag of €430 billion.

Hydrogen production is embryonic. In 2022, hydrogen accounted for less than 2% of Europe's energy consumption, primarily to produce chemicals, and 96% of it was created using natural gas.

Going from this state of affairs to 10 Mt of renewable hydrogen production by 2030 seems ambitious – not least because, in the global marketplace, the EU is in competition with the US to sweeten the deal for businesses, a race it is currently losing. Chatzimarkakis says the hydrogen bank should dole out €3 billion per year, not as a one-off, to remain competitive.

NATURAL ADVANTAGES

Some EU countries have natural geological or environmental advantages.

"Countries like Norway that have a lot of access to water are doing important work to find new ways of electrifying communities, getting people off gas, and into clean tech like green hydrogen," says Manish Nayar, managing partner at OYA Ventures, an investor in technology and projects combating climate change.

"A next step for Norway is to focus on green hydrogen, as it builds on existing infrastructure to help communities get access to clean energy faster."

To stand a chance of reaching ambitious targets, the EU will need a collective change of priorities, says academic and founder of Earth Eclipse, Sonia Madaan. "Let's not forget that this endeavor isn't only about establishing an industry, but also changing mindsets. These initiatives require ongoing investment, perseverance and, like any early-stage technology, rigorous research and collaboration. In my experience with renewable solutions, it's not just about hefty investments, it's about a steadfast focus and a collaborative effort."

Examples of projects are emerging fast. Those getting off the ground include Estonia's Elcogen, which is developing an electrolyzer with fewer raw materials thanks to an optimized manufacturing process. Dutch business Nedstack is creating fuel cells for fixed and maritime use with a view to increasing efficiency and applicability.

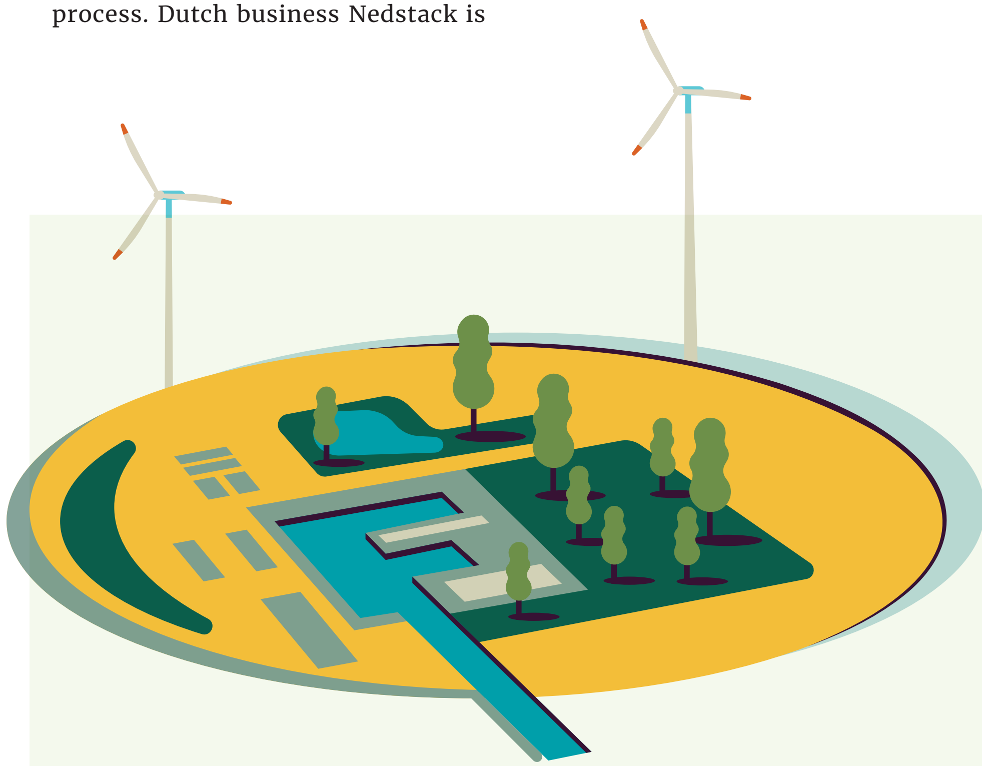
IPCEI Hy2Tech is a collaborative effort between 35 companies in 15 EU countries to build a functioning hydrogen market across Europe, the lack of which, the EU admits, "makes it risky for companies or even member states to invest alone in such innovative technologies." It comes with the potential for €5.4 billion investments, which will "crowd in" a further €8.8 billion of private investment.

Also at the larger end of the scale, a public-private partnership led by BP is aiming to make Valencia in Spain, a global leader in green hydrogen production. The HyVal cluster will see "world-scale green hydrogen production at BP's Castellón refinery of up to 2 GW of electrolysis capacity by 2030." The project is being funded by up to €2 billion of BP investment and will go online in phases, the first due for completion in 2027 with the installation of at least 200 MW of capacity, producing up to 31,200 tonnes of green hydrogen per year.

Projects like these are convincing analysts that green hydrogen production has reached an inflexion point. Bloomberg NEF estimates the global capacity of electrolyzers needs to soar from 2 to 242 GW by 2030 at an investment cost of $130 billion.

EU'S GLOBAL PLAYERS

Companies like Belgium-headquartered John Cockerill and Germany's ThyssenKrupp, as well as BP and ITM Power, both based in former EU member state the UK, are set to play pivotal roles on a global scale. Comparing current production levels of green hydrogen with near-term goals and looking at what needs to be done feels like placing an ant next to an elephant. But such is the goodwill, political backing, commercial interest and emerging technology associated with this carbon-busting energy source that reaching near-neutrality in 30 years could be a less outrageous target than it first appears. ■



PRIDE OF HOLLAND

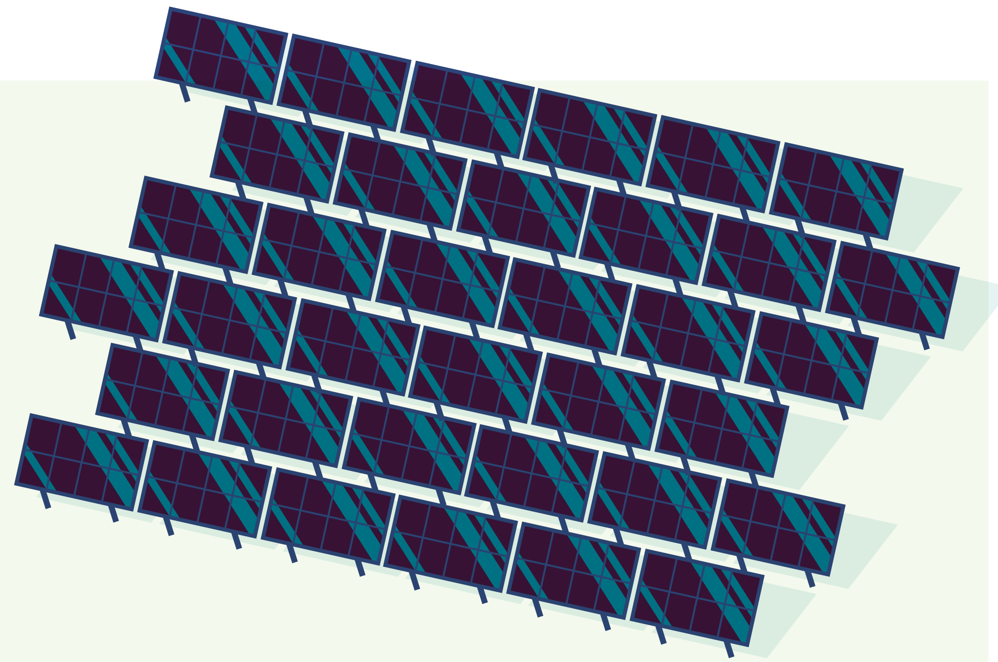
In July 2022, Shell Nederland and Shell Overseas Investments announced the decision to build Holland Hydrogen I, which the business claims will be Europe's biggest renewable hydrogen plant.

The 200 MW electrolyzer is to be constructed on the Tweede Maasvlakte, a large industrial area in the port of Rotterdam, and will produce up to 60 tonnes of green hydrogen per day when it goes live in 2025.

Shell said it wants to help build a global hydrogen economy by developing opportunities in the production, storage, transport and delivery of hydrogen to end customers.

"Renewable hydrogen will play a pivotal role in the energy system of the future and this project is an important step in helping hydrogen fulfil that potential," said Anna Mascolo, the company's executive vice president of emerging energy solutions.

Shell owns around 10% of global hydrogen electrolyzers, including a 20 MW plant in China and a 10 MW proton exchange membrane electrolyzer in Germany. It's working on several other projects with a potential capacity of 950 kt per year.



SPAIN'S SOLAR PIONEER

In May 2022, the King of Spain inaugurated a flagship green hydrogen production plant at Puertollano, once a coal-mining and oil-refining region in the southern central area. The installation, owned by Iberdrola, features 100 MW of solar energy production, 20 MWh storage capacity and a 20 MW of electrolyzer capacity.

It will produce about 8 tonnes of renewable hydrogen a day, supplying the Fertiberia Group's fertilizer factory in the town, thereby eliminating 48,000 tonnes of carbon emissions annually. It also boosted the local economy, involving around 80 companies and creating more than 1,000 new jobs.

Iberdrola's chairman, Ignacio Galán, said the project represents the launch of a €2 billion program to replace imported gas used for ammonia production. The Puertollano plant cost €150 million.

The plant will ensure that around 25% of the hydrogen consumed in Spain does not generate CO2 emissions.

Galán said the company plans to make Spain "a leading country in sectors of the future, such as renewable energies and now also green hydrogen and its industrial derivatives."

HYDROGEN PERSPECTIVE

1 In the EU, 27 independent countries must agree on priorities, balancing their own needs with collective ones for power generation and industry.

2 Success in green hydrogen is not just about researching technologies and establishing an industry, but changing the mindsets of consumers.

3 EU-based companies like Belgium's John Cockeril and Germany's ThyssenKrupp are global players in green hydrogen.

GOING BACK INTO EUROPE

Clean hydrogen made in the UK, could feed the industries and hydrogen highways of Europe, through an international grid, linking it to the EU, Norway and Switzerland.

THE UK WAS ONE OF THE FIRST countries in the world to industrialize, because of its abundant coal and iron ore resources. From the 1970s, it was able to extract large volumes of oil and natural gas from the North Sea.

The North Sea again became a valuable asset in the national quest to decarbonize that gained pace after the 2015 Paris climate agreement. The waters off the east coast of Britain are shallow and windy. They mean that the UK has more than one-third of Europe's total offshore wind resources and about one-third of its potential for carbon capture utilization and storage (CCUS) in saline aquifers and depleted oil and gas fields.

In October 2020, then prime minister Boris Johnson pledged the country would become the "Saudi Arabia of wind power," potentially supplying its entire electricity grid from that source by 2030. Also in 2020, the UK published a ten-point plan for a green industrial revolution and an energy white paper. In 2021, the year it hosted the high-profile COP 26 climate change conference in Glasgow, the UK announced a hydrogen strategy.

The strategy notes that the UK's geology, infrastructure and expertise make it well suited to rapidly developing a low-carbon hydrogen economy. Green and blue hydrogen will support the deep decarbonization, particularly in "hard to electrify" industrial sectors, and provide green flexible energy across power, heat and transport. The strategy sets a target of 10 GW of low-carbon hydrogen production capacity by 2030. It predicts that the UK will be a "world leader" in clean hydrogen, delivering up to one-third of UK energy consumption.

The UK has announced six areas for development as "zero carbon clusters." These are Grangemouth in Scotland, Teesside and Humberside (known as the East Coast Cluster), Merseyside, Southampton and South Wales. They are areas once associated with mining, iron and steel making, heavy industry, chemicals and North Sea oil.

Clusters will be used to trial CCUS. They are also hydrogen hubs, with plans for green and blue hydrogen production most advanced in the East Coast Cluster.

Anthony Boden, energy practice principal at consultancy Charles River Associates says: "Hydrogen as a support for decarbonization is nuanced around industry, power generation and storage – making sure that when there's less solar power, you've got backup hydrogen, either run through fuel cells or using power stations to create a power reserve."

He adds: "The electricity grid has to react in microseconds – an immediate supply/demand balancing act has to happen. Lithium-ion batteries are good for this. If you look at the mega packs built by Tesla in Australia, they can balance grids incredibly quickly. But I would imagine the energy systems of the future won't have one solution. It will be a multitude of solutions and storage methods lasting from milliseconds to six months and everything in between."

National energy systems will look at their existing infrastructure first to reduce the capital costs of transitioning to clean energy. In the UK, National Gas, which owns the national transmission system for gas, is carrying out a Future Grid project to see if it can be adapted to hydrogen for industrial or domestic purposes.

This question is not yet settled but the UK's first green hydrogen electrolyzers are moving closer to construction. Boden says: "What I envisage is collaboration on big, complex projects where you've got a demand center and a supply center and a connection between them being set up. Once that's formed it will be the basis of further connections and commercialization. Once you have national infrastructure, why not connect it?"

In the UK, Project Union is looking at repurposing existing pipelines to create a national network for hydrogen production, storage and use. The Ukraine crisis led to the UK importing liquified natural gas and exporting natural gas to Europe. Hydrogen interconnectors, Boden suggests, are likely to facilitate a pan-European energy economy.

Green and blue hydrogen made in the UK will feed the industries and hydrogen highways of Europe. A proposed European Hydrogen Backbone would consist of 60% adapted natural gas pipelines and 40% new ones. The 53,000 kilometer, €80-143 billion project would link the EU states.

Boden says: "There has been a dramatic change since the Ukraine invasion. Last winter, there was nervousness in Europe around whether the lights would stay on. There was talk of rationing. That has raised the topic of security of supply, and hydrogen has dominated a lot of conversations around large-scale energy flows."

HYDROGEN PERSPECTIVE

1 The North Sea, which provided oil and gas for the UK from the 1970s, is a great asset for offshore wind power and carbon capture and storage.

2 The crisis caused by the war in Ukraine led to the UK importing liquified natural gas and exporting it to Europe to maintain resilience.

3 A European Hydrogen Backbone supplied by the UK would- link the 27 EU member states using existing and new gas pipelines.

GREEN HYDROGEN IS A GAME-CHANGER

Green hydrogen can be produced far more cheaply than traditional fossil fuel energy, catering for local demand or global markets. For Africa, that's a chance to leapfrog the energy industry.

A STUDY COMMISSIONED BY the European Investment Bank, the International Solar Alliance and the African Union has revealed that green hydrogen has game-changing potential for Africa. The study focuses on three hubs – Mauritania and Morocco, southern Africa and Egypt. It states that "Africa has the best solar energy in the word."

The Africa Green Hydrogen Alliance was launched at COP26 and experts predict that the use of green hydrogen will help the continent to convert its abundant wind and solar resources and plentiful supplies of platinum group metals, used for batteries, into exportable energy, as well as providing affordable local electricity, decarbonizing fertilizer and steel production and supplying clean water from desalination. In Mauritania, several GW-scale green hydrogen projects are underway.

PILOTS AND PARTNERSHIPS

Analysis from international consultancy CV says that green hydrogen can be produced in Africa for less than €2 per kilogram, far cheaper than traditional fossil fuel energy, catering for local demand and allowing green hydrogen to be exported to global markets. As European countries try to free themselves from dependency on Russian gas, the study finds that Africa could annually supply 25 Mt of green hydrogen to global energy markets, equivalent to 15% of current gas usage in the EU.

It says €1 trillion investment in green hydrogen could reduce carbon emissions in Africa by 40%, replacing 500 Mt of CO_2 a year, and deliver the equivalent of more than one-third of Africa's current energy needs. Required to achieve this are national planning, regulation and incentive schemes to mobilize private sector investment, pilot projects and the development of commercial partnerships.

Mauritania in West Africa is set to be a key player in the continent's green hydrogen economy, thanks to the large deep-water port at Nouadhibou, the country's second-largest city. BP has also signed a memorandum of understanding with the Mauritanian government to collaborate on green hydrogen R&D and rolling out large-scale production.

The $40 billion AMAN project, with its 15 GW electrolyzer powered by 30 GW of solar and wind power, claims to be Africa's largest green hydrogen development to date. The project aims to produce 1.7 Mt tonnes of green hydrogen annually for local use and export by the end of the decade. It includes a scheme to supply 60 zero-emission hydrogen buses.

In another large project, the Chariot Energy Group is developing the 10 GW Project Nour at Nouadhibou. It has signed an agreement with the Port of Rotterdam to supply 600,000 tonnes of green hydrogen a year.

Meanwhile, a Mauritanian, German and Egyptian partnership is developing a $34 billion green hydrogen project near the capital Nouakchott, with an 8 Mt production capacity and a 10 GW electrolyzer.

> "Namibia has the potential to become one of the main renewable energy hubs on the African continent."
>
> **URSULA VON DER LEYEN**
> President of the European Commission

Namibia, one of the driest countries in Africa, "has the potential to become one of the main renewable energy hubs on the African continent and worldwide," says European Commission President, Ursula von der Leyen. Here, a major project is underway to provide Africa's first "net-zero village" – the Daures Green Hyrogen Village in the Dorob national park. The project will use solar and wind production with an energy profile of up to 1.5 GW.

It is being funded by the German ministry of research and education in its initial phase, with the aim of generating green hydrogen in the final quarter of 2023. Other notable projects include the $10 billion 3 GW Tsau Khaeb development from Hyphen Hydrogen Energy, the 2.5 GW Tumoneni project and the 50 MW Swakopmund project.

Namibia is also conducting feasibility studies for hydrogen valleys in Kharas, Kunene and Walvis Bay, which have been described as locations "blessed with a world-class blend of wind and solar renewable power resources."

HYDROGEN PERSPECTIVE

1. The European Investment Bank states that Africa has the best solar energy in the world, and that green hydrogen production has game-changing potential.
2. Africa could supply 25 Mt of green hydrogen to global energy markets annually, equivalent to 15% of current gas usage in the EU.
3. €1 trillion investment in green hydrogen could reduce carbon emissions in Africa by 40%, replacing 500 Mt of CO2 a year, and deliver more than a third of Africa's current energy consumption.

STEEP HILL TO CLIMB

In India, unfavorable cost economics, supply challenges and a lack of harmonized regulations and standards are holding back the replacement of fossil fuels, but the government has set an ambitious target for green hydrogen.

Aiming at 10% of the global market, India could annually export about 10 Mt of green hydrogen and ammonia.

NATIONAL GREEN HYDROGEN MISSION

ACCORDING TO THE PARIS Agreement, in order to keep global warming to no more than 1.5 °C, emissions need to reach net zero by 2050. While many countries have adopted this as their target, India's is two decades later – in 2070, an indication of the huge hill that the country has to climb.

Only China and the US are above India in the CO_2 emissions league table, with India's energy use doubling over the last two decades and the government estimating that it will increase by at least 25% more by 2030. The country now imports more than 40% of its primary energy requirements at a cost of more than $90 billion a year. Despite this, it has its sights set on becoming fully energy independent by 2047.

India hopes its landmark $2.3 billion National Green Hydrogen Mission will play a central role in achieving its targets. The focus is on shifting away from dependence on fossil fuels in key industries toward making India one of the world's leading producers and suppliers of green hydrogen. This will involve creating export opportunities – to Japan, South Korea, Europe and elsewhere – and pouring resources into developing India's green hydrogen manufacturing capabilities.

By 2030, India aims to have developed an annual green hydrogen production capacity of at least 5 Mt per annum, cutting almost 50 million tonnes of annual greenhouse gas emissions.

As of 2020, the country's hydrogen demand was 6 million tonnes a year, but the government estimates that hydrogen costs will have halved by 2030 and that demand will "see a five-fold jump to 28 million tonnes by 2050, with 80% of the demand expected to be green in nature."

India is basing the export element of its mission on an estimated global demand of more than 100 Mt of green hydrogen – and derivatives like green ammonia – by the end of this decade.

"Many countries are likely to rely on imports due to constraints on land and renewable resources required to produce green hydrogen domestically," the mission document says. "Aiming at about 10% of the global market," India could potentially annually export about 10 Mt of green hydrogen and green ammonia, it estimates.

SKILLING UP

One facet of the green hydrogen mission is the Strategic Interventions for Green Hydrogen Transition (SIGHT) program, which includes financial incentive mechanisms for domestic electrolyzer manufacture and green hydrogen. The mission will also incorporate a range of pilots, public-private R&D projects and green hydrogen hubs, as well as a coordinated programme to skill up the work-force to meet the sector's needs as it grows.

Given the scale of the challenge and the "nascent status" of the sector, the Indian government is looking to a phased roll-out of the mission. The initial focus will be on deploying green hydrogen in sectors that already use hydrogen, and "evolving an ecosystem for R&D, regulations and pilot projects". Later phases will then see green hydrogen initiatives spreading across different sectors of the economy.

The government sees significant potential in green hydrogen replacing fossil fuels in a wide range of sectors, including long-haul transport, refining, fertilizers, iron and the move towards "zero-carbon steel," as well as potentially aviation and shipping.

It's also looking at the potential of fuel cell electric vehicles (FCEV), with August 2022 seeing India's first hydrogen fuel cell bus enter service in the city of Pune. "The mission will support pilot projects in hard-to-abate sectors like steel, long-range heavy-duty mobility, shipping and energy storage for replacing fossil fuels and fossil fuel-based feedstocks with green hydrogen and its derivatives," the government states.

GREEN SPACE

Government confidence has been boosted by the fact that some of the country's key industrial players, including the National Thermal Power Corporation (NTPC), the Indian Oil Corporation and multinationals Reliance Industries and Larsen & Toubro are enthusiastically entering the green hydrogen space.

Reliance Industries aims to reduce the production cost of green hydrogen to less than $1 per kilogram by the end of the decade, while NTPC has embarked on the country's first blending project for green hydrogen with piped natural gas.

The Indian Oil Corporation, has set up green hydrogen plants at two of its major refineries – in Panipat and Mathura – and intends to replace at least 10% of its fossil fuel-derived hydrogen with green hydrogen. It has also commissioned the country's "first 99.999% pure" green hydrogen plant in Assam.

The huge Adani Group has announced its intention to become a leading green hydrogen producer, and in April 2023 Reuters reported that the government was planning to offer green hydrogen fuel producers incentives of at least 10% of their costs in a new $2 billion scheme to boost the sector.

"India's distinct advantage in terms of low-cost renewable electricity, complemented by rapidly falling electrolyzer prices, can enable green hydrogen to be not just economical compared to fossil-fuel-based hydrogen, but also compared to the green hydrogen being produced around the globe," the government claims.

However, alongside all the "unique possibilities and advantages," the Indian government also acknowledges that unfavorable cost economics, supply challenges and a lack of harmonized regulations and standards have "thus far held back the replacement of fossil fuels and fossil fuel-based feedstock with green hydrogen or its derivatives."

But the government adds that "recent trends and analysis indicate that, driven by technology advancements, reduction in costs of renewable energy and electrolyzers and aggressive national strategies by some of the major economies, green hydrogen is likely to become cost-competitive in applications across industry, mobility and other sectors within a short span."

Not everyone is quite so sure, however. As laudable and ambitious as India's stated mission is, some commentators have questioned quite how realistic its targets might be.

Although India has achieved a 66% increase in renewable energy capacity over the last five years, it still fell short of its installed renewable energy target for 2022 by more than 30%.

HYDROGEN PERSPECTIVE

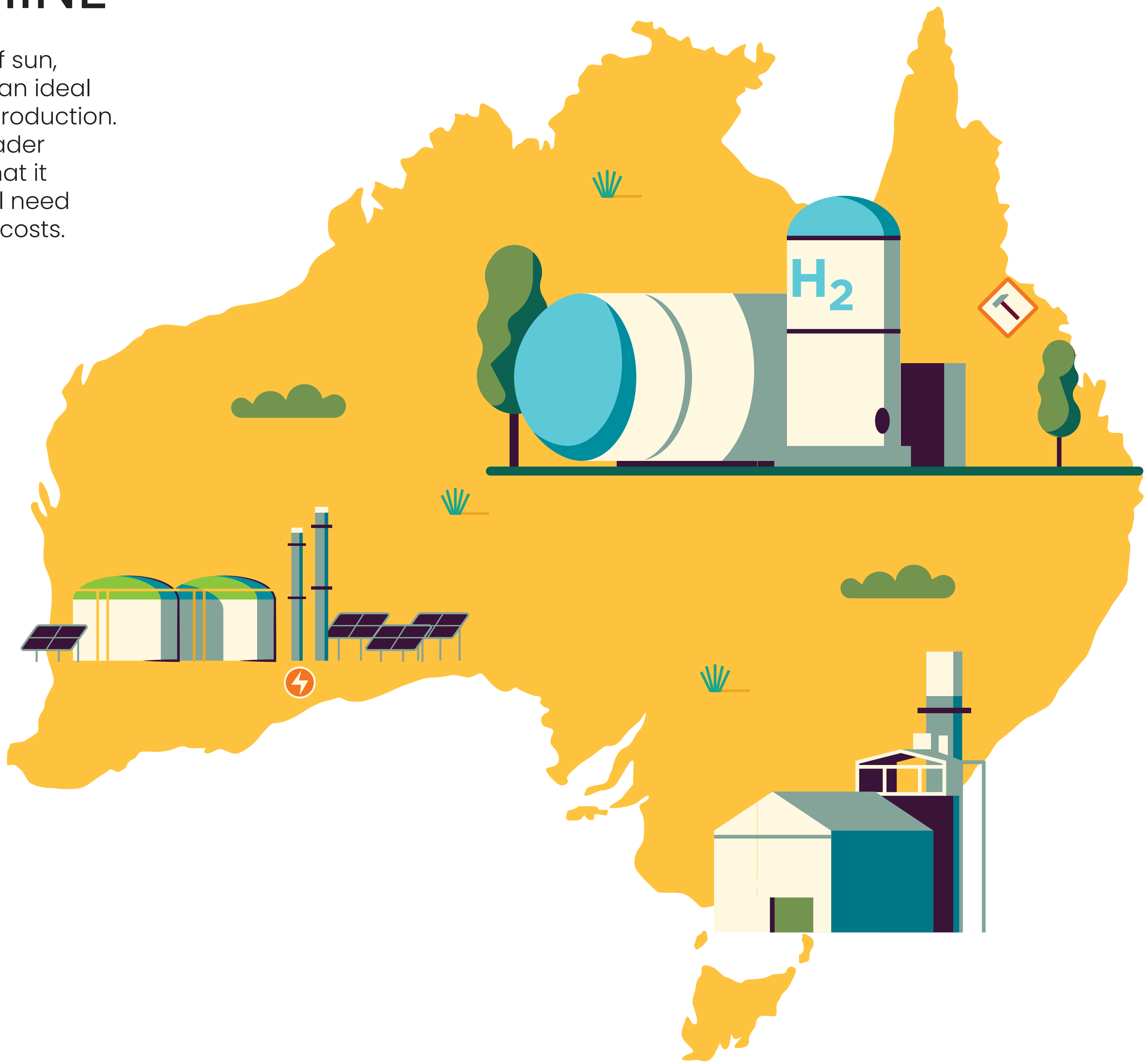
1 Unfavorable cost economics, supply challenges and a lack of harmonized regulations have held back progress on green hydrogen in India.

2 Water availability may be a constraining factor, as 1kg of green hydrogen requires 10 liters of water, and India is water stressed.

3 Hydrogen hubs will need to be water- and renewable energy-rich, and close to major demand centers to be commercially viable.

SHIPPING WIND AND SUNSHINE

With its abundant supplies of sun, space and wind, Australia is an ideal setting for green hydrogen production. But to become the global leader in green hydrogen exports that it aspires to be, the country will need to drive down its production costs.



AUSTRALIA IS AN IDEAL LOCATION to generate green hydrogen using clean energy. According to the International Energy Agency's World Energy Outlook report from 2022, Australia is set to become the second-largest net exporter of low-emission hydrogen by 2030 and the largest by 2050.

"Green hydrogen is at the heart of our vision for Australia as a prosperous, self-reliant nation in a net-zero future, as a renewable energy superpower and as a country that makes things," writes climate change and energy minister Chris Bowen in the foreword to the country's Trade and Investment Commission website.

Green hydrogen, it states, opens the door to products like green metals, green fertilizer, and green chemicals. Green iron could become a new green hydrogen derivative, helping to cut emissions and creating jobs. The country sees green hydrogen as crucial to supporting sectors like transport and fertilizer production and helping them to significantly reduce emissions. The national strategy has also identified opportunities for hydrogen vehicles in the fleet and public transport sectors, and Australia has been working hard to establish a range of regional hydrogen hubs.

Thanks to favorable regulation and direct government support of more than A$1.3 billion, Australia claimed to have, at 96, the largest number of green hydrogen production facilities anywhere in the world in 2022, followed by Germany and Spain with 50 each, and the Netherlands with 48.

The country has been proactively developing international supply chains through a wide range of partnerships to establish itself as a preferred supplier. In fact, 2022 saw Australia become the first country to export hydrogen – albeit blue hydrogen derived from carbon capture utilization and storage – on a specially designed ship, the Suiso Frontier, to Japan.

HUBS AND COLLABORATIONS

An A$454 million Regional Hydrogen Hubs program aims to establish hydrogen hubs in Gladstone and Townsville in Queensland, Bell Bay in Tasmania, and the Pilbara in Western Australia. In New South Wales, the government is pledging up to A$3 billion of incentives to support industry development to deliver 110,000 tonnes of green hydrogen production per annum by 2030, as well as a 90% exemption from electricity network charges for green hydrogen producers. A hydrogen refueling station network is being rolled out.

Another project is an ambitious attempt to green Australia's existing gas supply. A partnership with gas provider AGIG is blending green hydrogen into the country's gas network, with a 1.25 MW electrolyzer commissioned for AGIG by Siemens Energy in 2022.

"What's really making the difference this time round is the falling cost of renewable electricity," said AGIG's chief executive Craig de Laine. An important factor, he says, is keeping the electrolyzer running: "if you only use it a few hours a day, each kilogram of hydrogen produced will be expensive. So you need readily available, cheap renewable power."

According to PricewaterhouseCoopers, Australia's abundant land and "high-capacity renewable energy" could well be the building blocks to producing "globally competitive green hydrogen to service a growing international market."

But the country will need to drive down its production costs to become the global leader in green hydrogen exports that it aspires to be. This would need concerted efforts by both government and industry to reduce the cost of large-scale electrolyzers while also increasing their efficiency, as well as boosting investment in low-cost renewable energy.

"Australia will be competing with other energy-rich, export-oriented nations, such as Saudi Arabia, South Africa, Morocco and Chile," wrote PwC's Lachy Haynes in the report. "It's critical that export pathways, confidence and reputation are established today so that Australia remains at the forefront as the hydrogen export industry develops."

As Australia works toward its ambition of becoming a world-leading exporter of green hydrogen, dissenting voices are beginning to emerge. Some of the international collaborations are controversial, especially those that aren't based on renewable energy.

A joint venture with Japan to produce and export hydrogen from brown coal (lignite) has been launched in Victoria, for example. "Coal-to-hydrogen is going to be dead on arrival and is a waste of taxpayers' money," argues Nick Aberle of the Environment Victoria NGO. "The technology will be superseded in the next few years by clean hydrogen sourced from renewable energy."

HYDROGEN PERSPECTIVE

1 Austrailia is an ideal country to generate green hydrogen using renewable energy sources.

2 It will be competing with other energy-rich exporting nations, such as Saudi Arabia, South Africa, Morocco and Chile.

3 Some of the country's international collaborations, especially those not based on renewable energy, are controversial.

PLAYING CATCH UP

Japan's lack of natural resources has meant that historically it has imported the majority of its energy. Although it is making headway in becoming a "hydrogen society," it is lagging behind the EU, the US and China.

JAPAN BECAME WAS THE FIRST country in the world to adopt a national hydrogen framework when it published its Basic Hydrogen Strategy in late 2017. Four years later, in an update to its strategy for achieving carbon neutrality by 2050, it committed to expanding its hydrogen market from the current 2 Mt per year to 3 Mt by 2030 and a leap to 20 Mt by 2050. By this date it also hopes to have driven down the cost, so that green hydrogen will be cheaper than natural gas.

Japan's eagerness to embrace green hydrogen stems from far more than the need to address climate change and meet its carbon-neutral targets. It is a country that lacks many natural resources, with virtually no cobalt, nickel, bauxite, nitrates or phosphates, and, crucially, very little crude petroleum and natural gas. This means it has traditionally been dependent on importing almost 90% of its energy from overseas, making it the second-largest importer of liquefied natural gas after China.

The role of nuclear power in Japan's energy mix was dealt a crushing blow by the 2011 Fukushima disaster, in which the most powerful earthquake the country had ever experienced triggered a tsunami that hit the Fukushima Daiichi nuclear plant – and caused the worst nuclear accident since Chernobyl. Symbolically, a site that launched in March 2020 and claims to be the world's largest facility for producing green hydrogen, the Hydrogen Energy Research Field, is located at Fukushima. The 180,000 square meter site uses electricity from solar sources to conduct electrolysis in a 10 MW green hydrogen production unit.

RESEARCH AND DEVELOPMENT

The Japanese government's focus on funding research and development for emerging energy technologies – partly out of concern over European and US competition – saw Japan's national research and development agency, New Energy and Industrial Technology Development, commit $700 million toward generating green hydrogen in 2021 as part of wider $3 billion allocation to establish a large-scale hydrogen supply chain. The money for this comes from the country's Green Innovation Fund.

Japan's Strategic Energy Plan spells out how hydrogen will provide a key means of decarbonizing sectors like steel and petrochemicals. Its Shipping Zero Emission Project also includes plans for expanding the use of hydrogen and ammonia, with the aim of producing the rollout of the first generation of zero-emission ships by 2030.

Perhaps the most high-profile aspect of Japan's move towards becoming a "hydrogen society" is how it has been leading the way in producing hydrogen cars, or fuel cell electric vehicles (FCEV), in which fuel cells convert the hydrogen to electricity. Hydrogen tanks can be refueled from a pump in about five minutes, which is a far quicker process than recharging an electric car.

The Ministry of Economy, Trade and Industry aims to have 800,000 FCEV on the road by 2030 alongside a network of almost 1,000 fueling stations. The country already has the largest fleet of hydrogen refueling stations in the world, at more than 130, and there are fuel cell buses operating in Tokyo.

Toyota's flagship fuel cell vehicle, the Mirai passenger car, was launched as early as 2014. The company is now building a 700,000 square meter prototype city at the base of Mount Fuji: Woven City, with a "fully connected ecosystem powered solely by hydrogen fuel cells." Its partner, petroleum company ENEOS, will produce green hydrogen to supply the community.

Despite all the outward appearance of progress, according to some commentators, the reality is more complicated. A report by the Tokyo-based Renewable Energy Institute (REI), warned that "Japan's efforts in producing green hydrogen needed to achieve a decarbonized society have fallen behind those of European countries, China, and other nations."

One reason for this is the slower than hoped-for development of electrolyzers, another is higher renewable energy costs. "Europe will be able to take the lead in green hydrogen development as it is projected to generate nearly 70% of electricity from renewable energy sources by 2030 at less than half the cost of Japan," the report says.

For the next few years, it's likely that Japan will have to rely, much as it previously did with hydrocarbons, on imports. Hydrogen produced in Japan currently costs about $2.50 per kilogram, whereas that figure is expected to drop to $0.70 per kilogram by 2050 in Australia in India, according to the International Renewable Energy Agency

In the future, the Middle East is likely to become a key partner in supplying Japan's green hydrogen needs. The country has already begun importing blue hydrogen from Australia's Latrobe Valley, although the project has been the source of some criticism due to its dependence on carbon capture, utilization and storage.

> "Japan's efforts in producing green hydrogen have fallen behind those of Europe."
>
> RENEWABLE ENERGY INSITUTE
> Reexamining Japan's hydrogen strategy, 2022

HYDROGEN PERSPECTIVE

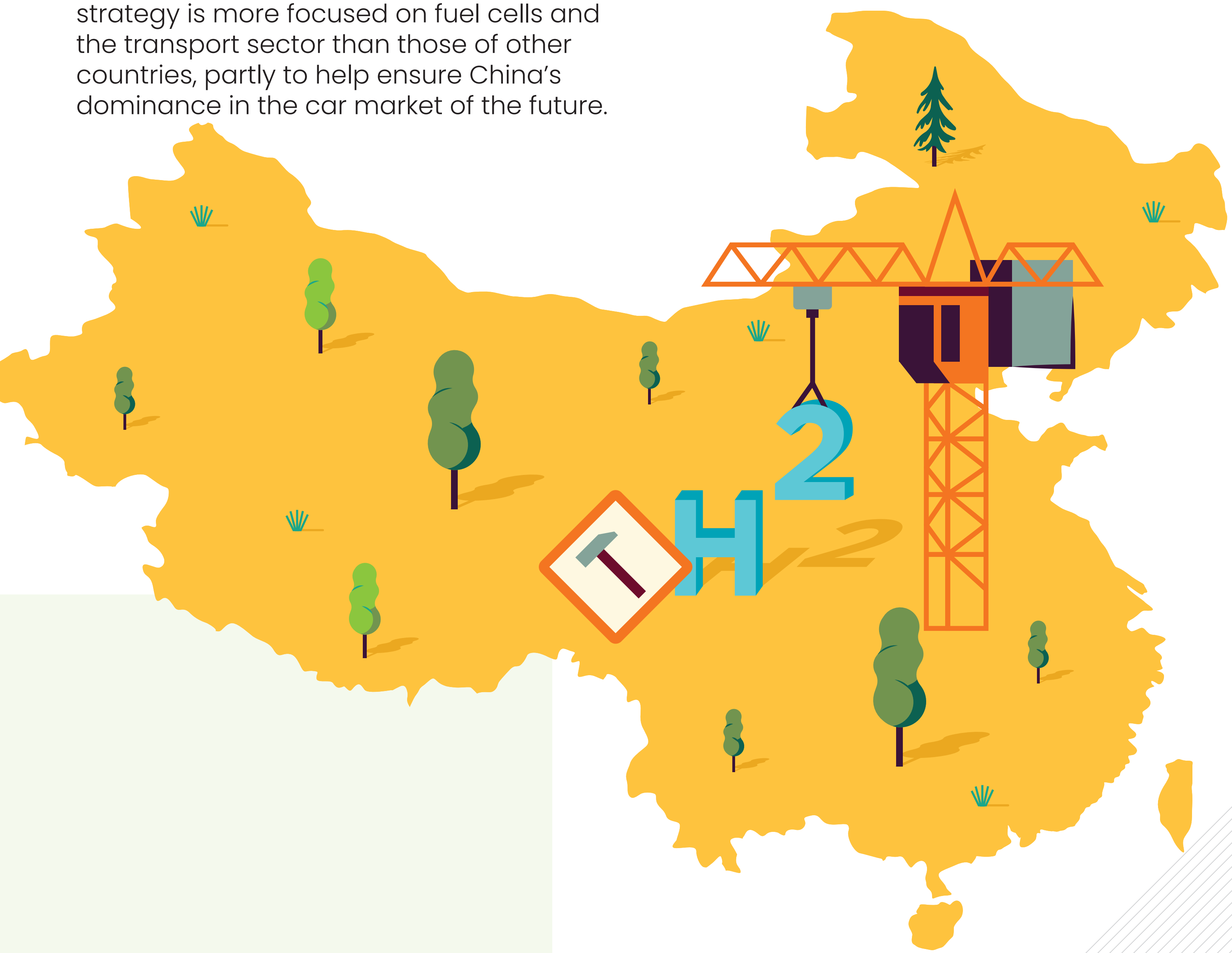
1 Japan has traditionally been dependent on importing almost 90% of its energy. It is the second-largest importer of liquified natural gas after China.

2 The role of nuclear power in the country's energy mix was dealt a crushing blow by the Fukushima disaster of 2011.

3 In the future, the Middle East is likely to beome a key partner in supplying Japan's green hydrogen needs.

RICH RESOURCES

China has the potential to be a global player in green hydrogen, but its current strategy is more focused on fuel cells and the transport sector than those of other countries, partly to help ensure China's dominance in the car market of the future.



WHILE CHINA IS CURRENTLY the world's largest producer of hydrogen – at around 30 Mt a year – the vast majority is created using coal and natural gas, with just 4% classified as green hydrogen. China's annual carbon emissions are also the largest of any country in the world, at more than 11 billion tonnes.

However, the National Development and Reform Commission (NDRC), the country's economic management agency, has plans to change that. And it sees green hydrogen production as an important element of a national low-carbon energy and industrial strategy.

The country set out its medium and long-term hydrogen development plans in 2022. It aims to produce between 100,000 and 200,000 tonnes of hydrogen from renewable sources by 2025. By 2030, the NDRC hopes to have "put in place a relatively complete hydrogen energy industry development system."

Other elements of the plan are 50,000 hydrogen fuel cell vehicles by 2025 and an extensive hydrogen fuel station network to power them. Zhejiang province alone aims to have 5,000 fuel-cell buses in operation by the same year.

China's planned $828 million green hydrogen plant in Ulanqab, central Inner Mongolia has been described as the world's largest "green hydrogen-coal chemical project." Being developed by Beijing-based oil and gas company Sinopec, the Erdos Wind-Solar Green Hydrogen Project will include wind and photovoltaic power generation, hydrogen production by water electrolysis, hydrogen storage and transport.

It aims to produce 30,000 tonnes of green hydrogen and 240,000 tonnes of green oxygen a year, which will be used to reduce carbon emissions from the adjacent ZTHC energy-intensive coal processing pilot project in Ordos.

It will include a 450 MW wind farm and 270 MW solar farm. A pipeline is planned to transport up to 100,000 tonnes of hydrogen per year to Sinopec's Yanshan Petrochemical plant in Beijing. The project has the capacity to store almost 300,000 m3 of green hydrogen.

> **"China has not yet fully embraced green hydrogen as a tool for decarbonization."**
>
> **INSTITUTE MONTAIGNE**
>
> China, a giant biding its time, 2023

Sinopec, which launched a $470 million green hydrogen pilot program in Kuqa, Xinjiang in 2021, says it expects the project to reduce CO_2 emissions by more than 1.4 million tonnes per year, by decarbonizing industry and helping to reduce reliance on gray hydrogen.

A 2023 report from the Institut Montaigne states that although China is "gradually implementing policies and strategies to promote green hydrogen, it has not fully embraced it as a critical tool for decarbonization."

This is because its strategy is still focused more on fuel-cell vehicles and the transport sector, it says – partly to help ensure China's dominance in the car market of the future, rather than in green hydrogen production itself.

The Institut Montaigne document agrees that, while Chinese electrolyzers are less expensive than their European counterparts, European PEM electrolyzers tend to outperform Chinese alkaline electrolyzers. But it also points to China's abundant resources of solar and wind energy in key regions such as Inner Mongolia.

A report in the previous year from the Mercator Institute for China Studies (MERICS) points out that, while China is already responsible for around one-third of the world's electrolyzer manufacturing capacity and can produce almost all the key components, apart from hydrogen valves, domestically and at competitive prices, some industry insiders claim these "are not yet up to international standards in terms of efficiency and reliability, especially for large systems."

However, the report argues that, with investment "pouring in" and an ever-growing number of demonstration projects, China's electrolyzer makers will be able to scale up and refine their technologies in the future so that they are comparable with those of other countries in the world.

This could mean that, with the help of the Inner Mongolia Erdos Wind-Solar Green Hydrogen Project, China could, in the next few years, become a global green hydrogen player.

HYDROGEN PERSPECTIVE

1 China sees green hydrogen production as an important element of the country's national low-carbon energy and industrial strategy.

2 It has abundant resources of solar and wind energy in key regions, such as inner Mongolia, site of a planned $828 million green hydrogen plant in Ulanqab.

3 China is responsible for about a third of the world's electrolyzer capacity and can produce almost all the key components.

ASSISTING THE TRANSITION

FOR THE WORLD TO MAKE AND use clean hydrogen on the scale required, coordination and agreement between countries will be vital, working to common goals and timescales. To help this process, we offer a nine-point charter, including a global hydrogen strategy.

The task is huge, even for a player as big as the global energy industry. Right now, 120 Mt of hydrogen are produced each year, of which two-thirds is pure hydrogen and one-third is in a mixture with other gases. Today's hydrogen production is mostly based on natural gas and coal as heating sources, which together account for 95% of production – gray, black and brown hydrogen.

There is currently no significant hydrogen production from renewable sources. Green hydrogen has been limited to demonstration projects adding up to a total capacity of less than 1 GW. It is calculated that, by contrast, limiting global warming to 1.5 °C would require 4-5 TW of capacity by 2050. That could only be achieved by a faster rate of growth than those of solar photovoltaic and wind technologies to date.

This points to a gargantuan global project. It's not just the transition of the hydrogen industry, it's a full-scale reinvention. And it's not just a typical growth process, but more an explosion, reaching ten, a hundred, a thousand times the size of today's green hydrogen production in less than three decades.

The market alone will not deliver the full benefits of integrating clean hydrogen into transport, power generation, heating and industry. For this aspect of the energy transition to have maximum impact, coordination and agreement between countries, working to common goals and timescales, would be highly desirable.

Why shouldn't that happen? Humans are at their best when working to solve a common problem. And this is a big one: saving the planet. Who could broker such an unprecedented project – a global hydrogen strategy? It would need to be a body acknowledged and recognized by all the countries of the world.

Impact would like to acknowledge the help of the International Renewable Energy Agency (IRENA), REGlobal and Environmental Defence Fund in producing this charter.

HTTPS://WWW.IRENA.ORG/ENERGY-TRANSITION/TECHNOLOGY/HYDROGEN

HTTPS://REGLOBAL.CO/STRATEGIES-FOR-COST-REDUCTION-OF-GREEN-HYDROGEN/

HTTPS://WWW.EDF.ORG/BLOG/2022/03/07/HYDROGEN-CLIMATE-SOLUTION-LEAKS-MUST-BE-TACKLED

A CHARTER FOR GREEN HYDROGEN

1. After conducting a cost-benefit analysis of applications and policy instruments, every country or region needs to produce an accessibly written and geographically specific hydrogen strategy, outlining overall ambitions and setting KPIs, including contribution to greenhouse gas reduction targets, sector by sector.

2. Strategies should be open-minded, "technology-neutral" and based on circular economy principles, such as using end-of-life materials, and not designed to favor one production method. In a nascent state like that of the hydrogen industry, even experimental or small-scale technologies can have enormous potential.

3. The role of a government or regional governance body is to facilitate market creation and help to scale up processes to commercial viability. This should be done by integrating clean hydrogen into net-zero policies, financing research and development and setting favorable taxes, including carbon disincentives, and production quotas, regulations and land-use policies.

4. Policymaking is not a one-way process. Consultation and listening to the views of stakeholders are essential. Policymaking should embody environmental justice, particularly when it involves changing current practices and creating significant infrastructure, affecting local and indigenous communities.

5. More research is needed on the warming effects of atmospheric hydrogen relative to other greenhouse gases. Preventing hydrogen leakage will require equipment capable of measuring hydrogen concentrations at the parts-per-billion level and avoiding "leaky" applications, for example by maximizing the security of gas grids.

6. Combusting hydrogen in air produces not only water, but also nitrogen oxides (NOx), which are not direct greenhouse gases but highly toxic. This is an issue for hydrogen-burning power plants and the use of hydrogen for space heating. NOx pollution should be minimized. Methane leakage must also be controlled for blue hydrogen to deliver net climate benefits.

7. A methodology should be adopted to evaluate the global warming effects of hydrogen, $C0_2$ and other greenhouse gases, based on a common standards, to allow meaningful near and long-term comparison. This is currently problematic, hampering the evaluation of different processes for climate impact.

8. The public need to be inspired and brought on board. This can be facilitated by clear explanation, focusing on benefits. Perhaps products derived from green hydrogen could have guarantee-of-origin programs and labels. Perhaps a universal labeling system could quantify carbon impact of products.

9. Clean hydrogen should benefit everybody. A global hydrogen strategy should be produced, guided by producing the maximum impact on climate change and the maximum leveling up between rich and poor countries. It should include a worldwide audit of resources and make recommendations on the optimum location of projects across the entire value chain.

THE FOURTH AGE OF HYDROGEN WILL HELP THE WORLD TO REACH NET ZERO

FII-I has three pillars to deliver its mission: THINK, ACT and XCHANGE

1 FII-I THINK
Identify societal challenges and current inhibitors. Curate the brightest ideas to address societal issues

2 FII-I ACT
Catalyze innovation and initiatives by mobilizing partners and resources

3 FII-I XCHANGE
Create platforms for live discussions on the future of humanity. Share knowledge, stories and publications with different stakeholders

IN 1807, THE WORLD'S FIRST internal combustion engine ran on hydrogen. However, it was more expensive and inconvenient than refined oil as a fuel for cars, and it failed to catch on. From the late 19th century, hydrogen seemed to promise an era of mass airship transportation, until the Hindenburg disaster of 1937 ended that dream. In the 1970s, a global oil crisis brought hydrogen to the attention of car manufacturers. That bubble burst when the crisis ended.

The fact that hydrogen can now be produced at scale using cheap renewable energy, geopolitical tensions making hydrocarbons expensive and hydrogen's net-zero credentials, have led to a remarkable renaissance. The "fourth age of hydrogen" is only just beginning. But it is here to stay.

Zero-carbon electrification and the use of clean hydrogen are set to transform the world long before the end of this century. By then, virtually all hydrogen will be clean – it will no longer be designated by color. But the role of hydrogen in reaching net zero is not well understood. In this report, we seek to explain it and provide some markers and policy imperatives for the fourth age.

ABOUT THE FII INSTITUTE

THE FUTURE INVESTMENT INITIATIVE (FII) INSTITUTE is a global nonprofit foundation with an investment arm and one agenda: Impact on Humanity. Global, inclusive and committed to Environmental, Social and Governance (ESG) principles, we foster great minds from around the world and turn ideas into real-world solutions in four key areas: AI and Robotics, Education, Healthcare and Sustainability. We are in the right place at the right time: when decision-makers, investors and an engaged generation of youth come together in aspiration, energized and ready for change.

We harness that energy into three pillars: THINK, XCHANGE, ACT.

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- Our XCHANGE pillar builds inclusive platforms for international dialogue, knowledge-sharing and partnership.

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is guided in all it does by a strong purpose, vision and mission.

PURPOSE
"Enabling a brighter future for humanity"

VISION
"Bringing together the brightest minds and most promising solutions to serve humanity"

MISSION
"Creating a purposeful present, promising future"

PHOTO: ADOBE STOCK, FII INSTITUTE

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“ONE DAY HYDROGEN AND OXYGEN WILL FURNISH AN INEXHAUSTIBLE SOURCE OF HEAT AND LIGHT.”

JULES VERNE, 1875

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